The Palgrave Handbook of Climate History

Edited by

Sam White · Christian Pfister
Franz Mauelshagen

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CHAPTER 1

General Introduction: Weather, Climate, and Human History

Christian Pfister, Sam White, and Franz Mauelshagen

In the twenty-first century, man-made global warming has emerged as one of the most pressing issues for the future of humanity and the environment. However, climate variability and climate change are not new. To put anthropogenic warming in perspective, we need to understand natural climate variations, extremes, and forcings, as well as the history of climate science. To appreciate how humans can (or cannot) deal with climate change, we need to consider how past climates influenced societies and how those societies responded and adapted to their challenges. Moreover, to fully understand events and developments in human history, we need to recognize the roles that climate and weather have (and have not) played in our past.

This handbook introduces students and scholars to the vital field of climate history: the interdisciplinary study of past weather and climate variations, and their place in human history. Drawing together dozens of experts from multiple disciplines, it presents the state of the field, including:

- methods of climate and weather reconstruction from human sources, such as written records and early weather instruments;
- techniques of indexing, mapping, and modeling climate data;

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- the history of weather and climate variations for each region and period of human history since the last ice age;
- the impacts of climate variations on agriculture, conflict, health, and migration in history;
- case studies of exceptional decades of climatic variability and their human impacts;
- the history of climate ideas and climate science.

This introductory chapter explains the basics of how climate history works, outlines the core issues in climate history, provides essential background to the field (in Europe and the USA), and concludes with a guide to using this volume.

1.1 Climate History and Historical Climatology

Climate history remains a diverse field. Its scholars come from many disciplines and academic departments, and they approach their work in different ways. Some deal primarily in quantitative methods and others in qualitative. Some would identify themselves as environmental historians and others as economic historians, geographers, or even climate scientists. Nevertheless, state-of-the-art research in climate history typically follows certain core principles.

First, climate history makes use of one or both of two approaches of climate reconstruction: *paleoclimatology* and *historical climatology*. Paleoclimatology here refers to the statistical reconstruction of past climates from physical sources left by natural processes, or what this volume will call "the archives of nature." Historical climatology here refers to the reconstruction of past climates and weather from physical and written sources left by humans, or what this volume will call "the archives of societies" (see Fig. 1.1 and Chap. 3). Because paleoclimatology has become a large and specialized area of research with its own textbooks, this volume will focus on the methods and results of historical climatology. It is particularly from this that climate historians derive much of the precise, local information needed to understand climate and weather impacts on the human world. The case studies provided in Chaps. 32–35 illustrate how climate historians combine paleoclimatology and historical climatology in state-of-the-art research.

Second, climate history draws on the methods and standards of *historical research*. These include training in languages, paleography, and the critical analysis of historical sources. Climate historians—just like other scholars of history—should be intimately familiar with the texts and contexts of their region and period of study in order to judge the reliability and meaning of their source materials (see Chap. 4). Many, but not all, also develop the same practices of narration and qualitative analysis practiced in conventional branches of history.

Third, climate history is concerned with understanding the role of climate and weather variations in events and developments of the *human* past. This concern distinguishes climate history from other fields. Unlike conventional history, climate history does not treat climate and weather as something exogenous to the human experience, nor does it assume that human history can be explained only by examining human factors. Unlike (paleo)climatology, climate history focuses on human experiences. Its researchers are interested in learning about specific past events for their own sake, and not only as they relate to larger climatic patterns or trends.

The term "climate history" has a complicated background. For climatologists, it means simply the history of the earth's climate, its long- and short-term variability from the beginnings of the atmosphere to the present. Paleoclimatology, as the study of climate prior to the period of instrumental measurements, constitutes a well-established field within climatology.[1] By contrast, historians began using the term "climate history" some fifty years ago to label a novel field of historical study: how weather and climate changed during the recorded past and how those variations affected human history. These two versions of "climate history" overlap in important respects. Both involve reconstruction of climates in the period before instrumental measurements. Each may contribute data and insights to the other. On the other hand, paleoclimatology has a scope of billions of years, uses physical rather than descriptive records, and is not concerned with the historical impacts of climate.

The term "historical climatology" is similarly complicated. Its usage was established by a seminal 1978 article in *Nature*, which outlined the techniques of reconstructing past climates from human records.[2] Researchers in the field used the term in part to help their research gain acceptance as a valid method of climate reconstruction within the larger discipline of climatology. Gaining that acceptance among climate scientists constituted a major achievement of the field. However, researchers trained in the humanist historical tradition have never felt entirely comfortable with the label "historical climatology." Most historians simply do not think of themselves as climatologists, even when involved in reconstructing climates of the past. At the same time, the practice of historical climatology has been inherently interdisciplinary, combining expertise from the humanities and natural sciences (meteorology, climatology, and physical geography). To understand their source material and carry out climate reconstruction, historical climatologists have also worked on issues of historical climate impacts, perceptions, vulnerabilities, and adaptations. Thus they have often used the term "historical climatology" in the same sense as historians have used the term "climate history."

In this volume we try to establish a clear and simple terminology. We use "climate history" in the historians' sense only; and we identify paleoclimatology and historical climatology as two different fields of climate reconstruction, the former using the archives of nature, and the latter using the archives of societies. Nevertheless, the reader should be aware of the inconsistent and overlapping use of these terms elsewhere.

1.2 Methodological and Conceptual Challenges

Methodologically and conceptually, climate history grapples with two sets of core issues. Many of the methods, themes, and case studies in this volume reflect these issues and the techniques employed to address them.

First, climate history must integrate data and perspectives from history and the humanities with those from the natural sciences and sometimes social sciences. This integration poses several challenges. Climate historians need to bridge qualitative and quantitative information and methods, particularly in the analysis of past climates reconstructed from written records. Moreover, the analysis of human history often operates on different scales from the analysis of climate science. Atmospheric events taking place over weeks, days, or even hours may have a decisive influence on human societies, while for the climatologist these may represent little more than statistical "noise." Historically, individuals rarely observed long-term climate change directly. They usually experienced climatic change in terms of the frequency and severity of extreme weather events or environmental challenges. Finally, the natural and social sciences tend to emphasize long-term patterns and probabilities, whereas history tends to focus on particularity and contingency. Historians, unlike scientists, "tend to eschew broad generalizations, partly because it is the detail, the differences from one case to another, which is central to historical research."[3]

Figure 1.1 provides an overview of evidence and approaches used in paleoclimatology and historical climatology, and how these relate to each other. Both disciplines have developed methods to reconstruct climate elements such as temperature and precipitation from *proxies*, or indirect representations of past climate. Examples from the archives of nature would include the width of tree rings, and from the archives of society the dates of grape harvests (see Chap. 3). Historical climatologists subsequently developed their own approach to climate reconstruction, climate indices, which combine the interpretation of historical weather narratives and proxy data (see Chap. 11). It often helps to compare the results of historical climatology with high-resolution evidence from the archives of nature, especially where written sources are not abundant. Human perceptions and interpretations of weather and its impacts on the human world constitute another focus of climate history, closely tied to cultural and economic history. Weather constitutes the physical and psychological nexus between people and the atmosphere.

The second set of methodological and conceptual issues in climate history concerns causality. In general, research in climate history seeks to demonstrate causation and not merely correlation between climatic and human develop-

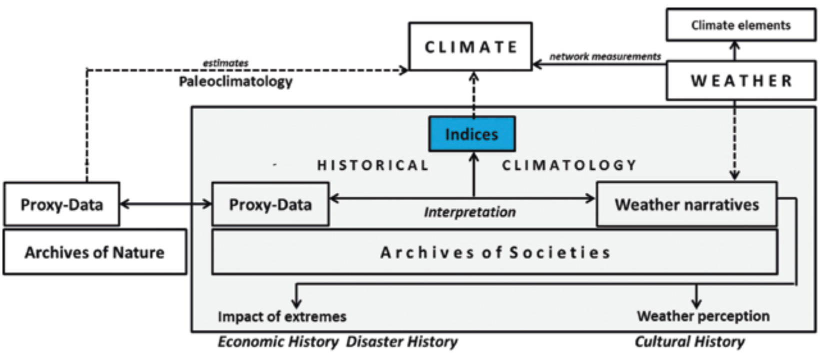

Fig. 1.1 Schema of evidence and approaches in paleoclimatology and historical climatology

ments. Even where circumstantial evidence strongly suggests some influence of climate change or variability on past societies, direct causal links can be difficult to prove. Figure 1.2 illustrates this problem schematically.

As shown in Fig. 1.2, at each step—from biophysical impacts to economic impacts to political and culture change—the role of weather variations becomes

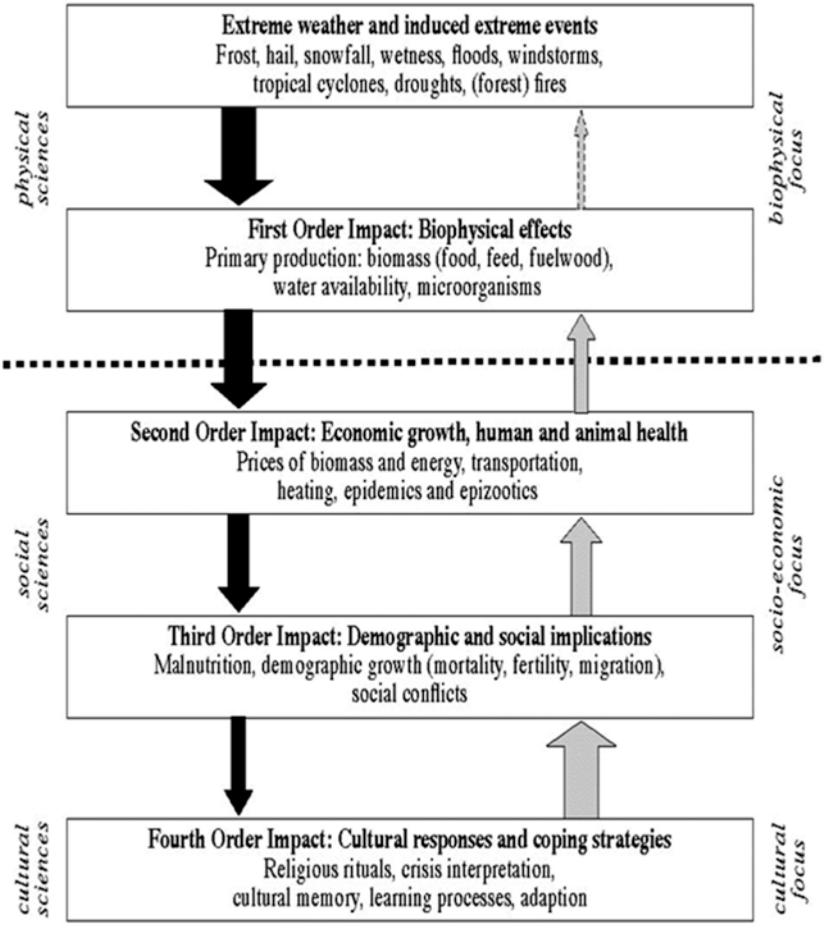

Fig. 1.2 A schematic linear model of climate–society interactions (from Krämer 2015). This simplified model of climate and society illustrates how extreme weather and climate can have a range of consequences, starting with immediate first-order effects on biomass production, which in turn may cause second-order effects on economic growth, water availability, and human and animal health. Third-order effects include demographic and social changes, and resource conflicts. Fourth-order (cultural) effects may range from the persecution of marginal people to the adoption of new adaptation strategies. The diminishing width of the arrows represents how causality becomes less direct moving from climate through biophysical, economic, social, and cultural effects, and back again.

less certain. Climate and weather reconstruction, therefore, is often just the first stage in climate history research. Much of the work in the field is involved in demonstrating actual series of events connecting climate change with human impacts; in exploring additional historical factors and explanations; and above all in understanding societal vulnerabilities, responses, and adaptation in the face of climatic and meteorological challenges.

For decades, climate historians have been anxious to establish the role of weather and climate in the past while avoiding the problem of *climate determinism*, or the fallacy that climatic factors control the development of societies. On the one hand, most historians and many sociologists "have chosen to ignore the possible importance of climate on the development of society," or have explicitly rejected the role of environmental factors altogether.[4] On the other hand, many science articles and popular science books that claim to identify some climate-driven crisis or collapse continue to confound correlation with causation. Sociologist Nico Stehr and climate physicist Hans von Storch argue that "a large proportion of today's climate impact research is genuine climate determinism."[5] The challenge for climate history lies in giving climate and weather their proper place in human affairs without obfuscation or exaggeration.

1.3 Background

The idea that climates and climate change could influence societies and history can be traced as far back as ancient authors such as Herodotus, or the works of Enlightenment thinkers such as Montesquieu, Voltaire, and Gibbon (who understood the term "climate" in a very different sense: see Chap. 36). Systematic efforts to compile evidence on past weather and climate date back only to the late nineteenth and early twentieth centuries (at least in Europe and the USA).[6] A few scholars, notably German geographer Eduard Brückner (1852–1927) and English meteorologist C.E.P. Brooks (1888–1957), gathered evidence of climate events and variability from European historical sources from the Middle Ages onwards, making the case for their economic and political consequences.

Starting in the mid-twentieth century, two scholars in particular helped establish climate history as a significant field of research. Celebrated French historian Emmanuel Le Roy Ladurie (b. 1929), who had a passion for studying past weather and climate, pioneered the integration of phenological data such as grape harvest dates with human records in order to reconstruct seasonal temperature during past centuries. His 1967 monograph *Histoire du climat depuis l'an mil* (*Times of Feast, Times of Famine*) spread his influence beyond the French-speaking world and drew public attention to historical climatology. This influential book also included an important chapter about glacier variations in the French and Swiss Alps, which helped popularize the concept of an early modern "Little Ice Age" (see Chap. 23). Nevertheless, Le Roy Ladurie concluded his book by stating that "in the long term the human consequences of climate seem to be slight, perhaps negligible, and certainly difficult to detect."[7] Although well aware of the human significance of short-term climate effects, he was concerned about problems of interpretation, and later admitted he feared being discredited as a climate determinist.[8] At the turn of the millennium, once global warming was drawing public and scholarly attention back to climate in human affairs, Le Roy Ladurie came out with a stronger case for short-term climate impacts in his three-volume *Human and Comparative History of Climate*.[9]

Hubert Horace Lamb (1913–97) was a meteorologist and climatologist with a passion for human history. Working in the UK Meteorological Office, he discovered "an immense archive of virtually untapped historical weather data," from which he was able to reconstruct "meaningful circulation patterns for past climatic periods."[10] During the 1960s, Lamb established the first modern synthesis of European climate over the last millennium, which formed the basis for his 1972 *Climate: Past, Present, and Future* and his later popular works. In particular, he drew a comprehensive picture of the "Medieval Warm Period," as he called it, based on archaeological, botanical, and documentary evidence. Moreover, Lamb was the first researcher to attempt a conclusive in-depth investigation of the global impacts of large tropical volcanic eruptions, for which he developed the well-known volcanic Dust Veil Index. He, too, took pains to eschew climate determinism: "Human history is not acted out in a vacuum but against the background of an environment in which many sorts of change are always going on besides the changes imposed by man," he wrote. Elsewhere he stated:

> "In sum, the impact of climatic fluctuations and change on history, and on human affairs today […] can best be seen as a destabilizing influence and catalyst of change. At the worst, we see reactions by human society which have amounted to shifting or concentrating the burdens of suffering onto the weakest members of the national and international community."[11]

Lamb also served as founding director of the Climate Research Unit (CRU) at the University of East Anglia in Norwich, UK. Still one of the world's leading centers of climate change research, it played a vital role in fostering the development of climate history, providing a center for historians to work alongside climatologists. Scholars at the CRU, including W.T. Bell and Astrid Ogilvie, developed standards for deriving reliable climate data from historical sources.[12] In 1979 the unit hosted the first major conference in historical climatology, providing an interdisciplinary umbrella for more than 250 historians, geographers, climatologists, and archaeologists from more than thirty countries, who had been working more or less in isolation.[13] Several participants, such as Maria del Rosario Prieto (see Chap. 21), helped bring historical climatology research to new countries and continents.

The conference resulted in seminal publications, establishing some key methodologies in climate history (see Fig. 1.3). For example, Christian Pfister introduced his innovative seven-point monthly temperature and precipitation index (see Chap. 11).[14] American economic historian Jan de Vries presented statistical models of climate impacts on food prices in the early modern Low Countries.[15] Swiss geographer Heinz J. Zumbühl provided the methodological tools for dealing with pictorial evidence of glacier movements (see Chap. 8).[16] In line with public discussion about the food and energy crises of the 1970s, a number of attendants presented papers on the role of weather and climate in past subsistence crises, which became an important subject of climate history research (see Chap. 27). Economic historian John Post examined the key factors in mortality peaks during subsistence crises using case studies of the 1740s and 1810s in Europe, demonstrating that the poor sanitary conditions of famine refugees promoted deadly outbreaks of diseases such as typhus and typhoid.[17] Figure 1.3 outlines the main methodological steps in the development of climate history starting with the approaches of Le Roy Ladurie and Lamb.

During the late 1980s and early 1990s, climate history lost some ground, especially among the new generation of historians in the USA and Western Europe. During these years, sometimes known as the "cultural turn," mainstream historians shied away from quantitative approaches and "positivistic" facts of material life. Instead of further investigating socioeconomic implications of past weather and climate, historical climatologists became involved in national and international research programs directed at reconstructing past climate, primarily temperatures. For instance, the 1989 European Science Foundation project entitled European Palaeoclimate and Man since the Last Glaciation involved spatial reconstructions of monthly weather in Europe for the Late Maunder Minimum (1675–1715), mostly based on documentary evidence in the framework of a database named Euro-Climhist.[18] In this context, Joel Guiot conducted some of the first ever research to assess temperatures through a combination of biophysical and written records; and climatologists Heinz Wanner and Jürg Luterbacher developed statistical approaches for spatial field reconstruction (see Chap. 12).[19] The CRU broadened its work into paleoclimatology and climate modeling, while continuing to support research into historical climatology.

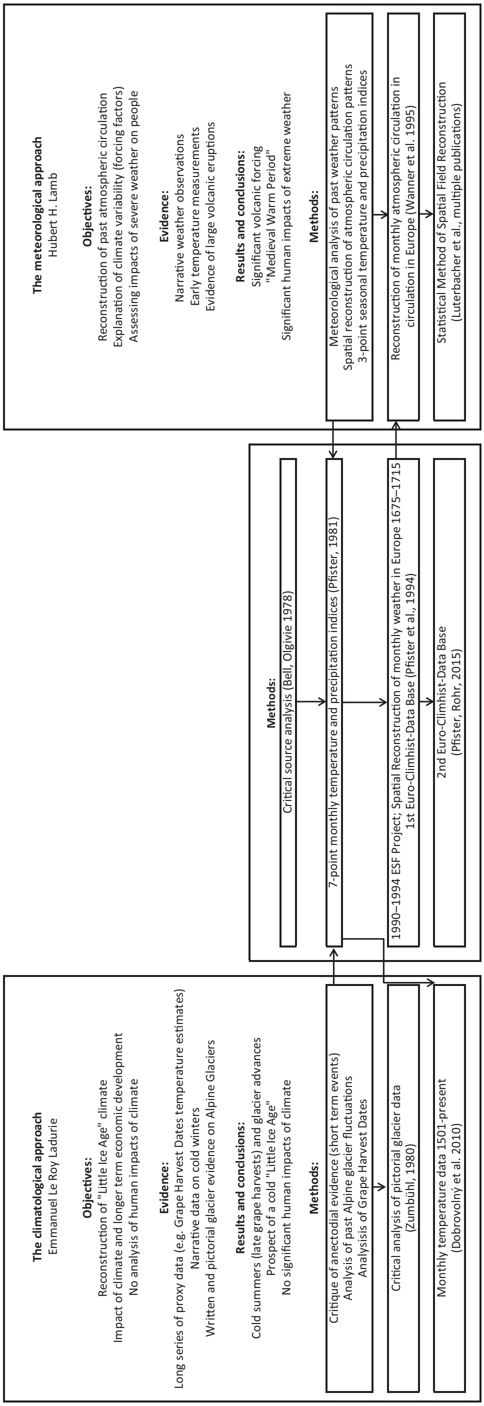

Fig. 1.3 The main methodological steps in the development of climate history

1.4 New Influences: Environmental History, Globalization, and Global Warming

By the 2000s, several developments restored interest in historical climatology and reshaped the field of climate history. First was the rise of environmental history as a major scholarly field in the USA and then Europe. Although climate and weather were not leading themes in environmental history until the 2010s, the rise of environmental history nevertheless opened up new possibilities for the study of environmental factors in the human past, as well as the use of natural sciences and interdisciplinary insights in historical research. Climate history has also fitted into other major research areas of environmental history, particularly natural disasters. Even as historical climatologists and climate historians organized fewer independent conferences and publications, more researchers became involved in environmental history, historical geography, and geophysical science societies and meetings. In 2011, talks at the American Society for Environmental History led to the creation of the Climate History Network, an informal organization to share news and publications and to coordinate meetings in the field.[20]

By the late 1990s, both environmental and climate history were also gaining ground beyond Europe and North America. As discussed in Chaps. 17–21, scholars had begun to undertake more systematic work in documentary-based climate reconstruction in Africa, Australia, Latin America, Japan, and to a lesser extent South Asia and the Middle East. In China, where work in historical climatology was already advanced, a few scholars began to publish in international journals and to address issues of historical climate impacts and adaptation as well as reconstruction. This globalization of the discipline came at a time of rising interest in global history, particularly in US universities.

In the meantime, increasing public concern about global warming and related environmental disasters brought more scholarly attention to historical climate variability and impacts. The sudden growth in climatological research generated vast new sources of high-resolution paleoclimate data relevant to human history. Efforts to project future climate variability and extreme weather generated new interest in past climate variations and their impacts as well.

Within the field of history, scholars personally concerned about the impacts of warming could no longer reject the study of historical climates as mere determinism. In some cases, historians with little or no previous background in historical climatology turned to climatic and other environmental factors as explanations for major historical developments, such as the Late Bronze Age crisis and the seventeeth-century "general crisis" in Europe and Asia.[21] The trend has been most pronounced in the "new world history" focused on large-scale connections and patterns rather than individual events and nations. For example, Victor Lieberman's *Strange Parallels*, a vast comparative history of the early modern world, appealed to climatic changes as a principal factor tying together political and economic cycles across Eurasia.[22] A 2012 article in the *American Historical Review* proposed that a “new materialism” was already replacing the “cultural turn” of the early 1990s.[23] In the following years, forums or special issues devoted to climate history appeared in leading history journals, including the *American Historical Review*, the *Journal of Interdisciplinary History*, *Environmental History*, and the *William and Mary Quarterly*.

As the field has grown and diversified, so have its topics, approaches, methods, and conceptual frames. In a number of reviews of historical climatology and climate history, Rudolf Brázdil and co-authors have defined the major findings and topics in the field as:

- *reconstructing temporal and spatial patterns of weather and climate* as well as climate-related natural disasters for the period prior to the creation of national meteorological networks (mainly for the last millennium);
- *investigating the vulnerability of past societies and economies* to climate variations, climate extremes, and natural disasters;
- *exploring past discourses and social representations* of weather and climate.[24]

In a 2012 review, American historian Mark Carey argued that climate history would benefit from including race, class, and gender as well. Moreover, he suggested focusing on the social or cultural aspects of global warming research instead of just reporting the narratives of scientists.[25]

1.5 Prospects

Climate history emerged as a new research field prior to widespread concern about global warming and its causes, and so its purpose and methods developed independently of those issues. Starting in the 1980s, however, climate historians became involved in and have made significant contributions to the understanding of climate change in historical periods, which has helped to place global warming in the context of Holocene climate history. For instance, historical climatologists have informed sections of Intergovernmental Panel on Climate Change Working Group I reports. On the other hand, Working Group II reports on impacts, adaptation, and vulnerability make only occasional references to historical experience and even less to climate history research. Economists, political scientists, and sociologists who lead discussions on impacts, adaptation, and vulnerabilities need first to open up to historical studies, while historians must better connect their findings to present and future challenges.

One way to achieve this goal could be more in-depth research on climate–society interactions during recent periods. The nineteenth and twentieth centuries remain relatively neglected by climate historians. Most individuals have worked on earlier eras, in large part because their work has specialized in climate reconstruction for periods before standardized instrumental data, rather than in applying that data to the human history of recent times. Conversely, very few historians of modernity—including environmental historians—have been interested in working with climate data or analyzing climate–society relations. Precipitation is another field of research calling for more effort by climate historians. Since precipitation patterns are highly localized, historical instrumental records cannot adequately cover any large part of the globe. On the other hand, documentary records often include descriptions of precipitation because it was (and still is) crucial for agricultural work (see Chap. 27).

The emergence of climate science during the second half of the twentieth century was accompanied by a paradigmatic shift from descriptive climatology to causal explanations of climatic changes (see Chap. 38). Descriptive climatology, rooted in nineteenth-century positivism, was, as Hubert H. Lamb put it so aptly, "the book-keeping branch of meteorology—no more and no less."[26] It focused on the statistics of new reams of weather data from standardized instrumental networks. The picture began to change during the twentieth century with the development of new fields, including paleoclimatology, atmospheric chemistry, and eventually modeling. The need to understand the causes of climate change, now as well as in history, has been the driving force behind that paradigm shift. However, as historical climatology emerged, historians and geographers still worked from traditional, purely descriptive concepts of climate; and historical climatologists are still working out how to modernize their definitions of climate and thus adapt to the new causal approach. It remains a future challenge for climate and environmental historians to provide valuable information drawn from historical records in order to better explain and model past climatic changes. That applies, for example, to deforestation, which influences the carbon cycle and changes planetary albedo.[27] Measures of deforestation have been recorded worldwide and throughout documented history. Though incomplete, this evidence might have the potential to improve modeling of deforestation prior to 1800, which until now has been based on very general assumptions.

Until the 1990s, this descriptive paradigm led historical climatologists to focus on reconstructing just a few meteorological features—temperature, precipitation, and air pressure—to contribute datasets to paleoclimate reconstructions. Important extreme events (e.g., wind storms, hail storms, and snow cover) were often neglected, leaving gaps in existing databases.[28] This information about extremes is key to understanding impacts of climate variability on societies past and present. A recent World Bank study has projected that low-probability, high-impact events—notably heatwaves, droughts, and floods—will occur more frequently. Few sources from the archives of nature can provide information about these extremes, especially information with the specificity found in records from the archives of societies.[29]

Even as climate historians have learned to better integrate research on past climate reconstruction and impacts, the third branch of research—past discourses and social representations of weather and climate—remains fragmented. The prevailing cultural practices of a time and place are deeply interwoven with the study of climate–society relations. “For intellectual and cultural historians, weather reports are a relatively unexamined territory, a treasure trove of human thinking about what it meant to live in particular worlds at particular times.”[30] Culture has been neglected in studies applying mechanistic, and potentially deterministic, models of climatic impacts, but that is no option for historians. The cultural and intellectual history of weather and climate, although a vital field of study in its own right, has been spread across multiple disciplines, including philosophy, psychology, sociology, religious studies, geography, and anthropology. Integrated multidisciplinary surveys will require more research and collaboration.

A final trend in the field—and challenge for researchers—is the globalization of climate history. So far, few academic (as opposed to popular) works have undertaken global climate histories. Theory and practice in global history have favored cultural interactions and societal or economic networks as the dominant forces of social and political transformation. Global climatic change and its effects, whether short term or long term, remains a new topic in the field. Recently, Geoffrey Parker’s account of “global crisis” during the seventeenth century has drawn attention to the impacts of this phase of the Little Ice Age,[31] and recent books by Gillen D’Arcy Wood and Wolfgang Behringer have explored the global effects of the 1815 Tambora eruption and ensuing “year without a summer” (see Chap. 35).[32]

1.6 A Guide to this Handbook

This volume was designed to combine the advantages of a textbook and an edited volume. It offers an integrated and consistent overview of the field of climate history in language that is accessible to non-specialists, while bringing together the expertise and perspectives of specialists in many regions, periods, and methods. It may be used as a work of teaching or reference, or as an introduction to the field for scholars seeking to acquire the methods and insights of climate history.

There is no expectation that readers will work from the beginning to the end of the volume. Each chapter represents an independent work of synthesis or original research. The chapters include numerous citations and cross-references for readers in search of more information and examples. The editors have allowed for some overlap among the chapters rather than forcing the reader to repeatedly look up information.

The volume is organized into six parts. Following this introduction, Chaps. 2–14 lay out the methods and sources of the field. Chapters 15–26 review the results of climate history research by era and region. Rather than force each of these chapters into the same format, the editors allowed their length and periodization to reflect the unevenness of evidence and research. Chapters 27–31 examine several themes in climate impact, vulnerability, and adaptation research, focusing on reviews of the current literature. Chapters 32–35 offer case studies of decades with exceptional climate anomalies, including the 530s–540s, 1310s, 1780s–1790s, and 1810s. Finally, Chaps. 36–38 cover the emergence of modern climate science. Given the state of the field, and a decision to focus on the antecedents of the modern discipline of climatology, these chapters emphasize the work of European and American scientists. However, the editors do not wish to imply that ideas about climate were exclusively the work of white men. Colonial exchanges of knowledge and encounters with indigenous peoples played an important role (see Chap. 37), and we expect further modifications to this story as research on the history of climate science expands into new parts of the world.

This handbook reflects the state of the field at a moment when climate history has achieved established methods and validated results. Nevertheless, the fast pace of research means that important new publications appear continuously, forever raising new ideas and revising old ones. Readers looking for up-to-date news and publications in the field are advised to consult the bibliography, links, and databases at http://www.climatehistory.net/.

Notes

1. Bradley, 2015.
2. Ingram et al., 1978.
3. Wigley et al., 1985, 558.
4. Wigley et al., 1985, 558.
5. Stehr and Storch, 2000, 187.
6. Fleming, 1998.
7. Le Roy Ladurie, 1971, 119.
8. Pfister, 2011, 303.
9. Le Roy Ladurie, 2004.
10. Kington, 2007. See also Martin-Nielsen, 2015.
11. Lamb, 1995, 6 and 318.
12. Bell and Ogilvie, 1978.
13. Lamb and Ingram, 1980, 137.
14. Pfister, 1980.
15. De Vries, 1980.
16. Zumbühl, 1980.
17. Post, 1985.
18. Pfister et al., 1994.
19. Frenzel et al., 1992; Wanner et al., 1995; Guiot, 1992.
20. http://climatehistory.net.
21. Cline, 2014; Parker, 2013.
22. Lieberman, 2009.
23. Thomas, 2012.
24. Brázdil et al., 2005.

25. Carey, 2012.
26. Lamb, 1995, 11.
27. Mauelshagen, 2014.
28. Exceptions include Pfister, 1985; Mann et al., 2009; Pfister et al., 2010; and Rohland, 2017.
29. World Bank, 2014.
30. Dutton, 2008, 169.
31. Parker, 2013.
32. Wood, 2014; Behringer, 2015.

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PART I

Reconstruction

CHAPTER 2

The Global Climate System

Eduardo Zorita, Sebastian Wagner, and Fredrik Schenk

What we call the Earth's climate system consists of several subsystems. These interact with each other on very different timescales: the atmosphere over several thousands of kilometers can change substantially on daily and subdaily scales; the ocean currents vary over timescales of months to millennia; and the huge ice sheets change significantly on millennial timescales. Over even longer periods, other parts of the Earth's system also come into play, such as plate tectonics, which modify the Earth's surface by generating new ocean basins and mountain ranges and by moving the geographical position of continents. This characteristic of multiple systems and timescales renders the climate system hard to predict because myriad different physical processes have to be included to provide any realistic description of the whole.

The subsystems of the climate system—atmosphere, ocean, land ice, land vegetation cover, and so on—all with their variations on different timescales, interact through the exchange of energy and matter. In particular, greenhouse gases such as water vapor, carbon dioxide, and methane are constantly being exchanged; and when set free in the atmosphere, they significantly influence the balance between absorbed and emitted energy at the Earth's surface. In this regard, water vapor, liquid water, and ice in the atmosphere deserve special consideration since they lead to the formation of several types of clouds each with different properties regarding the reflection and absorption of radiation.[1]

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The interplay among these climate subsystems is strongly non-linear, so that some perturbations can be rapidly amplified once they arise. The Earth's climate is an open system, absorbing shortwave radiation from the sun, which is then distributed among its subsystems until it is finally radiated back to space in the form of longwave (thermal) radiation. These non-linear interactions and the continuous flow of energy result in internal climate variability on all timescales. This variability would occur even if the orbit of the Earth and the output of the sun were constant, providing exactly the same external source of energy to the Earth's climate: each year, each decade, each century would be different, each being but one sample of that probabilistic distribution that we call "climate."

Most of the incoming solar energy is transformed at the surface, with some smaller portions absorbed in the troposphere (the lowest level of the atmosphere) and in the stratosphere (just above the troposphere). Therefore the lower portion of the atmosphere is a system that is mainly heated from below (heat radiating up from the land or sea surface), whereas the ocean is mainly heated from above (incoming solar radiation). Warm air is lighter than cold air and warm seawater is lighter than cold seawater. Since warmer air usually underlies cold air in the atmosphere, but warmer surface ocean water rests on top of colder subsurface water, we tend to find unstable and turbulent atmospheric dynamics, but generally stratified and stable oceans, especially in tropical and subtropical regions with high upper-ocean temperatures.

An additional important factor that determines the state of the climate is the unequal distribution of energy between the equator and the poles. Over equatorial areas, the net input of energy (incoming solar energy minus outgoing infrared emission to space) is positive (net gain), whereas at mid and high latitudes it is negative (net loss). This imbalance drives a continuous flow of energy from low to high latitudes and from the surface to the top of the atmosphere, from where it can leave the Earth (Fig. 2.1). This transport is accomplished by atmospheric and oceanic circulation.

Moreover, the tilt of Earth's axis (currently 23.5°) means that the zone of maximum solar insolation shifts from the northern tropics (in the Northern Hemisphere summer) to the southern tropics (in the southern summer). This alternation generates the annual cycle of thermal (hot and cold) and hydrological (wet and dry) seasons over most of the globe. In general, lower latitudes typically show hydrological seasons, whereas mid to high latitudes are characterized by a more or less pronounced seasonality in temperatures.

The poleward transport of heat by the atmosphere is framed by three circulation cells.[3] The first is the Hadley Cell. Over low-latitude tropical areas, warm air rises. Once it reaches the upper troposphere (around 16 km above sea level) it is deflected towards the poles. As it moves towards the mid latitudes, the air descends into lower tropospheric levels creating large subtropical high-pressure cells. From these zones of high pressure, air flows back towards the equatorial regions in the form of more or less constant southeasterly trade winds, which blow into the low-pressure Inter-Tropical Convergence Zone. (Note that winds are named after the direction from which they flow, so an "easterly" blows from east to west.)

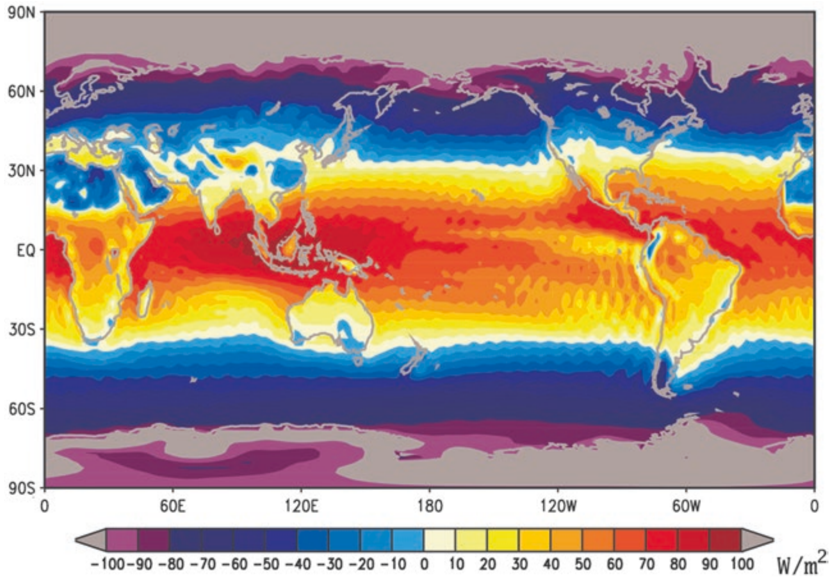

Fig. 2.1 Net radiation balance (incoming solar radiation minus outgoing thermal radiation) of the Earth's climate as simulated by the Earth System Model of the Max Planck Institute for Meteorology over the period 1850–2005.[2] The large amount of solar energy entering the tropical regions is distributed by the ocean and the atmosphere towards mid and high latitudes. At high latitudes (more than 40°N or S), more thermal energy is lost to space than is gained from the sun. The continents disturb the otherwise symmetrical distribution of the energy balance, with the Indonesian subcontinent absorbing more net energy than other tropical areas. The Sahara and Arabian deserts, with their high surface reflectivity, are in radiation deficit and import energy from the surrounding areas through atmospheric advection. Taken globally, the net energy balance, about 0.8 watts/m^2, is not zero because the climate system is currently not in equilibrium: the continuous increase in atmospheric carbon dioxide and methane hinders the release of thermal energy and continuously increases the energy content of the climate system. This apparently small global imbalance is, however, systematic; it slowly and continuously drives up surface temperatures and sea level, as observed

Second, at its poleward branches the Hadley Cell interferes with the Ferrel Cell. This cell, located mainly over the mid latitudes, is characterized by prevailing westerly winds. These come mainly from the deflection of the upper tropospheric air particles towards the east in the presence of the Coriolis force—that is, because the (west to east) rotation velocity of the Earth's surface decreases from the equator to the poles. In addition, atmospheric turbulence causes the familiar transient low- and high-pressure systems of the mid latitudes. The Ferrel Cell accounts for a considerable poleward heat transport. Third, over high latitudes the air cools further and descends, forming large high-pressure cells over the polar regions. This movement creates the Polar Cell, with prevailing easterly winds.

The oceanic part of the energy transport is more strongly determined by the shape of the ocean basins. One important mechanism is the narrow western boundary currents flowing along the eastern side of major continents at mid latitudes, such as in North America (the Gulf Stream) and eastern Eurasia (the Kuroshio). These currents result from the interplay of three factors: the wind force provided by the semipermanent subtropical high air-pressure cells, the rotation of the Earth, and the generally longitudinal orientation of the coastlines. These narrow currents transport warm tropical waters polewards. The waters then generally flow back towards the equator along the eastern side of the ocean basin, forming much broader current systems, such as the Canary Current.

The Atlantic Ocean deviates from the Pacific Ocean in one important respect: in the North and South Atlantic at high latitudes, the surface waters are colder and more saline, and therefore denser. This density leads to "deep water formation": deep convection that transports high-latitude cold water masses from the surface to the ocean interior, leaving them to be replaced by warmer water masses from lower latitudes. This poleward flow at the surface, known as thermohaline circulation, not only is another driver of poleward heat transport but also represents an important way in which warm surface waters and cold deep waters are mixed in the oceans, which are generally stratified—that is, layered between waters of different temperature.[4] In this way, heat stored in the upper oceanic layers can penetrate down into the deep ocean, a mechanism that is important for controlling and mediating climatic changes on millennial timescales.

The geographical arrangement of the continents also results in particular regional climates in specific bands of latitude. One example is the Indian monsoon system, largely a result of the Himalayas and the Tibetan plateau being located close to the tropical Indian Ocean. A monsoonal climate is defined by a seasonal change in prevailing wind direction of at least 120°. With some simplification, the monsoon can be thought of as a sort of land–sea breeze but on a continental and seasonal scale. During winter, the Tibetan plateau cools down, giving rise to descending air masses and hence producing a pronounced high-pressure system and easterly winds. As the winds flow from continental areas, they carry little moisture, and precipitation is low (with the exception of the areas facing towards the Bay of Bengal). The summer monsoon, on the other hand, is driven by a strong low-pressure system developing over the Asian land masses owing to the higher heating rates over land during the (northern) summer season. This results in very humid southwesterly winds flowing from the Indian Ocean across the Indian subcontinent, bringing heavy seasonal rains and orographic amplified precipitation (i.e., precipitation enhanced by the rising of moist air as it passes over mountains) along the coastal ranges of the Ghats. Similar monsoon systems can be found in other parts of the tropics, including Africa, Southeast Asia, and North America.

Mean climate, as described above, represents only an average picture, not what is actually observed. At any particular point in time, we find configurations of the atmosphere, ocean, and cryosphere that are constantly varying within certain ranges around the mean climate state. In a stable climate, this variability is the result of numerous interactions within each subsystem and among the climate subsystems.

A paramount example of this internal variability is the El Niño-Southern Oscillation phenomenon.[5] Usually, the easterly trade winds in the Tropical Pacific drive warm surface waters towards the west, triggering an upwelling of colder subsurface waters off Peru. This phenomenon maintains a temperature and surface pressure gradient across the whole Tropical Pacific, which in turn reinforces the trade winds. That is, the colder waters and higher air pressure in the Eastern Tropical Pacific and the warmer waters and lower air pressure in the Western Tropical Pacific help sustain the usual east-to-west winds. If for any reason the trade winds slacken, the temperature and pressure gradient also weaken, thus further weakening the trade winds. For a few months, about every five years or so, the whole Tropical Pacific shifts to this different "state," called "El Niño," when trade winds slacken and the Eastern Tropical Pacific becomes unusually warm. El Niños change surface temperatures, ocean vertical mixing, and surface heat fluxes so strongly that they may affect the atmosphere not only in the Tropical Pacific but also globally, via so-called "teleconnections." Strong El Niño years are therefore associated with climatic effects as diverse as heavy rainfall in Peru and droughts in East Africa, India, and Australia (see Chap. 34).

The term "climate change" (as opposed to "climate variability") denotes a modification in the statistics of the weather in the atmosphere—and, expanding the meaning of the concept of "weather," also of the ocean and other subsystems. These changes can be brought about by various "forcings." The term "forcing" denotes a driving factor that is considered to be external to the climate system. It may be embedded in the Earth's system, as in the case of volcanoes, or be truly extraterrestrial, as in the case of the sun. Examples of external forcings include shifts in the configuration of the continents by plate tectonics (on geological timescales), variations in the output of the sun, volcanic eruptions, and anthropogenic emissions of greenhouse gases, such as carbon dioxide and methane.

All of these forcings at least temporarily disturb the balance of energy that is absorbed and released by the Earth. For example, continental masses at high latitudes allow the formation of permanent ice sheets. These increase the albedo (reflectivity) of the Earth's surface, and a higher albedo means that more solar radiation is reflected back to space before it even enters the energy cycle of the climate system. Another example is the increase in atmospheric greenhouse gases. These gases hinder the release of longwave radiation from the Earth's surface back to space, so that more energy becomes trapped within the climate system.

The climate system will adjust to such perturbations until a new energy balance is reached. In the first example, the surface temperatures will tend to cool, thereby emitting less longwave radiation to space and reducing energy losses. In the second example—the situation which we are currently in (see Chap. 26)—surface temperatures will tend to increase, thus radiating more thermal radiation upwards, compensating for the "trapping" effect of atmospheric greenhouse gases. These readjustments are accompanied by changes in atmospheric and oceanic circulation, cloud cover, atmospheric water vapor, and many other factors that in turn also affect surface temperatures.[6] The theoretical term "climate sensitivity" summarizes all of these complex processes in a single number, which states the amount of surface warming that is required to achieve a new state of energy balance.

Notes

1. Stevens and Schwartz, 2012.
2. Stevens et al., 2013.
3. Schneider, 2006.
4. Wunsch, 2002.
5. Holton and Dmowska, 1990.
6. Bony et al., 2006.

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CHAPTER 3

Archives of Nature and Archives of Societies

Stefan Brönnimann, Christian Pfister, and Sam White

3.1 Introduction

Paleoclimatology and historical climatology share the common goal of reconstructing climates before regular instrumental records. However, these two disciplines work with two different sets of evidence. Paleoclimatologists work to reconstruct the past from physical traces in the cryosphere, hydrosphere, biosphere, and lithosphere that record the influence of climates centuries and millennia ago.[1] By contrast, historical climatologists reconstruct the past from written records and human artifacts, which may range from direct descriptions of weather to indirect indicators of climatic and meteorological impacts.

This volume distinguishes between these two sets of evidence as the *archives of nature* and the *archives of societies*. Both archives require some of the same techniques and pose some similar methodological and conceptual challenges. Their periods of coverage and of spatial and temporal resolution overlap. As described below, both often involve working with "proxies" rather than direct representations of past weather and climate.

Nevertheless, these two archives also present distinct issues. The archives of nature tend to be more homogeneous, continuous, and precisely located, and in some cases can reach very far back into the past. The archives of societies, on the other hand, tend to be more heterogeneous, and their data is

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often scattered over time and space. Yet they can often provide more precise information, reaching back centuries or even millennia, revealing those climatic and meteorological events most relevant to human history. Moreover, as explained in this volume, diligent research and appropriate methods can overcome some of their apparent shortcomings for climate reconstruction. Climate history necessarily requires research in both kinds of archives.

This chapter first provides a brief introduction to the archives of nature and the archives of societies, and then outlines some of the common techniques and challenges in working with proxies from each. The chapters in Part I of this volume explain in more detail the use of evidence and the creation of climate reconstructions from the archives of societies. For further information about climate reconstruction from the archives of nature, we refer readers to Raymond Bradley, *Paleoclimatology. Reconstructing Climates of the Quaternary* (3rd ed., 2015) and to Neil Roberts, *The Holocene: An Environmental History* (3rd ed., 2014).

3.2 The Archives of Nature

The Earth's climate influences physical, chemical, and biological processes taking place over the planet's land, water, and ice, and in its living creatures. Variations in temperature and precipitation (and sometimes in sunshine, sea ice, and other such variables) produce corresponding variations in all sorts of natural developments: the build-up of snow and ice over glaciers, the accumulation of lake deposits, the ratios of stable oxygen isotopes in precipitating water, the blooming of certain species of algae and plankton, the growth of shells in marine life or the rings of tree trunks, and so on. In some cases these processes leave behind physical remnants that preserve these variations in such a way that scientists can study them in order to reconstruct past climates. The storage mediums of these processes, such as ice, peat bogs, stalagmites, or tree trunks, are named archives of nature.

Researchers extract information from these archives through different methods of sampling, such as coring ice or drilling trees. Depending on the sensitivity to local conditions, they create time series of measurements from either a single sample or by averaging several samples (often called "composite" records). The analysis of each archive requires specific scientific skills related to the underlying physics, chemistry, or biology of the process captured in the archive and how it relates to past climates.

The archives of nature now include a remarkable variety of records, as researchers have developed ingenious ways of extracting ever more climate information from different physical remains. The most useful records are those where some process that is highly sensitive to a specific climate variable has left some very regular and well-preserved sequence. Some of the best-known and most widely used examples include growth rings in trees, variations in oxygen isotopes in ice cores, and pollen types in sedimentation layers ("varves") at the bottom of lakes and estuaries. However, new techniques have been continuously developed in order to extract more climate data from more parts of the world. Keeping up with those techniques and that data remains an essential task of climate history. Examples of different proxies (ring width, oxygen isotope ratios, varve thickness, and sulfate and lead concentrations) from different archives (tree rings, ice cores, stalagmites, sediments, and peat bogs) are shown in Fig. 3.1.[2]

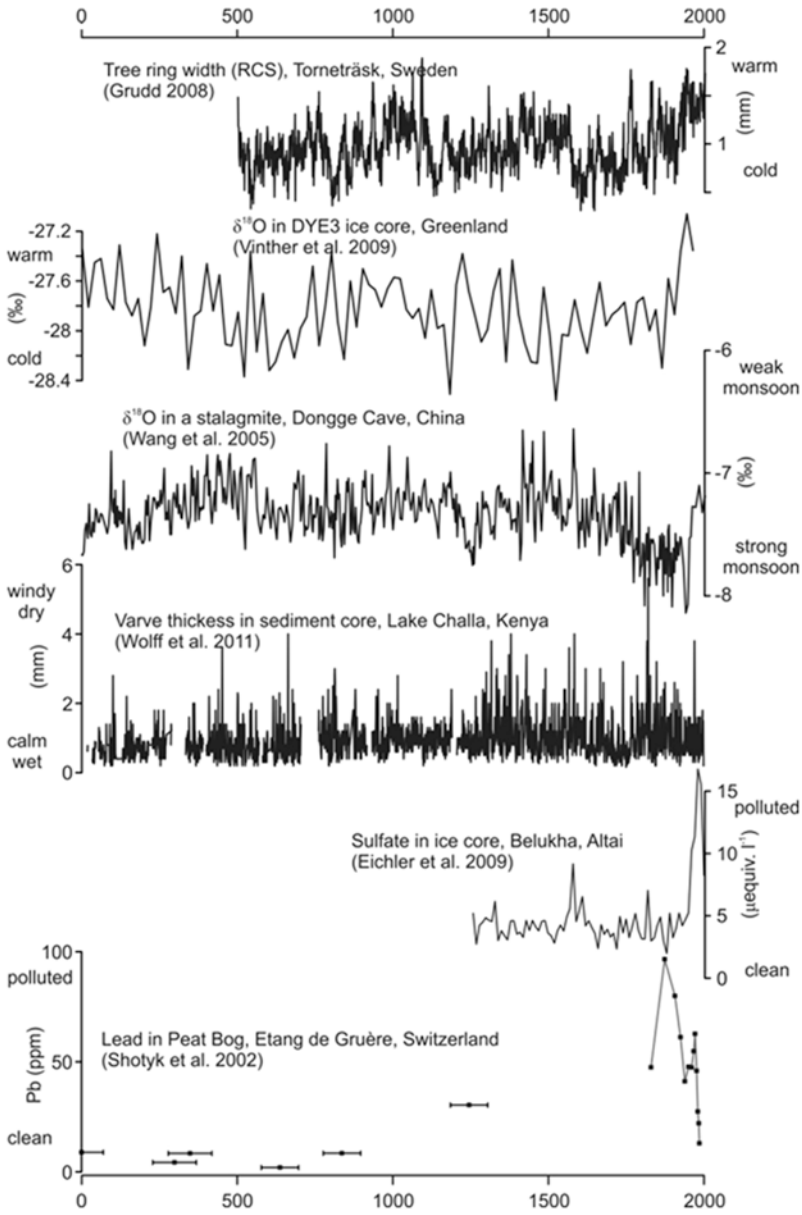

Fig. 3.1 Examples of time series over the past 2000 years drawn from the archives of nature, along with the authors' interpretation (from the National Oceanic and Atmospheric Administration paleoclimatology website)

3.3 The Archives of Societies

The term "archives of societies" is used here in a broad sense to refer to both written records and evidence preserved in the built environment that can help researchers reconstruct past climate and weather. The former includes documents such as personal manuscripts and official records, as well as printed materials, artworks, and now electronic data. The latter includes physical indicators of events ranging from relevant archaeological artifacts to high-water marks.[3] This diversity of records in the archives of societies poses particular problems of homogenization (i.e., of making them all commensurable).[4] What all these sources have in common is that they present data coded by humans that can be used to reconstruct past weather and climate.

Aside from instrumental records, the archives of societies present two kinds of information. On the one hand, there are sources such as chronicles and diaries that include descriptions and narratives of weather patterns—that is, of short-term processes in the atmosphere and their effects on the hydrosphere, cryosphere, biosphere, and anthroposphere (see Table 3.1). These descriptive and narrative sources present particular problems of interpretation that are discussed in the chapters of Part I. On the other hand, there are records of recurring physical and biological processes, ranging from the flowering of plants and the ripening of grains to the freezing of lakes and rivers. These records provide sorts of "proxy" climate information. As discussed in the following section, climate reconstruction from proxies requires some similar methods and poses some similar challenges whether the proxies are drawn from the archives of nature or the archives of societies.

3.4 Reconstructing Past Climate from Proxies

"Proxies," as their name suggests, are indirect representations of past climate. Measurements of these proxies provide indirect measurements of the underlying climate variable that researchers are trying to reconstruct. For instance, tree trunks are not rain gauges, but where tree growth is limited by rainfall, measuring annual tree-ring growth can provide an indirect measurement of growing-season precipitation. Lakes are not thermometers, but in the right circumstances the duration of a lake's winter freeze can be an indirect measurement of seasonal temperature. No proxy offers a perfect measurement of past climate. Its use requires careful attention to method and context.

Proxies are often subdivided into the biological and non-biological. The former preserve biological and biophysical processes—at the level of individual species or the ecosystem—that respond to one or more climate variables. Examples from the archives of nature include rates of plant growth (e.g., tree-ring width and density), variations in species abundance and distribution (e.g., pollen assemblages), and changes in biochemistry (e.g., the composition of

Table 3.1 Examples of evidence from archives of nature and archives of societies (T = temperature; P = precipitation; p = air pressure)

Archives of nature (nature-generated data)					*Archives of societies (anthropogenic data)*			
Archive	*Proxy*	*Climate variables*	*Time resolution*	*Temporal range*		*Climate variables*	*Time resolution*	*Temporal range*
Weather					**Narrative**			
					(Weather) chronicles	Weather, impacts	Hours to seasons	>5 centuries
					Weather diaries	Weather, impacts	Hours to seasons	5 centuries
					Ships' logbooks	Wind, weather	Hours to days	3 centuries
					Weather reports	Weather, impacts	Days to months	>5 centuries
					Art			
					Paintings, literature, poems, etc.	Weather, impacts	Days to weeks	Centuries
					Instrumental			
					Instrumental measurements	T, P, p, etc.	Secs to days	1–3 centuries
Climate	**Biological proxies**				**Biological proxies**			
Tree rings	Ring width	T, P	Seasons	Centuries	Plant observations	T	>1 month	Centuries
	Maximum late wood density	T			Time of agricultural work	T	>1 month	Centuries
	Oxygen isotopes	T			Agricultural production	T, P	>1 month	Centuries
Lake sediments	Pollen assemblages	T, P	Annual	Millennia				
	Chironomids	T						
Corals	Oxygen isotopes, Sr/Ca ratio	T, Salinity	Seasons	Centuries				
Peat bogs	Trace chemicals	Pollutants						

(*continued*)

Table 3.1 (continued)

Archives of nature (nature-generated data)					*Archives of societies (anthropogenic data)*			
Archive	*Proxy*	*Climate variables*	*Time resolution*	*Temporal range*		*Climate variables*	*Time resolution*	*Temporal range*
	Non-biological proxies				**Non-biological proxies**			
Ice cores	Oxygen isotopes	T		>100 kiloyears	Freezing of water bodies	T	>1 month	Centuries
	Accumulation	P			Snow cover	T, P	Days to months	Centuries
	Air bubbles	Trace gases			Floods	P, T	Days to weeks	Centuries
	Snow chemistry	Aerosols						
Lake sediments	Grain size	T, Floods, Wind						
Speleothems (stalagmites)	Thickness, oxygen isotopes	P, T						
Glaciers		T, P	Years	Millennia				

shells from marine creatures such as foraminifera). Examples from the archives of societies include grape harvest dates and data on the time of cultural activities such as the Cherry Blossom Festival in Japan.[5] Since various life forms in diverse environments react to changes in climate, biological proxies cover a range of regions.

Non-biological proxies preserve physical processes in the environment that respond to climate variables. Examples from the archives of nature in this case include precipitation chemistry (e.g., the snow composition of firn), the sedimentation process (e.g., grain size or abundance of sediments at the bottom of lakes), and isotope fractionation (e.g., the stable oxygen isotope ratio $\delta^{18}O$ of water ice in ice cores). Examples from the archives of societies include written and visual records of glacier movements and records of ingoing and outgoing ships in ports, revealing the length of the winter freeze.[6]

The first challenge of proxy-based climate reconstruction, whether from the archives of nature or the archives of societies, comes in establishing properly dated measurements. With respect to the archives of nature, the most precise and reliable dating often comes from stratigraphy—that is, the counting of layers, as in the growth rings of old trees or the visible layers in some ice cores. However, most natural records do not preserve dates so clearly. In these cases, paleoclimatologists may make use of specific markers in the record (e.g., sulfur from volcanic eruptions, or radioactive fallout from nuclear tests) and/or by using radiocarbon dating, which dates buried materials according to the decay of the radioactive ^{14}C isotope. Once they have established a few dates using these methods, paleoclimatologists may then model an "age-depth curve" to provide an approximation of dates in the rest of the sample, such as in a sediment core. The choice and accuracy of dating methods will vary according to the archive in question, and the accuracy of dates usually deteriorates farther back in time. The resolution (precision) of dating can vary from several months (e.g., tree rings and corals) to centuries or millennia (e.g., ocean sediment cores).

Records from the archives of societies are usually dated at least by their year, and in most cases by their season, month, or day. Nevertheless, these records also present dating challenges. Historical climatologists must first determine whether the author of a document really witnessed the events described, or whether they are dealing with an (error-prone) copy. For instance, the new Euro-Climhist database of European climate and weather observations has systematically labeled all non-contemporary sources in order to alert researchers to this problem.[7] Dating styles vary according to era and country (e.g., Julian vs. Gregorian) as well as culture and religion (e.g., solar calendars in Europe vs. lunar calendars in China and the Islamic world, see Chap. 17). Similar to the archives of nature, the accuracy of written records usually deteriorates farther back in time. Manuscript sources pose uncertainties in data extraction: handwriting may be difficult to read, the ink may fade, or the paper may become damaged. Prior to the late nineteenth century, records were often written in older forms of languages or in regional dialects, and the meanings of terms have changed over time.[8] Table 3.1 outlines some of the most common proxies from the archives of nature and the archives of societies, along with their temporal range and resolution.

The second challenge of proxy-based climate reconstruction comes in establishing the association between the proxy and the past climate. This process usually involves establishing a statistical relationship between measurements of the proxy and some climate variable or variables. Usually this relation, termed a "transfer function," needs to be calibrated. For some proxies, calibration may be achieved by experimental or laboratory measurements. More often, statistical methods are used, working from some period of overlap between proxy measurements and the instrumental climate record (see Chap. 10). The application of a transfer function relies on the concept of stationarity—that is, the assumption that the relationship between the proxy and the climate was the same in the past as it is in the present (or in the period of overlap). This assumption may be questionable in some cases, and it can create uncertainty.

Proxy-based climate reconstructions try to isolate the relevant climate "signal" in their proxy measurements from the "noise" of other factors. For example, although tree growth reacts to climate everywhere, tree rings are best sampled near a growth limit, such as at a mountain tree line (for temperature) or a desert margin (for precipitation). Even in the best circumstances, no proxy measurement will produce a pure signal from only one climate variable: other climatic and non-climatic factors will always influence proxy measurements, whether taken from the archives of nature or the archives of societies.

To put this relationship in perspective, many climate reconstructions work with proxy measurements that have correlation coefficients of around 0.5–0.6 with the climate variable they are trying to reconstruct—or about the same as the correlation coefficient between the height and weight of adult men. Just as some men might be short and fat while others are tall and skinny, not every thin tree ring reflects a cold or dry season and not every wide ring records a warm or wet one. (This is one reason why proxy-based reconstructions often show moving averages instead of, or in addition to, annual values.) Further sources of error come from uncertainties in measuring proxies, and the possibility of non-linear relationships between climates and proxies. For proxies from the archives of societies, researchers also need to carefully establish the context in which records were created in order to assess any possible human bias.

Nevertheless, these difficulties do not undermine the validity of proxy-based climate reconstructions, nor their usefulness in climate history. Many reconstruction techniques have proven to be remarkably robust, producing well-verified results that strongly agree with each other and with historical descriptions. While discrepancies and disagreements persist, one of the great achievements of climate history comes from the way that diverse physical and written records so often complement each other and create a more complete and reliable picture of the past.[9]

3.5 Conclusion: Combining the Archives of Nature and Society

This handbook focuses on reconstruction techniques from the archives of societies and from early instrumental records. Whereas research in the archives of nature has produced a voluminous literature of review articles and textbooks, this volume is the first of its kind to provide a complete introduction to historical climatology. Nevertheless, we stress that climate history requires a judicious use of all available evidence, from natural as well as human records. As Christian Pfister has explained,

> "The objectives of palaeoclimatologists and historical climatologists are similar to the extent that both attempt to reconstruct climate for the period prior to the creation of national meteorological networks from the mid-nineteenth century. To that extent, data from Archives of Nature and Society to some extent complement each other. Where anthropogenic data are fragmentary or lacking, longer-term temperature or precipitation trends may be drawn from evidence contained in the Archives of Nature. In cases where it is important to establish the nature and severity of extreme conditions, anthropogenic data are temporally higher resolved, more differentiated and case-specific."[10]

Part III of this volume (Climate and Society) therefore considers both physical and written records of past climate, and Part IV (Case Studies) provides illustrations of how climate historians can combine research in the archives of nature and society in order to achieve the most complete reconstructions of climate and weather at the level of human experiences and impacts.

Notes

1. Masson-Delmotte et al., 2014.
2. For a regularly updated database of paleoclimate reconstruction relevant to human history, see http://www.climatehistory.net/bibliography/ (last accessed April 8, 2016).
3. Brázdil et al., 2010.
4. Ayre et al., 2015.
5. Aono and Saito, 2010; Daux et al., 2012.
6. Leijonhufvud et al., 2010.
7. Pfister and Rohr, 2015.
8. Pfister et al., 2008.
9. Büntgen et al., 2015; Pfister et al., 2015.
10. Pfister, 2015.

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CHAPTER 4

Evidence from the Archives of Societies: Documentary Evidence—Overview

Christian Pfister

4.1 Introduction

When dealing with archives of societies, researchers need to distinguish between sources and data. A climate historical source is a unit of information coded by humans which refers to weather and climate, usually from the viewpoint of individuals. Data are found within these sources, and their interpretation is content-specific. Human archives contain three kinds of data: instrumental measurements, narrative data providing direct weather information, and observations of climate proxies providing indirect data.[1] This documentary-based proxy evidence includes both plant- and ice-phenological data as well as historical hydrology, which aims at "reconstructing temporal and spatial patterns of runoff conditions as well as extreme hydrological events (floods, ice damming, hydrological droughts) for the period prior to the creation of national hydrological networks."[2] We can further classify these archives by their authors and circumstances of production. This chapter distinguishes between documents produced by members of official bodies (institutional sources) and those produced by individual amateur observers (personal sources), although some source types may belong to both categories (see Table 4.1). To assess and interpret these sources, researchers need to know who produced them, why, and how they recorded meteorological conditions and their human consequences.[3]

Communicating climate risk through narratives of extraordinary events dates back to early civilizations, including the Assyrians, Babylonians, Egyptian

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Table 4.1 Major categories of climate and weather sources from the archives of societies discussed in this handbook

Data	*Sources*	
	Personal	*Institutional*
Instrumental	Measurements by individual observers	Measurements within meteorological networks
Direct: narrative or visual	Chronicles (Weather) diaries Newspapers Letters Scientific journals Broadsheets, etc. Visual art, photographs	Manorial audits Mandatory reports Rogation ceremonies Damage reports Ships' logbooks Reports on crop development
Indirect: proxy	Plant-phenological observations Ice-phenological observations Flood and low water marks	Time of harvest (grain, grapes) Wage accounts Flood marks Agricultural production Port records

pharaohs, Chinese emperors, and Aztec kings, who recorded these events, whether in chronicles or pictograms written on clay tablets, in birch-bark, parchment, or in the Nilometer.[4] However, this section focuses on the medieval and (early) modern eras. In addition to presenting an overview of different types of source, this chapter discusses guidelines on dating applicable to all kinds of evidence.

4.2 Institutional Sources

Institutions are here defined as bodies in charge of performing official functions including taxation, law, war, and pastoral care, whether as states, municipalities, armies, or navies. Regulations determined who was in charge of keeping these records, how frequently, and often in what form. Beginning in the later Middle Ages, some institutions began keeping records in the same places for several centuries using more or less standard formats and bureaucratic practices. In agrarian societies the timing of most agricultural activities, receipts, and expenditures varied with the weather in some way, which was usually reflected in institutional documents. Of course, the officials in charge could not know that their records would be used as raw material for climate reconstruction in some distant future. It is up to the researcher to investigate whether there is really a relationship between the assumed indicator and some feature of climate, how strong that relationship is, and whether it changes over time. In the best case, the researcher may establish continuous, multi-centennial, quantified time series of temperature or precipitation indices, akin to those from natural archives. Chapters 5 and 6 will describe these sources and their use in more detail.

Among the earliest and best-known institutional sources are vintage (grape harvest) dates. To prevent theft or tax evasion, local officials had to decide on a single day each year to start this important event in the life of rural communities.[5] Daily wage accounting records can serve the same purpose. In late medieval England, estate managers noted down daily wage and food expenditures for harvesters, and so the date of each year's first payment indicates the beginning of the harvest.[6] Long series of grain harvest dates are available for Switzerland and Czech lands.[7] Andrea Kiss and colleagues provided a May to July temperature reconstruction of Budapest based on five vine- and grain-related historical phenological series from the town of Köszeg in west Hungary.[8]

Customs fees paid from incoming and outgoing ships serve as a proxy for winter and spring temperatures in harbors where the sea regularly freezes, as series from Tallinn and Stockholm demonstrate.[9] Moreover, some official accounts reference extreme weather when justifying extraordinary expenses. For example, weekly account books kept in the town of Louny in northwest Bohemia in the Czech Republic from the mid-fifteenth century list infrastructure maintenance expenses such as clearing the snow from roads.[10] In the city of Wels in Upper Austria the office of the bridge master was responsible for bridge repairs in case of flood damage. Weekly account books registered workers' wages and timber costs, which researchers can use to reconstruct the frequency and severity of river floods.[11] Likewise, governors in Venetian possessions of the Adriatic and the Eastern Mediterranean had to report annually to their superiors about events that affected income and expenditure in their territories, such as storms that damaged port installations or droughts that ruined the harvest.[12]

Ships' logbooks provide a unique source of weather information for the world's oceans. The English Admiralty obliged all officers of the Royal Navy to keep a logbook in which the wind and weather had to be recorded daily if not hourly, as did the admiralties of other naval powers.[13]

Chinese emperors ordered provincial administrators to keep detailed weather records related to the development of crops.[14] Bishops in Spain and in the Spanish world used to schedule rogation ceremonies to assist people in coping with meteorological stress such as droughts (Pro Pluvia Rogations) or excessive rain (Pro Serenitate Rogations).[15]

4.3 Personal Sources

Personal sources refer to those created by individuals rather than institutions. These present certain characteristics that can complicate their use. They usually suffer from gaps, their time of reporting is rather short (several decades at best), and they necessarily end with the death of the author. Observers often moved during their lifetime, and they frequently focused on a personal field of experience and activity, usually agriculture, meaning that we get somewhat different, but still usually meteorologically coherent, information from vine growers, cereal growers, and herdsmen. Issues of language, particularly old dialects, can create almost insurmountable barriers to interpretation. They often present difficult handwriting, although numbers remain universally comprehensible.

Until the late eighteenth century, meteorology dealt primarily with weather narratives. From the point of view of climate reconstruction, the language used to describe these events and the focus of the narrator can render the narratives subjective and difficult to compare. On the other hand, they shed light on the interplay of different weather elements, such as temperature, precipitation, snow cover, cloud cover, and wind, and they often include conditions in the surrounding area. The observations were made by humans for humans, thereby linking natural phenomena and human experiences. They describe, for example, the impact of destructive weather on crops and infrastructure, and they lay down social and cultural information about weather perceptions and discourse.[16] In doing so, storytelling also addresses people's emotional side.

Within scientific journals, however, the narrative approach gradually disappeared. In 1787

> the Irish chemist Richard Kirwan introduced a tradition which would persist until our own time […] He distinguished between the "Empyric" method—vague and uncertain—and "Scientific," still in its infancy, but "grounded on a long series of observations accurately taken of all the changes of the atmosphere, from whence some general law may at length be deduced."[17]

This tendency became dominant during the nineteenth century, and soon observers stopped keeping records of phenological observations and natural disasters such as floods, windstorms, and avalanches. The First International Meteorological Congress in Vienna, 1873, started work on standardized instructions and procedures for land observations. In the years that followed, member states stopped publishing narrative observations in their yearbooks altogether in favor of bare instrumental observations. Narratives even disappeared from newspaper weather reports for some time, at least in Switzerland. More research is needed about this "quantitative turn" in meteorology.

Systematic weather diaries contain short, dry weather notes, often in the form of hardly legible abbreviations. From these, historical climatologists can derive some quantitative information by counting the frequency of binary meteorological phenomena (e.g., days with/without precipitation, snowfall, or frost).[18] Most European weather diaries come from Germanic, English, and Slavic countries. In France, family account books (*livres de raison*) handed down from one generation to the next occasionally included notes on the weather. Weather diaries have also been identified for China (Chap. 17), India and Japan (Chap. 18), North America (Chap. 24), and Latin America (Chap. 19).

Chronicles refer to a broad category of medieval and modern works, whose common denominator is that they list important events in chronological order. Depending on the interest of the authors, weather usually makes up only a small part of the information found in them. Some chroniclers noted the weather frequently and quite systematically, although not on a daily basis, while others just reported disasters and extreme events. Some noticed only local conditions, while others included a variety of regional events. The merchant Philippe de Vigneulles (1471–1527), for example, paid great attention to weather relevant to the development of vines and the sugar content of grapes around his native town of Metz in France because his income depended on it.[19]

Most chroniclers wrote about extreme anomalies with serious human consequences. In the same way, some clergymen noted extreme events and those memorable for their communities in their church registers. The more outstanding an event the more chroniclers usually went into detail. For example, the eleven-month-long heatwave and drought of 1540 in Europe, a disaster of unspeakable dimensions, is described in hundreds of chronicles.[20] The "domestic colouring" of such reports, as Theodore Feldman remarked, shows how much their authors were at home in the weather, how much it formed part of their daily lives, and how little able they were to objectify the weather for the purpose of analysis.[21]

Newspapers and early scientific journals and papers are goldmines for weather observations and early instrumental measurements in many parts of the world. For example, in the absence of instrumental observations, Maria Prieto and colleagues gathered information about climate in the Argentinian and Chilean Andes from newspapers from 1885 to 2000 (see Chap. 19).[22] Likewise, newspaper reports were crucial for reconstructing weather series for Australia since its first European settlement (Chap. 21). In Europe, newspaper information remains important for reconstructions of natural disasters, including hailstorms and the freezing over of lakes and rivers.[23]

Travelers' journals provide important climate-related reports in areas without permanent settlement or with few endogenous records, such as parts of Africa (see Chap. 20).

Broadsides and pamphlets were short publications often inspired by nature-induced disasters and meteorological anomalies, describing the events in detail, and sometimes placing them in the context of earlier analogous disasters. Likewise, secular or religious authorities published their views of meteorological events, often in the form of exhorting sermons, as in the case of the disastrous European ice floods in spring 1784 (see Chap. 34).[24]

Paintings, etchings, and early photographs of historical glaciers provide among the most impressive evidence of climatic change. Together with written evidence, they make it possible to reconstruct the position of well-documented glaciers with remarkable precision over the last 400 to 500 years, including examples in Norway, the Gorner and Lower Grindelwald

Glaciers in Switzerland, and the Mer de Glace in France (see Chap. 8).[25] Paintings of winter landscapes from the Netherlands during the Little Ice Age, such as *The Return of the Hunters* (ca. 1565) by Pieter Bruegel the Elder, make the viewer feel the coldness of this period—although such images need to be interpreted carefully before being taken as evidence of actual weather conditions.[26]

With regard to *early instrumental observations*, the earliest instruments and networks date back to the seventeenth century (see Chap. 7). Barometers and thermometers sold by traveling salesmen became increasingly fashionable in better-off households from the early eighteenth century onwards. In England "by the 1790s, for instance, the barometer was said to be a widely owned piece of furniture, and often used as nothing more than a toy."[27] Most amateur observers ignored the problems of standardizing instruments, units of measurements, and observational techniques such as the location of instruments and schedule of readings. Thus using their early instrumental measurements in climate reconstruction requires an understanding of the instruments themselves, how the measurements were taken, and whether their data display artificial breaks and trends (see Chap. 9).[28] Outside the world of professional scientists, instrumental readings went hand in hand with narrative weather reports.

From the Middle Ages onwards, chroniclers increasingly cared for intergenerational comparability by referring to quasi-objective climate indicators in the human and natural environment. These include the level of bridges to indicate the magnitude of a flood, the absence or duration of snow cover, the freezing of bodies of water, the appearance of spring flowers, and the advance or delay of agricultural work.[29] Such objective observations may be compared to parallel cases in the instrumental period. Of course, in order to properly interpret sporadic climatic indicators, the researcher needs to become familiar with similar data from the instrumental period. In some cases, such as Norway, farmers regularly noted certain agricultural activities in their diaries such as the start of the cereal harvest, and this data has been used to reconstruct rising seasonal temperatures.[30] High-water marks on the walls of public or private buildings visually represent the frequency and severity of disaster over time, in a manner akin to actuarial data.[31]

4.4 Dating

Globally, there have been two major systems of calendars: solar calendars based (approximately) on the revolution of the Earth around the sun, and lunar calendars based on the orbit of the moon. The former have historically been used in Europe (and its colonies), India, and Iran, while lunar calendars were historically used in the Islamic world and imperial China.[32]

It should be noted that the meaning of terms—for example those of the seasons—may have been different in the past. In continental Europe, for example, "winter" could be equated with the duration of snow cover, which often included March, whereas "Herbst" (autumn) indicated the period of grape harvest. In (medieval) England, "summer" was equivalent to the period from May to July, and "autumn" to August and September. In the tropics, what mattered was the alternation between dry and wet seasons.

It is also important to distinguish between Julian ("old style") and Gregorian ("new style") dates. Roman emperor Julius Caesar first introduced his calendar in the first century BC. As time went on, astronomers discovered that each Julian year was 11 minutes and 10 seconds too long. In 1582, under the auspices of Pope Gregory XIII, most Catholic territories corrected this error by skipping ten days, in order to bring the calendar date back in line with the solar year. However, most Protestant territories waited until 1701 to adopt the Gregorian calendar; England (including the colonies) waited until 1752; and Russia until 1917. In many cases, this difference in dating will make little or no difference in climate reconstructions. In other cases, failure to correct for this change can introduce serious errors, as becomes apparent when comparing an uncorrected grape harvest series with a corrected one (see Fig. 4.1).

In medieval and early modern Europe, the calendar year did not necessarily begin on January 1. To make matters worse, most medieval and many early modern writers were silent about which dating system they used. This fact can produce puzzling results, particularly with regard to winters. Today, winters

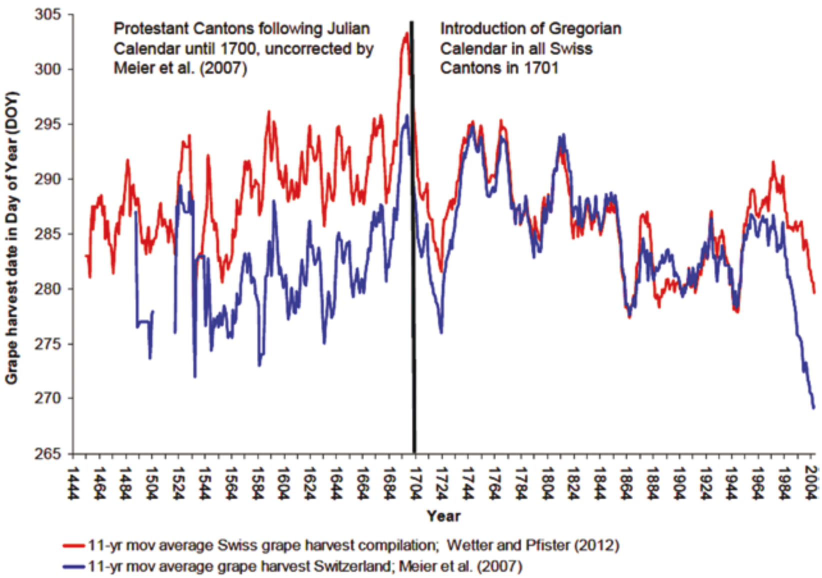

Fig. 4.1 A comparison between a grape harvest date series that has not corrected its dating for the switch from the Julian to Gregorian calendar (Meier et al. 2007) and a series that has corrected for this change in dating. (Image reproduced without changes from O. Wetter and C. Pfister, "An Underestimated Record Breaking Event. Why Summer 1540 Was Likely Warmer than 2003," *Climate of the Past* 9 (2013): 41–56, doi:10.5194/cp-9-41-2013., under a CC-BY 3.0 license: https://creativecommons.org/licenses/by/3.0/.)

are usually dated by the year in which January falls. However, in calendar systems in which the new year begins on March 25, the meteorological winter (December to February) falls in the previous calendar year. Sources using different calendar styles may thus refer to the same winter under two different dates.[33]

Individual dates were long named after religious feasts, such as Easter, or after saints. Some conventional handbooks on chronology offer catalogues of saints' days together with their corresponding Gregorian dates.[34] Most research by non-specialists has failed to observe that saints' days in the Julian and in the Gregorian calendars correspond to different (Gregorian) dates. This section has highlighted only the most important pitfalls. For further information about how to grapple with medieval and early modern European dating, see E.G. Richards, *Mapping Time: The Calendar and its History* (Oxford University Press, 1998).

Notes

1. Pfister, 1984; Brázdil et al., 2005, 2010a, 2010b; Ge, 2008.
2. Brázdil and Kundzewicz, 2006.
3. Bell and Ogilvie, 1978.
4. Schwemer, 2001; Seidlmayer, 2001. See also Chaps. 17 and 19.
5. Wetter and Pfister, 2011.
6. Pribyl et al., 2012.
7. Wetter and Pfister, 2011; Možný et al., 2012.
8. Kiss et al., 2011.
9. Leijonhufvud et al., 2010; Tarand and Nordli, 2001.
10. Brázdil and Kotyza, 2000.
11. Rohr, 2013.
12. Grove, 1995.
13. Wheeler and Pfister, 2009; Wheeler et al., 2006, 2010.
14. Ge, 2008.
15. Barriendos, 2005.
16. Adamson, 2015.
17. Quoted in Janković, 2001, 154.
18. Pfister et al., 1999; Adamson, 2015.
19. Litzenburger and Le Roy Ladurie, 2015.
20. Wetter et al., 2014.
21. Janković, 2001, 34.
22. Prieto et al., 2001.
23. E.g., Franssen and Scherrer, 2008.
24. Brázdil et al., 2010a, 2010b.
25. Nesje et al., 2008; Zumbühl et al., 2008; Holzhauser, 2010.
26. Behringer, 2010, 139–40.
27. Janković, 2001, 34.
28. Janković, 2001, 122.
29. Wegmann, 2005.
30. Nordli, 2001.

31. Pfister, 2011.
32. Richards, 1999.
33. Rohr, 2015.
34. E.g., Grotefend, 1997; Cheney and Jones, 2000.

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CHAPTER 5

Evidence from the Archives of Societies: Personal Documentary Sources

Christian Pfister and Sam White

5.1 Introduction

Personal documentary sources are highly diverse, fragmentary, and inherently limited by the lifetime of the author. Grasping their full meaning demands familiarity with their context and the nuances of their language. It helps to know the personal background of the observers and their motivations in order to understand which climatic elements they would have highlighted or disregarded. In the best cases, critical editions provide accessible texts with modernized language and spellings as well as biographical information about the authors and explanations of their terminology.

Most of the evidence discussed in this chapter comes from Europe. Evidence for other continents is discussed in Chaps. 16–21. The private recording of weather observations in pre-industrial times was an overwhelmingly male enterprise. A 2012 study by Georgina Endfield and Carol Morris found just a single female-authored weather diary from the UK.[1] The diaries of Märta Helena Reenstierna (1753–1841) from outside Stockholm also included descriptions of plant and animal phenology relevant to climate.

This chapter will not consider compilations—that is, chronologically arranged extracts from various sources about past weather without critical explanations. Most compilers have not distinguished between contemporary

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and non-contemporary sources, resulting in a mishmash of reliable and unreliable evidence.[2] Some compilers have not even cited their sources. One exception is Pierre Alexandre's critical catalogue of 3500 source excerpts from 1000 to 1425 CE, of which 300 are identified as non-contemporary.[3]

Instead, this chapter provides an overview of climatic information derived directly from personal sources. It is primarily concerned with situations where there is no overlapping period between the documentary and instrumental periods, rather than situations where observations can be calibrated to instrumental data and converted into temperature or precipitation indices. (For calibration and indexing, see Chaps. 10 and 11.) Where there is no overlap with instrumental measurements, researchers must either settle on qualitative descriptions or find objective standards by which to assess the magnitude of climatic changes and extremes.

5.2 The Objectivity of Weather Narratives

Natural scientists have often criticized evidence from weather narratives found in personal documentary sources as subjective, rather than objective. By this, they have meant that the evidence is biased and not (quantitatively) measured. Yet this issue requires closer examination. Any narrative is by definition "story-like" and reflects an individual's perspective. Nevertheless, weather narratives deal with physical processes that are by definition objective—that is, "in the realm of sensible experience independent of individual thought and perceptible by all observers having reality independent of the mind."[4] Furthermore, insofar as accounts by different observers prove meteorologically consistent, we can overcome inevitable problems of individual perception and selection of events.

Most importantly, past observers were themselves aware of these problems of subjectivity and therefore made deliberate reference to more objective standards. In some cases, they supported their descriptions of cold or warmth by referring to the development of crops and wild plants. The annual cycle of nature, particularly the rhythm of the agricultural year, provided a widely understood frame of reference. People cultivating the same crops at the same place year after year became acutely aware of changes in plant development. Major deviations from the usual pattern of crop development or the timing of spring blossoms were known indicators of anomalies in growing-season temperatures. In other cases, observations of physical changes could provide quantifiable measurements of changes and extremes, even in the era before weather instruments. The freezing of lakes, rivers, and seas could provide objective indications of extreme cold, as an anonymous chronicler wrote about the severe winter of 764: "In these days the river Seine was covered with a thick ice so that people could cross it like a bridge."[5] Chinese historical climatologists have even adopted a typology for personal evidence "grouped into 'objective' records [based on indicators in the natural environment] which can be compared directly among the different sources, and 'subjective' [purely descriptive] records, which are difficult to compare quantitatively."[6]

Likewise, subjective evaluations of meteorological disasters such as "the worst flood in living memory"—basically a topos for "very large"—are usually supported by objective references to the scale of damage. For example, we read in one medieval chronicle:

> On December [20,] 1206, in order to punish mankind for its sins, there was a flood of such magnitude that no contemporary had witnessed it or heard of it before. The water destroyed three [wooden?] arches of the Petit Pont and washed many houses away causing huge damage in many places.[7]

In general, contemporary reports on floods and low water tables need to be regarded as objective evidence.[8] High-water marks offered another convenient way to objectively compare the frequency and severity of floods over time.[9] At the same time, they served as a basis of comparison for subsequent floods, which maintained preparedness for prevention. Rather than being purely communicative, high-water marks can be read as visual expressions of institutional risk memory in the sense used by the insurance industry, which defines risk as the likelihood that a loss of a certain magnitude will occur (Fig. 5.1).

5.3 (Weather) Chronicles

Chronicles are a broad category of historical information listing miscellaneous events in chronological order. The focus is not always evident from the title. For example, the chronicle of Hans Stolz, mayor of Guebwiller (France)—subtitled "testimony about the [German] Peasants' War [of 1525] in the Upper Rhine area"—actually contains numerous weather reports for the 1530s.[10] Chronicles have a spatial focus, be that the world, a territory, a town, a village, or an abbey. Chronicles representing large areas tend to be parsimonious about weather events. Town and village chronicles are more promising because local chroniclers more closely witnessed the weather and the related ups and downs of everyday life in the rural world. They paid particular attention to phases of weather known to make a difference in the development of the most important crops. Severe frost in winter and spring as well as persistent rain in summer were disastrous for vines, whereas grain crops suffered most from long snow cover in spring and rainy midsummers.[11] In their tendency to focus on extreme events, chroniclers act as a "human high pass filter recording short-term fluctuations about an ever-changing norm."[12] Indeed, as Christian Rohr has demonstrated from accounts about bridge repairs in Austria, chroniclers often overlooked smaller floods.

5.4 (Weather-Related) Pamphlets and Broadsides

As print became more widespread and literacy rose in Northern Europe, printers began to publish large numbers of cheap short books (pamphlets) and single-page illustrations with text (broadsides). Since these formats aimed at a wider audience, they often focused on popular genres, such as sermons, and on

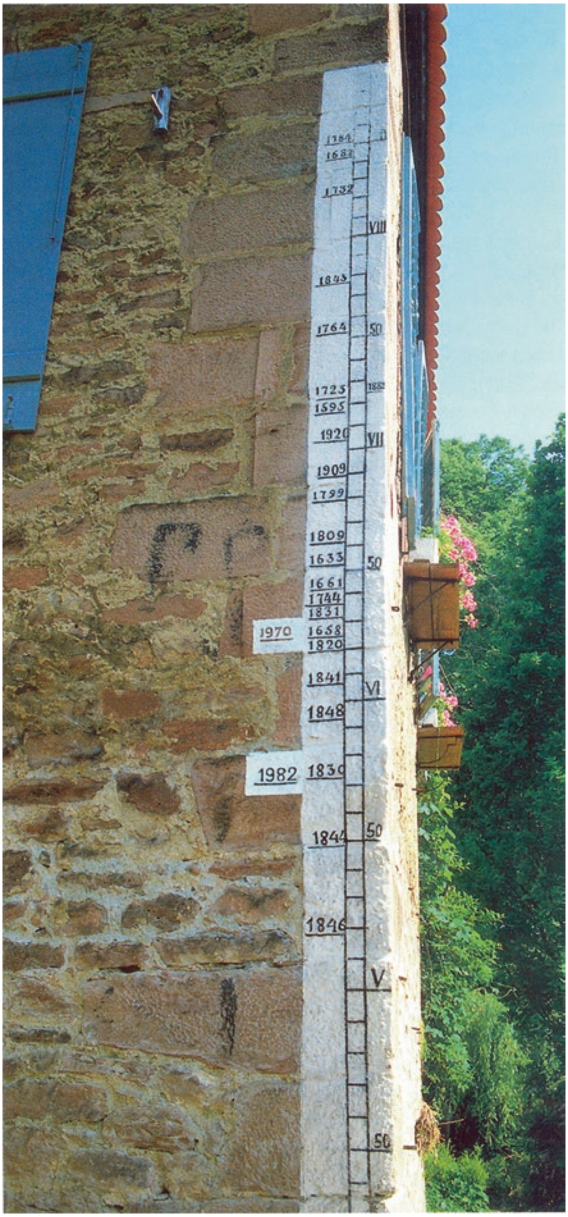


Fig. 5.1 Assemblage of 24 water marks on the wall of a private house situated at the Tauber River in Wertheim (Germany). Photograph: Rüdiger Glaser, 2013

sensational topics, including meteorological disasters. Pamphlets could be particularly useful for providing additional detail on weather events in late sixteenth- and seventeenth-century England and the Netherlands, where these sources are especially plentiful but weather diaries are less common or have not all been analyzed. Broadsides, which sold for as little as an English penny, were once very common and constituted almost a tabloid press on current events. However, most were not preserved, and there are not many surviving broadsides related to weather.[13]

Even more than chronicles, pamphlets provide evidence of extremes rather than average weather conditions. For instance, a major flood in southwestern England in early 1607 inspired at least a half-dozen pamphlets, two even translated into French and Dutch.[14] These include details about the extent of the flooding and the damage inflicted on humans, livestock, and farms. Yet typical of the genre, all of them depict it as a singular event and a divine warning or punishment. On occasion, pamphlets do provide more measured descriptions of weather events and even attempts to place them in long-term context. For instance, a 1608 pamphlet attributed to playwright Thomas Dekker not only gives a detailed account of the "frost fair" held on the frozen Thames that year but also offers commentary on its social and economic impacts and compares it with similar events in decades and even centuries past.[15]

5.5 (Weather) Diaries

Weather diaries refer to diaries that contain more or less continuous daily weather records for a significant period.[16] They have long been recognized as one of the "most valuable kinds of non-instrumental meteorological evidence."[17] As George Adamson has explained, "Private diaries constitute a unique set of materials within climate change research in that they provide information both on past climate variability *and* on the ways that people live within, and interact with weather and climate."[18] Observations in weather diaries benefit from daily resolution, an absolute dating control, and a rather standardized vocabulary, often including abbreviations. Most importantly, they are reasonably continuous with reference to features such as sunshine, rainfall, snowfall, fog, hail, and frost, and are therefore suited to statistical analysis and comparison with the recent past. This property is crucial for the reconstruction of past precipitation patterns, which despite their significance for the human and the natural world remain systematically under-researched.

One of the world's oldest weather diaries was kept by Ptolemy (Claudius Ptolemaeus) of Alexandria, Egypt (ca. 120 CE). It reveals remarkable differences from today's climate in the occurrence of rain every month of the year except August.[19] In Japan, several weather diaries were kept starting around 1000 AD.[20] In China, about 200 private diaries containing daily weather records or weather-related natural phenomena have been found so far, dating back to the twelfth century (see Chap. 17).

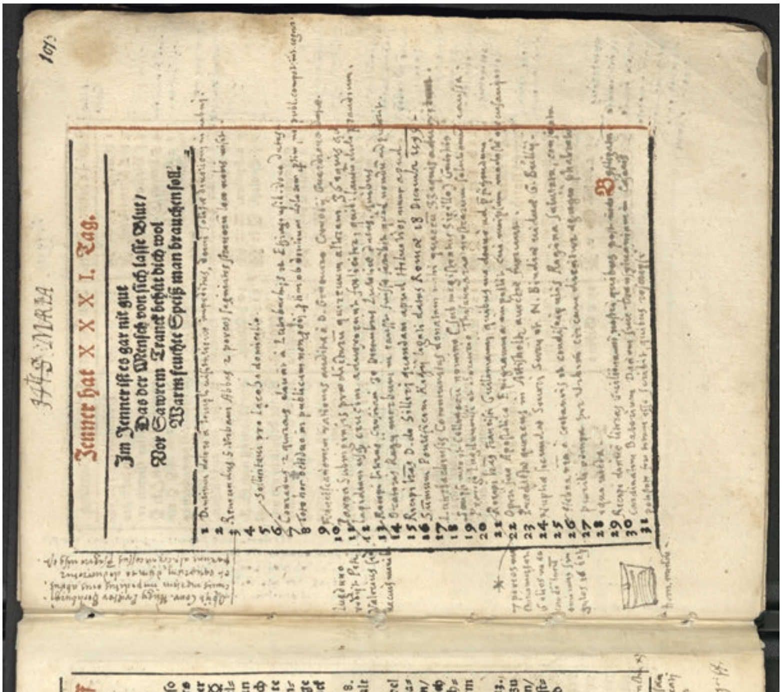
The oldest daily weather observations in Europe, for 1269/70, appear in an anonymous astronomical calendar attributed to the philosopher and scientist Roger Bacon (1229–1292), a forerunner of empirical methods in scientific studies. His notes are already at the same level of sophistication as most of those made in later centuries.[21] The Reverend William Merle in Lincolnshire, England, kept a weather diary from 1337 to January 1344.[22] An anonymous weather diary was kept in Basel or in neighboring France from 1399 to 1406.[23]

Astronomical almanacs, published in large numbers starting in the late fifteenth century, became an early form of today's agenda planner. Monthly tables listed the saints for each day next to icons indicating astronomical constellations and suitable conditions for activities such as planting, harvesting, bleeding, and weaning babies.[24] The line on the opposite page was left vacant for personal entries, a space often used for noting weather observations (Fig. 5.2).[25] Many early diarists were astronomers and astrologers who believed that weather patterns were governed by a conjunction of the planets. By attempting to make astrometeorological predictions, they hoped to link their observations of celestial bodies to weather and life on Earth in order to justify their studies.[26] Gabriela Schwarz-Zanetti provides an elaborate detailed analysis of sixteen weather diaries kept in Central Europe between 1331 and 1521, some written into almanacs.[27] A study by Pfister and colleagues provides a survey of thirty-two sixteenth-century weather diaries for Central Europe each yielding a minimum of 100 daily observations.[28] In Iberia, weather diaries are scarce, with serial weather descriptions mostly being attached to early meteorological measurements.[29] Klaus-Dieter Herbst provides a survey of weather diaries in Germany that covers the seventeenth century with only a few gaps (Fig. 5.3).[30]

The most important information in weather diaries concerns changes in the monthly frequency of precipitation (distinguishing between rainfall and snowfall), something that cannot be obtained from the archives of nature. In order to assess how carefully and completely a diarist might have observed precipitation events, the researcher needs to compare the average annual number of his precipitation days with those measured at a neighboring weather station during the instrumental period. The average number of measured precipitation days depends on the threshold, which is offered in the statistic: the higher the threshold, the lower is the average number of precipitation days. Changes in monthly precipitation frequencies are obtained by comparing percentages from the annual average (see Table 5.1).

Precipitation in the early sixteenth century tended to be lower in winter and higher in summer than in the twentieth century, probably because observers may have overlooked feeble snowfalls in winter, and because the summer half-year tended to be wetter. The high values obtained from many eighteenth-century diaries suggest that the diarists were able to observe values above 0.3 mm of measured precipitation, which is remarkable.[31]

The long duration or absence of snow cover was recognized as a feature of exceptionally severe or mild winters. Historical climatologists have used records of snow cover to reconstruct past winter temperature. For instance, Hermann Flohn assessed winter temperatures in Zürich from 1551 to 1576 by compar-


Jenner hat XXXI. Tag.

Im Jenner ist es gar nit gut
Das der Mensch von sich lasse Blut
Vor Sawrem Tranck behüt dich wol
Warm feuchte Speiß man brauchen soll.

Witterung auff das 1600. Jahr.

New Januar. Jenner.

A Christ.99

Fig. 5.2 Almanac for the year 1600. The calendrical part for January (left) compares the "New" with the "Old" calendar alongside three icons representing the astronomical constellation and recommended activities. Note that "New" and "Old" saints' days refer to different Gregorian dates. Tiny weather notes are squeezed into the margin. The empty lines to the right are filled with the personal notes of the owner (not shown). Source: Hans Jakob vom Staal, Kalendernotizen, Zentralbibliothek Solothurn, Cod S 5 (3) p. 100, 101

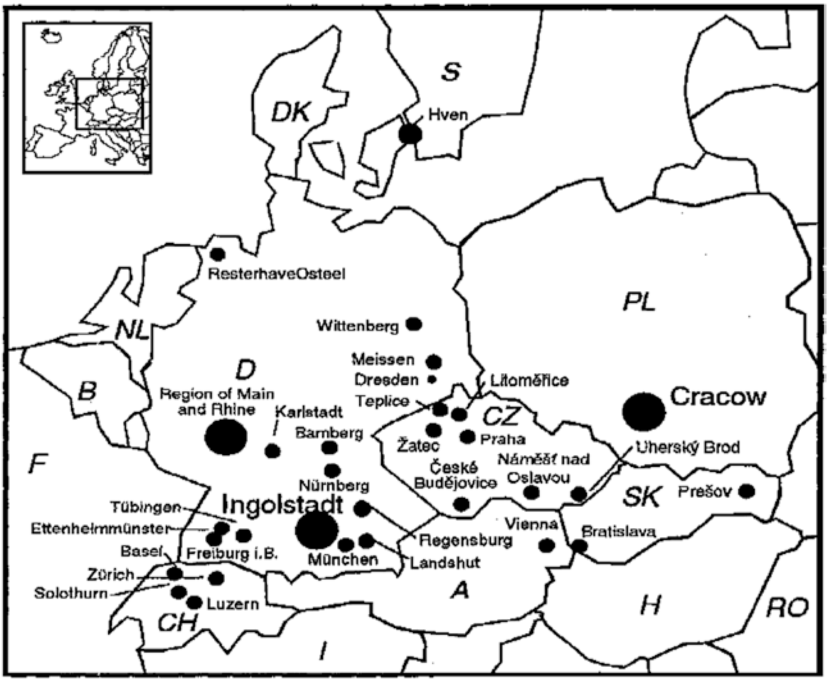


Fig. 5.3 Places where comprehensive weather diaries were kept in sixteenth-century Central Europe. A considerable number of diaries were kept by graduates of the universities of Cracow (Poland) and Ingolstadt (Germany), from where the practice probably spread to Protestant universities such as Tübingen, Wittenberg, and Basel. Reproduced from Christian Pfister et al., "Daily Weather Observations in Sixteenth-Century Europe." *Climatic Change* 43 (1999): 111–50

ing the frequency of rain days and snow days in the Wolfgang Haller diary. Breaking down the series into two subseries, he showed that the frequency of snow from 1564 to 1576 was 19.3% higher than in the period 1801–1938, which points to winter cooling.[32] Likewise, observers since the late sixteenth century recorded snowfalls on mountains related to cold snaps during the warm season. The Zürich diarist Johann Heinrich Fries regularly described the appearance and melting of snow cover during the late seventeenth century, which has made it possible to assess the total duration of snow cover at the time.[33]

The earliest instrumental temperature observations were being made within the Medici network (1654–70), set up and sponsored by the Grand Duke Ferdinand II de' Medici.[34] The subsequent spread of weather instruments during the late seventeenth and eighteenth centuries (see Chap. 7) also encour-

Table 5.1 Mean monthly precipitation in Cracow 1502–38 and Eichstätt 1514–31 against instrumental measurements

Observers	*Period*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual average*
Marcin Biem[a] (%)	1502–38	6.5	7.5	9.3	7.8	9.7	10.1	10.7	9.1	8	7	7	8	132.2 days (100%)
Instrumental (%) *(Cracow, Poland)*	1931–60	9.6	8.6	8	7.6	8	8.6	8.6	7.6	7	7.6	9.2	9.6	186.0 days (>0.1 mm)
Difference		−3.1	−1.1	1.3	0.2	1.7	1.5	2.1	1.5	1	−0.6	−2.2	−1.6	
Kilian Leib[b] (%)	1514–31	8.3	8.9	8.8	6.3	8.3	8.5	10.1	9.5	8.1	7.9	7.7	7.5	160.6 days (100%)
Instrumental (%) *(Weissenburg)*	1891–1930	8.8	7.4	8.3	8.8	9.2	8.4	8	8.3	7.5	8.6	8	9.5	185.7 days (>0.1 mm)
Difference		−0.5	1.5	0.5	−2.5	−0.9	0.1	2.1	1.2	0.6	−0.7	−0.3	−2	

Source: Pfister et al. (1999)

[a]Marcin Biem (*c*.1470–1540), a famous Cracow University professor, carefully logged daily weather for 682 months (with gaps)

[b]Kilian Leib (1471–1553), abbot of a monastery near Eichstätt (Germany), came close to log days with (<0.3 mm) precipitation

aged the keeping of weather diaries incorporating narrative observations and measurements. This boom involved prominent figures such as Peter the Great, George Washington, and James Madison.[35]

Louis Morin (1635–1715), the physician of France's King Louis XIV, was perhaps the most outstanding pioneer of early meteorology. His meteorological diary kept in Paris from 1665 to 1713 contains, among other things, three daily readings of the following elements: air temperature and pressure, cloudiness, wind direction and strength, rainfall duration and intensity, and the provenance and speed of clouds.[36] With these observations, Morin was probably the first individual to observe the dynamics of the free atmosphere.[37]

5.6 (Personal) Plant-Phenological Observations

Plant phenology is the study of plant life-cycle events, which are triggered by environmental changes. The term "phenology," coined in the mid-nineteenth century, gradually replaced customary terms such as "periodical features." Time series of plant-phenological observations may be used to detect climate change because every plant species requires a specific sum of positive daily temperatures to achieve a certain phenophase, such as leafing or flowering.[38] Quantifying phenological growth stages involves first converting all dates into Day of Year (DOY).[39] For an unequivocal designation of plant species, the Latin name needs to be added in italics. In order to get valid average phenophases, the plants in question should have been regularly observed for at least ten years. In comparing phenological observations from different places, researchers must account for changes in altitude and exposure. Over larger distances, differences in latitude also need to be considered.[40]

In China, occasional phenological observations began around 2000 years ago, whereas systematic observations date back to around 1500 CE. In Europe, phenological observations began to appear in manuscripts during the high Middle Ages, reflecting a new understanding of nature known as the Renaissance of the Twelfth Century. Milene Wegmann demonstrated from more than 400 texts that phenological observations soon became an element of monkish record-keeping.[41]

Kilian Leib, abbot of a monastery near Eichstätt, Germany, may have been the first to leave long-term phenological observations. Between 1513 and 1531, he noted down in his weather diary the date of the greening of meadows, the foliation of beech trees (*Fagus sylvatica*), and the beginning of the rye (*Secale cereale*) harvest.[42] Hans Rudolf Rieter, a baker in Winterthur, Switzerland, stands out for the number of early systematic observations he left. Between 1721 and 1738 he recorded nineteen phenological stages mostly relating to fruit trees, cereals, and vines, as well as the unfolding of beech leaves (*Fagus sylvatica*) and the time of the first ripe strawberries (*Fragaria vesca*). More extensive still are the records of Parson Johann Jakob

Sprüngli made at three locations in the canton of Bern between 1759 and 1803.[43] The Marsham family in Norwich, UK, set a record for continuous private phenological records. Their observations cover more than 190 years, from 1730 to 1925. They regularly noted the leafing of thirteen trees, including beech (*Fagus sylvatica*), four flowering events, and the seasonal appearance of animals such as frogs.[44] Dates about the earing, blooming, and harvesting of rye (*Secale cereale*) for the territory of Estonia and neighboring countries were systematically collected and interpreted over the period 1671 to 1985.[45] Some nineteenth-century Norwegian farmers systematically noted down the grain harvest dates (barley or oats), which enables estimates of spring-summer temperatures.[46]

Regional phenological networks were initiated from the mid-eighteenth century onwards. For example, the Imperial Royal Patriotic–Economic Society of Bohemia (today's Czech Republic) not only made meteorological observations but also set up a network of phenological stations. Between 1827 and 1847, these stations recorded the stages of thirty-one forest plants, fruit trees, and field crops in Bohemia; from 1851 to 1877, it expanded its activities throughout the Austro-Hungarian Empire.[47] A network of volunteers in Europe was established by Egon Ihne and Hermann Hoffmann in 1884 and survived until 1941. Following a recommendation of the World Meteorological Organisation in 1953, many national meteorological services started regular observations.[48]

Historical phenological data was not always gathered according to present-day guidelines, and therefore it presents some uncertainties. This poses more difficulty in identifying long-term trends but is less important in dealing with single observations made to document extreme events in the pre-instrumental period. Such observations, usually documented in several narrative sources, may be cautiously compared with analogous cases in the instrumental period in order to get a rough idea of the magnitude of temperature deviations.[49]

5.7 (Personal) Ice-Phenological Data

The freezing and break-up dates of bodies of water were used as early proxies for cold-season temperatures both in China and Europe.[50] Sums of negative daily temperatures are calculated to assess the freezing condition for a body of water. Anthropogenic changes in the hydrological conditions through canal building, the channeling and damming of rivers, and industrial water pollution need to be taken into account, as well as the effects of strong winds agitating the water surface. Seawater freezes at lower temperatures than freshwater, at −1.9° on average, depending on its salinity.

A number of historical climatologists have reconstructed cold-season temperatures using personal records of the *freezing of the sea and inland waters near the coast*. For instance, Koslowski and Glaser investigated winter severity in the low-salinity western Baltic Sea area between 1501 and 1995 using narratives about the duration of ice cover and remarks on ice thickness, as well as evidence on ship traffic and weather conditions in the German "Tambora" database. They assumed an ice thickness of at least 35 cm for pedestrian traffic and 50 cm for loaded wagons. Dario Camuffo catalogued instances of the freezing of the Venetian lagoon from early medieval times until the 1960s, when the construction of a deep canal for tankers modified its hydrology.[51]

Switzerland possesses a vast array of *inland lakes* of varying surface area and depth. A very long record of freezing dates going back to the Middle Ages exists for Lake Constance (473 km^2) and Lake Zürich (88 km^2). The hydrological conditions of both lakes have hardly been affected by anthropogenic modifications, making them largely homogeneous indicators of winter severity. A complete freezing of Lake Constance requires a negative temperature sum of >440° for people to safely walk on the ice, something which occurred for the last time in 1963. For Lake Zürich, a negative temperature sum of only >350° is necessary; and the number of known freezings of Lake Zürich in 1501–1963, an event often associated with public festivals, was about five times as frequent as those of Lake Constance.[52]

Descriptions of the most severe winters of the Little Ice Age regularly record *freezing or ice flows on large rivers* with a slow current. Sudden warming in spring then often led to disastrous floods caused by ice jams on bridges. For instance, a disastrous ice jam disaster in spring 1784 affected France and Central Europe, including the Danube catchment.[53] Ice on the Rhine was monitored by gauges from the late eighteenth century, and it has decreased remarkably since the late nineteenth century as a result of rising temperatures and water pollution.[54] Engineers heavily modified most of the major rivers in Central Europe for navigation between the eighteenth and twentieth centuries, also rendering them less likely to freeze.[55] An ice break-up series of the River Tornionjoki (northern Finland) since the 1690s was set up as an indicator of spring temperatures.[56] The break-up date of Lake Ransfjord (southeastern Norway) was registered systematically by local farmers from 1758 until the late nineteenth century.[57]

Finally, *glaciers* in mountain areas provide one of nature's clearest signals of decadal-scale warming and cooling. Fluctuations in the size of glaciers are primarily influenced by summer air temperature and secondarily by annual precipitation.[58] Systematic measurements of glacier length and thickness began during the late nineteenth century. Researchers must rely on written and especially visual evidence to reconstruct the movements of glaciers in earlier times (see Chap. 8).

Notes

1. Endfield and Morris, 2012.
2. After all, as Bell and Ogilvie (1978) long ago demonstrated, one should strictly differentiate between contemporary and non-contemporary information, as

names are often misspelled and numbers miscopied. For example, the Italian eighteenth-century astronomer Giuseppe Toaldo understood from a sixteenth-century source that the artillery of Pope Julius II, fighting against France's King Louis XII, crossed the frozen River Po in 1503. However, he misread the Roman numeral MDXI (1511), thus duplicating the event. Camuffo and Enzi, 1995.

3. Alexandre, 1987.
4. http://www.merriam-webster.com/dictionary/ (accessed January 15, 2015).
5. Pertz, 1829.
6. Ge et al., 2008.
7. Alexandre, 1987, 373.
8. Pfister et al., 2006.
9. Munzar et al., 2006.
10. Stolz, 1979.
11. Pfister, 2015.
12. Bradley, 2015.
13. E.g., D. Sterrie, *Briefe Sonet Declaring the Lamentation of Beckles, a Market Towne in Suffolke Which Was in the Great Winde upon S. Andrewes Pitifully Burned with Fire …* (London: Nicholas Colman, 1586). On German pamphlets, see Bellingradt, 2008.
14. (Anon.), *1607. A True Report of Certaine Wonderfull Overflowings of Waters …* (London: Edward White, 1607); (Anon.), *Een Warachtich Verhael van de Schrickelicke Springh-Vloedt in het Landtschap van Summerset* (Amsterdam: C. Claesz., 1607); (Anon.), *God's Warning to His People of England … by the Late Overflowing of the Waters …* (London: W. Barley and J. Bayly, 1607); (Anon.), *Miracle upon Miracle or A True Relation of the Great Floods …* (London: Nathanael Fosbrook and John Wright, 1607); *Discours veritable et tres-piteux, de l'inondation et debordement de mer, survenu en six diverses provinces d'Angleterre, sur la fin de janvier passé, 1607* (Paris: Fleury Bourriquant, 1607).
15. Dekker, 1608; Janković, 2001.
16. Schwarz-Zanetti, 1998.
17. Manley, 1953.
18. Adamson, 2015.
19. Lamb, 1995.
20. Maejima, 1966.
21. Long, 1974.
22. Lawrence, 1972.
23. Frederick et al., 1966.
24. Bepler and Bürger, 1994.
25. Pfister et al., 1999.
26. Pfister et al., 1999.
27. Schwarz-Zanetti, 1998.
28. Pfister et al., 1999.
29. Domínguez-Castro et al., 2014.
30. Herbst, 2016.
31. Pfister et al., 1999.
32. Flohn, 1949.
33. Pfister, 1985.

34. Camuffo and Bertolin, 2012.
35. Chernavskaya, 1994; Heidorn, 2012; Druckenbrod et al., 2003.
36. LeGrand and LeGoff, 1992.
37. Pfister and Bareiss, 1994.
38. Meier et al., 2009.
39. Tables are available at http://disc.gsfc.nasa.gov/julian_calendar.shtml (last accessed January 21, 2016).
40. Ge et al., 2008.
41. Ge et al., 2008; Wegmann, 2005.
42. Pfister et al., 1999.
43. Pfister, 1984.
44. Margary, 2007.
45. Tarand and Kuiv, 1994.
46. Nordli, 2001.
47. Brázdil et al., 2010.
48. Hudson and Keatley, 2010.
49. Pfister, 1992.
50. Ge et al., 2008; Pfister, 1998.
51. https://www.tambora.org/ (accessed October 10, 2016); Koslowski and Glaser, 1999; Camuffo et al., 2017.
52. Pfister, 1984, 65–66.
53. Brázdil et al., 2010.
54. Jansen, 1983.
55. Blackbourn, 2006.
56. Vesajoki and Tornberg, 1994.
57. Nordli et al., 2007.
58. Oerlemans, 2001.

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CHAPTER 6

Evidence from the Archives of Societies: Institutional Sources

Christian Pfister

6.1 Introduction

Institutional sources recording past weather and climate differ from personal sources in their duration, their continuity and localization of reporting, and their state of preservation. Personal sources are usually incomplete and rather short, often made in different places, and end with the death of the observer. Institutional sources (apart from official chronicles) were produced in the same place, continuously, over a much longer period of time, and they are usually preserved in official archives. They are the most accurate documentary sources, usually written with the purpose of being precise and objective.

Institutional sources can offer many kinds of information about past weather and climate, but they most often provide proxies for temperature. It is up to the researcher to investigate whether there is a relationship between the assumed proxy and climate parameters, how strong that relationship is, and whether it changes over time. It requires a critical evaluation of human decision-making and the institutional framework to determine whether an apparent proxy yields the same signal throughout the lifetime of the institution (the "principle of stationarity") (see Chap. 3). Ideally, researchers look to create a proxy series that overlaps sufficiently with the instrumental record for appropriate calibration and verification (see Chap. 10). For cases where a sufficient overlap between the proxy and instrumental measurements is not available, Fernando S. Rodrigo has proposed a simple approach to reconstructing climatic variables for decadal periods from documentary-based time series.[1]

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6.2 Agricultural Phenological Series

Agricultural phenology utilizes the dates of recurrent agricultural work, such as planting and harvesting.[2]

Records of *grape harvest dates* obtained from institutional sources provide the longest continuous series of phenological data in Europe. They were first used by the Swiss physicist Louis Dufour in 1870 for climatic change research and became widely known through the work of Emmanuel Le Roy Ladurie.[3] An open database including 378 series, mainly from France, was set up by Valérie Daux and colleagues.[4] Historically, grapes have been grown in Europe up to the northern limit of their natural habitat. The underlying climate signal of grape harvest dates has been the subject of longstanding discussion.[5] Guerreau demonstrated that August temperatures are not significant for grape maturity, so grape harvest dates are not perfect proxies for assessing "summer temperatures."[6] Besides grape maturity, several factors could influence the harvest date, including local traditions, human decision-making, differences in fertilization, changes in grape variety (particularly in the late nineteenth century), and economically motivated behavior in extreme situations.[7]

Prior to the French Revolution, vine-growers had to wait for a public order to begin the harvest. As soon as the grapes were found to be ripe, the vineyards were banned—that is, guarded day and night to prevent anyone from entering. This vintage ban dates back to Roman times.[8] It was probably intended to prevent clandestine grape-picking and tithe evasion. The lifting of the ban was a public act whose date was recorded in municipal registers. After the French Revolution, vine-growers were theoretically free to begin the harvest when they pleased, but in practice the vintage ban was maintained.[9]

The relationship between April to July temperatures and grape harvest dates is not stationary: Marcel Lachiver showed that prior to the seventeenth century the vintage in France began on some preferred day of the week depending on local tradition. For a long time, decisions about grape cultivation were dominated by risk aversion. Vine-growers planted a mixture of early and late varieties to maintain a minimum yield in bad years. As local wines began to face wider market competition from the seventeenth century onwards, cultivation was directed more towards obtaining a high sugar content.[10] In exceptional situations, such as military invasions or plagues, harvesters might start the harvest before the grapes had reached full maturity or they might skip the vintage altogether.[11] Premature harvests also occurred when the grapes froze or decayed as a result of unseasonable weather.

Grape harvest dates became relevant in the debate about the summer of 2003, which was the hottest in the instrumental record for Western and Central Europe. Based on the analysis of a long series of grape harvest dates in Dijon, France, published in the journal *Nature*, Chuine and colleagues argued that temperatures in the summer (June to August) of 2003 were probably "even higher than in any other year since 1370."[12] Since then, this claim has been echoed in more than 100 scientific papers. However, subsequent analyses revealed that the authors neglected critical analysis of the sources. It turned out that not until 1607 did the municipal council in Dijon prioritize grape maturity in determining the harvest date.[13] Moreover, it became obvious that the study suffers from incorrect raw data and from a questionable oenological model.[14] Most importantly, the authors overlooked the extreme heat and drought documented for 1540.[15] Thomas Labbé and Fabien Gaveau set up a new series for the period 1371–2010 from the archives of the famous Burgundian wine commune of Beaune situated south of Dijon where vine-growers always cared about quality. It turned out that in Beaune the 1540 vine harvest took place on August 20, just one day after the date in 2003.[16] Western and Central Europe suffered that year from a bone-dry spring followed by a torrid summer and almost rainless autumn.[17] In many regions of France, Germany, and Switzerland this vintage was postponed because the grapes had almost dried out by the time they turned ripe. Vine-growers chose to wait until the next abundant rain spell, on St. Michael's Day (October 8), so that regardless of the quality and price of the wine, they would still get enough liquid from the press to make a profit. Therefore this artificially late harvest date appears in several municipal records, giving a misleading impression about summer temperatures (Fig. 6.1).[18]

Grain harvest dates: Cereals have been the most widely grown crops worldwide since the Neolithic Revolution. Historically, wheat, barley, rye, and rice have been the most important grains in Europe and Asia. Their date of maturity depends on the species and the variety of crop, and on the year's weather. Analyses carried out in several countries have confirmed the value of grain harvest dates as a proxy for spring-summer temperatures.[21]

Nevertheless, as with grape harvest dates, historical climatologists must pay attention to human and historical factors. The timing of the grain harvest depends not only on ripeness but also on calculations of risk and profit. The onset of long rainy spells can prevent sufficient drying and may postpone the start of the harvest. On the other hand, if the plant becomes overripe, there is the risk of substantial loss of grains during harvesting. The introduction of the combine harvester thresher radically changed grain harvesting, starting in the early twentieth century in North America and after the mid-twentieth century in the rest of the world. A combine requires grain to be ripe seven to ten days before cutting, which is much later than had been customary.[22]

Historical climatologists in several countries have found different methods to determine grain harvest dates and their relationship to climate. In Switzerland, the right to collect the grain tithe was sold by auction, usually to a member of the village elite. In 1979, Christian Pfister discovered that the date of the auction could serve as a good proxy for average March–July mean temperatures.[23] For example, the books of expenditure kept by the hospital in Basel between 1454 and 1705 list daily wage payments to laborers. They indicate the start dates of various agricultural field and vineyard work, including the start of the winter rye harvest. Using tithe auction dates, Wetter and Pfister

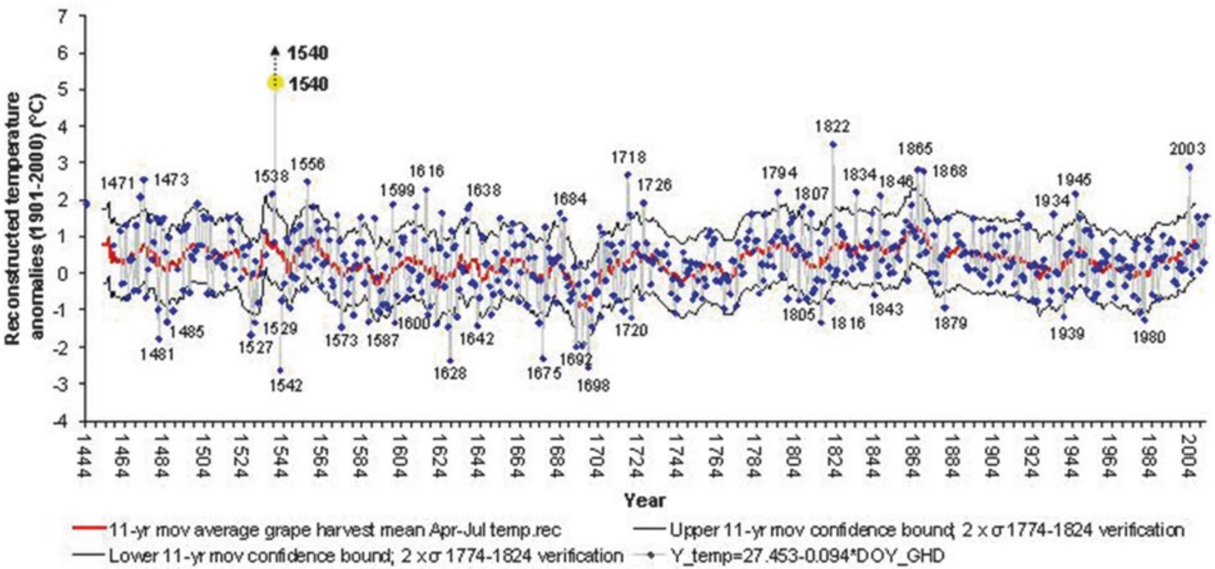


Fig. 6.1 April to July mean temperatures estimated from a new series of Swiss grape harvest dates in 1540 were significantly higher than those in 2003. The time of grape maturity in 1540 is estimated here from phenological observations because the harvest date was delayed in order to wait for rain (see the text). (Image reproduced without changes from Oliver Wetter and Christian Pfister, "An Underestimated Record Breaking Event: Why Summer 1540 Was Likely Warmer than 2003," *Climate of the Past* 9 (2013): 41–56, under a CC-BY 3.0 license: https://creativecommons.org/licenses/by/3.0/.) Note that August temperatures cannot be assessed from grape harvest dates.[19] According to a model-based approach, summer (June, July, August) temperatures were probably somewhat higher in 2003 than in 1540[20]

were able to extend this series to 1825, providing a suitable period for calibration and verification with the long Basel temperature series (beginning 1755).[24]

Manorial records of medieval England have provided further grain harvest dates suitable as climate proxies. English manorial records include the oldest wage payment dates in Europe as well as specific information about weather and its effects on agriculture (see Chap. 27). As historical climatologist Kathleen Pribyl has explained,

> "The manorial accounts enabled a non-resident landlord to control and assess the economic performance of his directly managed estate (as opposed to leasing out to farmers). These documents report the cost and profits of the farming activities on the manor; they list expenses and receipts and consider the state of the agricultural and pastoral sectors."[25]

Accroding to Jan Titow,

> "References to the weather were made to explain why certain expenditures exceeded those standards or why certain items of income did not meet them. For example, references to hard winters (which included most of spring), are usually made to explain why unusually large quantities of grain were fed to the manorial hogs and sheep which could not find enough feed in the open."[26]

If an account does not mention extraordinary weather-related expenses, we may assume that outstanding weather extremes did not occur during the harvest year:

> "The accounts covered the agricultural year, which is the time from Michaelmas (September 29) to the following Michaelmas (the year of harvest). The information was supplied by the personnel managing the manor, recorded by scribes in medieval Latin on a parchment roll and was checked in an audit process by the landlord or his representatives."[27]

This system of manorial record-keeping ended in the early fifteenth century. The longest series, from Norwich Cathedral Priory in southeast England, augmented by shorter series from neighboring institutions, yielded 616 dates indicating the onset and often the end of the grain harvest. Needless to say, there is no overlap between the medieval time series and the Central England Temperature Series, the longest English instrumental record, which begins in 1659. But using a long time series of wheat harvest dates from Langham, England, between 1768 and 1867, Pribyl established a relationship between growing season temperature and grain harvest dates, and that relationship in turn served to determine medieval temperature values. It turned out that April–July average temperatures fell from 13.0° to 12.4° between 1256 and 1431, a decline that possibly indicates the onset of the Little Ice Age (see Chaps. 22 and 23).[28]

Tithes of grain paid in kind were roughly proportional to harvest size.[29] However, they are not suitable climatic indicators in mid latitudes because grain harvests there are related to different seasonal temperature and precipitation patterns (see Chap. 27). Otherwise, rainfall from late October to early April is the dominant factor for harvest size in regions with a Mediterranean climate. García-Herrera and colleagues showed that between 1595 and 1836 the amount of tithe paid to the Spanish authorities on the Canary Islands (near the Atlantic coast of Africa) fluctuated widely according to rainfall. Small harvests often coincided with Pro Pluvia rogations (see Sect. 6.5), whereas harvests were abundant in years when floods destroyed bridges near the capital. Statistically, the authors demonstrated that years of dearth and plenty also agreed well with movements in the North Atlantic Oscillation, which controls the strength and position of westerly winds in the North Atlantic.[30]

6.3 Municipal Accounts

Municipal governments in Europe often recorded income and expenditure related to city services and infrastructure, and in some cases these may serve as climate proxies. For instance, continuous information about floods may be obtained from municipal accounts of *bridge repairs*, as Christian Rohr has demonstrated for the town of Wels in Austria. The weekly accounts of the bridge master from 1441 to 1520 list the timber purchased and the wages of craftsmen for repairing bridges damaged by floods and other events. The amount of timber needed and the duration of the repair were taken as indicators of flood intensity.[31]

To take another example, the town of Louny in today's Czech Republic owned a number of fields, meadows, and vineyards, which were managed using hired labor. *Account books*, kept in Latin up to 1450 and then in Czech from 1450 to 1632, list wages paid each Saturday to day laborers for different kinds of work in the fields and vineyards, as well as expenses for maintenance following extreme events. The series ends in 1632 because the municipality switched from weekly to monthly accounting.[32]

6.4 Hydrological and Ice-Phenological Series

In some cases, state and religious institutions regularly recorded the *freezing dates of lakes and rivers*. For example, historical climatologists have found continuous freezing dates for the small Lake Suwa in central Japan that go back to the fifteenth century, and these are highly correlated to December and January temperatures. When this lake freezes, the shrinkage and expansion of the ice resulting from diurnal temperature variations produces an unusual type of ice cracking, named *Omiwatari*, which resembles a bridge crossing the lake (see Fig. 6.2). For six centuries, the Suwa Shrine has celebrated the annual formation

Fig. 6.2 The *Omiwatari* feature, an unusual form of ice cracking on the frozen Lake Suwa in Japan, has been recorded since the fifteenth century. It is related to December and January temperatures. Photo: T. Mikami

of Omiwatari with a special ceremony, the date of which has been recorded in the shrine's records.[33]

Records on the *entry and departure of ships* were kept in most ports because customs and fees were levied on unloaded or uploaded goods. In high latitudes the sea usually freezes during winter, blocking maritime traffic. The date on which the first ship arrives in spring thus indicates that the sea has become ice free. The longest series of this kind, starting (with some gaps) in the fourteenth century and almost continuous after 1500, relates to the harbor of Tallinn in Estonia. This series was used to estimate December to March temperatures in the country.[34] A similar series from Stockholm has been used to assess January to April temperatures in this town since the early sixteenth century. A team of researchers led by Lotta Leijonhufvud and colleagues looked through hundreds of bulky volumes of documents related to port activities kept from 1535 to 1892 in order to set up a time series for the dates of entry and departure of the first ships in spring. The dates fluctuate widely. In 1676, for example, the first ship entered the port of Stockholm on March 22. In 1685, on the other hand, the first ship entered no earlier than April 27, which indicates a long freezing of the Baltic. The statistical evaluation of this series can serve as a model for sophisticated time series analysis of documentary data.[35] Likewise, the freezing of canals connecting the major cities in the Netherlands has been registered since 1634, which allowed de Vries to extend the long temperatures series of De Bilt (from 1706) back to the early seventeenth century.[36]

In Spain, the books of municipal acts provide detailed descriptions of extreme meteorological events (torrential or persistent rains, storms at sea, huge snow cover, cold waves) that interfered with people's daily life. In this way the authorities tried to assess the damage caused to buildings and infrastructure in order to organize their reconstruction. Fernando Rodrigo and Mariano Barriendos systematically combed 1463 volumes of handwritten information originating from six cities (Bilbao, Barcelona, Murcia, Toledo, Seville, and Zaragoza) representing the main climatic regions of Spain.[37] *High-water marks* on public buildings such as bridges and town halls were probably commissioned by the authorities to keep the memory of flood disasters alive and keep the public aware of risks. These may be regarded as a reliable source, but the dating needs to be checked using independent evidence (Fig. 6.3).[38] In general, records on floods contained in institutional sources, such as in municipal acts or Chinese local gazettes (see Chap. 17), can be regarded as objective evidence.

Fig. 6.3 An assemblage of high-water marks, initially attached to the "Old Bridge" over the River Main in Frankfurt, Germany, and today placed at a pedestrian bridge over the river. By far the highest mark of the assemblage (just below the white lamp on top to the left) reminds us that the worst flood ever known on the river occurred on July 22 (or July 30 in the Gregorian calendar), 1342. It destroyed the Old Bridge and cut 14 m deep ravines in the fields.[39] Until the Protestant Reformation, a memorial procession was always held on the anniversary of the disaster. © Eveline Zbinden, Bern, April 19, 2008

6.5 Rogation Ceremonies

Records of certain liturgical acts held in Spanish churches, known as rogation ceremonies, can provide a special source of climatic information. Mariano Barriendos demonstrated that these ceremonies, which were administered in the same way throughout the Iberian Peninsula, were a response to environmental stress. Moreover, he developed a methodology that recovers detailed data on floods and droughts for Spain and the Spanish colonies, principally in Latin America.[40]

Unlike ordinary processions—for example those held on a particular saint's day—rogations were extraordinary processions held only during adverse sociopolitical or environmental circumstances, such as military defeats, epidemics, or climatic hazards. Different climate-related rogations included responses to drought ("Pro Pluvia"), persistent rain ("Pro Serenitate"), torrential rain and floods, and storms or cold spells during the growing season. Barriendos has established a procedure for categorizing these rogation ceremonies: associations of farmers noticed signs of weather stress in the fields, such as the wilting of crops. In such a case they informed the city council in the local town (Step 1). These bodies, which mostly consisted of aristocratic families engaged in commerce or law, then decided whether or not to call a rogation (Step 2). The council communicated its decision to the ecclesiastical authorities, who in turn figured out when and how the ceremony could be incorporated into the pattern of regular liturgical activities (Step 3). The rogation ceremony would take place within a week of the first warnings.

The meteorological conditions giving rise to weather-related rogation ceremonies are hardly mentioned. The severity and duration of adverse climate can be assessed from the kind of liturgical act organized by the ecclesiastical authorities. For drought—by far the most frequent and formidable hazard—we can distinguish five levels of severity. The first two levels involved simple prayers and the exposure of relics in the church; the third level involved a public procession; fourth-level ceremonies had a greater solemnity; and at the fifth level, the authorities organized a pilgrimage to a venerated sanctuary, such as from Barcelona to the Virgin of Montserrat 45 km away. The system of rogations was insulated from alteration or abuse because the ecclesiastical authorities had to provide the ceremonies while the civil authorities had to pay for them. Hence the church could not expand rogation ceremonies against the opposition of the municipalities that bore the cost, nor could municipalities shorten the ceremonies against the objections of ecclesiastical authorities, who argued to uphold tradition.[41]

6.6 Ships' Logbooks

Ships' logbooks are the most abundant institutional sources recording direct weather observations. A ship's officer navigating in open seas needed information about wind speed and direction over the previous twenty-four hours in order to determine the position (latitude and longitude) of the ship. Logbooks also provided a general-purpose official record of the voyage. In case of loss or damage to cargo and claims from insurance companies, they were the principal document used in court, comparable to the black box in an airplane or the trip recorder in a lorry.[42] The navies and merchant marines of different nations ordered the keeping of logbooks and set procedures. In the British Royal Navy, every officer on board a vessel had to keep his own logbook, ensuring a high level of correlation among logbooks from officers on the same ship and those from other ships sailing in convoy.[43]

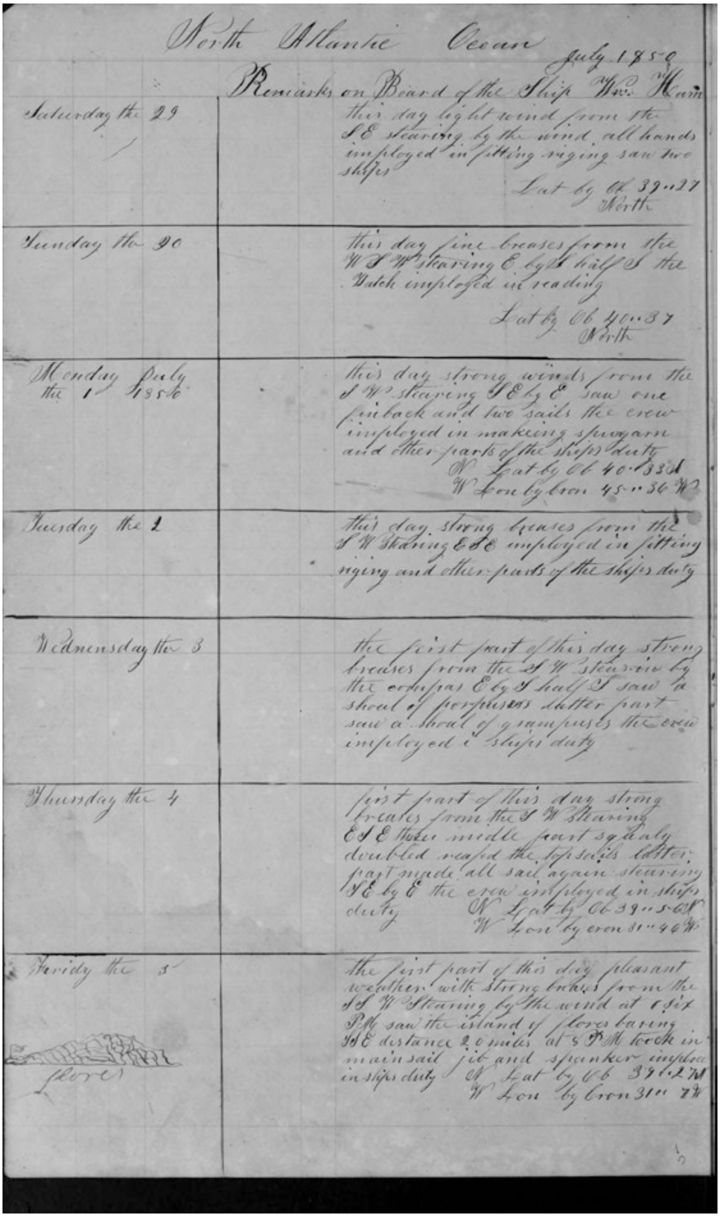
One of the advantages of logbooks is their consistency of content, layout, and vocabulary. The descriptive structures were brief and note-like, presumably to meet the needs of officers for uncomplicated and unambiguous descriptions of weather during the voyage.[44] The major shortcoming of logbooks as records of past climate is the spatial scattering of the data on account of the mobility of ships (Fig. 6.4).

The interpretation of wind direction records is straightforward because standard compass directions were used. Wind speed data, on the other hand, required much more careful work. Of course, no anemometers were available on board these sailing ships, but the officers were highly skilled in estimating wind from the state of sea, sails, and clouds. These estimates were recorded using descriptive terms rather than expressed numerically.[45] Around 1600, the first information about wind force began to appear routinely in ships' logbooks of the Dutch East India Company. By the middle of the seventeenth century, wind force terminology had evolved into a more or less standard system. Around 1700, practical scales of wind force terms such as "fine breeze" and "hard gale" were developed and ultimately evolved into today's international Beaufort scale of wind force.[46]

Tens of thousands of logbooks have survived in the archives of the great naval powers, including those of the UK, France, the Netherlands, and Spain.[47] The European Union project CLIWOC (Climatological Database for the World's Oceans 1750–1950) digitized and quality checked nearly 300,000 daily records from British, Spanish, Dutch, and French logbooks of open-ocean voyages for the period 1750–1854. The data are available in an open access database.[48] These provide the date, geographical position of the ship, wind direction, wind force, present weather, sea state, sea ice reports, and—from the turn of the nineteenth century onwards— temperature and air pressure.[49] Weather data from the logbooks of British whaling ships in the Arctic are distinguished by their valuable records of sea ice cover and iceberg incidence.[50]

6.7 Mandatory Reporting

In different parts of the early modern world, various imperial and religious institutions required their agents to make regular reports about conditions—including the weather—to their superiors in the central administration. Historical climatologists have investigated records from this kind of mandatory reporting in imperial China (Chap. 17), the Spanish Empire (in the minutes of city council meetings, or *Actas Capitulares*) (Chap. 19), and the Venetian Empire in the eastern Mediterranean.[51] Members of the Company of Jesus were required to report to their superiors or brothers any remarkable military,



North Atlantic Ocean July 1850

Remarks on Board of the Ship Wm Ham

Saturday the 29
this day light wind from the SE stearing by the wind all hands imployed in fitting riging saw two ships
Lat by Ob 39"27 North

Sunday the 30
this day fine breases from the W S W stearing E by S half S the Watch imployed in reading
Lat by Ob 40"37 North

Monday July the 1 1850
this day strong winds from the S W stearing S E by E saw one finback and two sails the crew imployed in makeing spunyarn and other parts of the ships duty
N Lat by Ob 40"33
W Lon by Cron 45"36 W

Tuesday the 2
this day strong breases from the S W Stearing E S E imployed in fitting riging and other parts of the ships duty

Wednesday the 3
the first part of this day strong breases from the S W stearing by the compas E by S half S saw a shoal of porpusses latter part saw a shoal of grampuses the crew imployed i ships duty

Thursday the 4
first part of this day strong breases from the S W Stearing E S E these middle part squaly doubled reafed the topsails latter part made all sail again stearing S E by E the crew imployed in ships duty
N Lat by Ob 39"5
W Lon by Cron 31"46 W

Friday the 5
the first part of this day pleasant weather with strong breases from the S S W Stearing by the wind at 6 six PM saw the island of flores baring S E distance 20 miles at 8 PM took in mainsail jib and spanker imploed in ships duty
N Lat by Ob 39"27
W Lon by Cron 31" 7 W

flores

Fig. 6.4 Logbook of the *William Hamilton* of New Bedford, mastered by Humphrey Allen Shockley, on a voyage from June 1850 to November 1852, giving information about wind speed and wind direction (from Wikimedia Commons, with permission of the Bedford Whaling Museum) political, ecclesiastic, or weather events that occurred in their environment. Rodrigo and colleagues investigated climate-relevant passages in more than 1000 letters sent from various Spanish cities to the historian Father Rafael Pereyra.[52] Under such circumstances we may assume that an absence of evidence with regard to extreme weather may be regarded as evidence of absence, provided that all the relevant reports survive. Finally, diplomatic dispatches from regular postings in Europe and the Ottoman Empire, starting in the sixteenth century, provide frequent (typically biweekly or monthly) although inconsistent reporting about weather conditions.[53]

Notes

1. Rodrigo, 2008.
2. Ge, 2008.
3. Le Roy Ladurie, 1967, 1971.
4. Daux et al., 2012.
5. Wetter and Pfister, 2013.
6. Guerreau, 1995.
7. Guerreau, 1995.
8. Ruffing, 1997.
9. Wetter and Pfister, 2011.
10. Wetter and Pfister, 2011.
11. Chuine et al., 2004, 289.
12. Garnier et al., 2011.
13. Labbé and Gaveau, 2011.
14. Wetter and Pfister, 2011.
15. Glaser et al., 1999.
16. Labbé and Gaveau, 2013.
17. Wetter et al., 2014.
18. Wetter and Pfister, 2011.
19. Wetter and Pfister, 2011.
20. Orth et al., 2016.
21. Kiss et al., 2011.
22. Wetter and Pfister, 2011.
23. Pfister, 1979.
24. Wetter and Pfister, 2011; Možný et al., 2012.
25. Pribyl et al., 2012, 395.
26. Titow, 1960, 368.
27. Titow, 1960, 394.
28. Pribyl et al., 2012.
29. Le Roy Ladurie and Goy, 1982.
30. García-Herrera et al., 2003.
31. Rohr, 2013.
32. Brázdil and Kotyza, 1999.
33. Mikami et al., 2015.
34. Tarand and Nordli, 2001.
35. Leijonhufvud et al., 2010.

36. de Vries, 1977.
37. Rodrigo and Barriendos, 2008.
38. Wetter et al., 2011.
39. Glaser, 2001, 66.
40. Garza-Merodio, 2007.
41. Barriendos, 2005.
42. Wheeler and Wilkinson, 2005.
43. García-Herrera et al., 2003, 1027.
44. Wheeler and Wilkinson, 2005.
45. García-Herrera et al., 2003.
46. Wheeler, 2005.
47. García-Herrera et al., 2003.
48. Wheeler et al., 2006.
49. Wheeler, 2005.
50. Ayre et al., 2015.
51. Grove and Conterio, 1995.
52. Rodrigo et al., 1998.
53. E.g., White, 2011 for examples from Istanbul.

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CHAPTER 7

Evidence from the Archives of Societies: Early Instrumental Observations

Dario Camuffo

7.1 Introduction

This chapter defines early instrumental observations and explains their significance for climate reconstruction. It also addresses their problems and explains how best to work with them. The following sections discuss the development and shortcomings of early instruments—thermometers, barometers, and rain gauges—the relevant measurement practices, and the history of early instrumental observation networks.[1]

The transition between early and modern instrumental measurements came in around the middle of the nineteenth century, when meteorological instruments were well developed and their uncertainties known.[2] In 1860, George Biddel Airy (Greenwich Observatory) and Urbain Jean-Joseph Le Verrier (Paris Observatory) signed an agreement to collect British and French observations to forecast storms. A few years later in 1873, under the direction of Christoph Buys Ballot, the International Meteorological Committee was founded in Vienna, incorporating the newly organized national weather services. In 1950 the International Meteorological Committee became the World Meteorological Organization, with 160 country members, under the direction of the United Nations.[3]

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7.2 Early Temperature Observations

The discovery that liquids are subject to thermal expansion led to the invention of the liquid-in-glass thermometer. Galileo made the earliest experiments with a "thermoscope"—the ancestor of the air thermometer—but it had no scale and was sensitive to atmospheric pressure. He also invented a thermometer composed of a number of glass spheres with slightly different densities immersed in spirit. It was nicknamed the *Termometro Infingardo* ("Sluggish Thermometer") because it took so long to react.[4] In 1642, the last year of Galileo's life, the Grand Duke of Tuscany and Evangelista Torricelli invented the true liquid-in-glass thermometer. The most accurate type, the little Florentine thermometer (Fig. 7.1), used a scale in Galileo degrees (1 °G = 1.44 °C).[5] It was employed in the first network of regular meteorological measurements from 1654 to 1770.

The Florentine Thermometers long remained unequaled for their quality, consistency, and durability. However, only a wealthy patron such as the grand duke could support the cost of distributing hundreds of them all over Italy and Europe. The "normal" thermometer of the late seventeenth and early eighteenth centuries used a different technology, based on a capillary tube fixed to a wooded tablet. The instrument maker had to produce a glass tube with a bulb, fill it with the thermometric liquid, and finally seal the top of the tube.[6] The choice of the thermometric liquid was crucial: it needed a high expansion coefficient, it should not freeze during measurements, and it should not adhere to the glass tube. Daniel Gabriel Fahrenheit used mercury, and it proved to be an excellent choice because the thermal expansion of mercury is linear. A number of calibration

Fig. 7.1 The little Florentine thermometer (Museo Galileo, Florence; photo by Franca Principe and Sabina Bernacchini)

scales were proposed, each with pros and cons. In 1742, Anders Celsius proposed the centigrade scale, originally inverted with 100 °C for the freezing point and 0 °C for boiling point.[7] The mercury thermometer had a very small linear departure in temperature (±0.1 °C), followed by Newton's linseed oil thermometer (±0.15 °C). Wine spirit in the 0–80 °R Réaumur calibration had a bias reaching −5 °C at 30 °C in warm climates; however, if the calibration was made in a restricted range (e.g. 0 °C and 30 °C as in the Florentine thermometers) the bias was much reduced (e.g. ±0.5 °C in the Florentine thermometers).[8]

Early "normal" thermometers were not weatherproof and could not be kept outdoors, especially in rain or fog. This limited their use in humid regions and rainy seasons. Readings taken in massive brick buildings obscured the real temperature cycle, and one or two readings were considered representative of the whole day. Most people lived in unheated rooms, so monitoring indoor temperature was considered useful for public health purposes. One of the most famous long instrumental records, the Central England temperature series, had to combine short indoor or outdoor instrumental records in the roughly triangular area bounded by Bristol, Lancashire, and London.[9] Another crucial problem was inadequate shielding from direct sunlight. In 1785, Giuseppe Toaldo in Padua employed a screen for the first time,[10] but such screens were often missing or insufficient until the 1860s.[11]

7.3 Early Pressure Observations

In 1643 at the Accademia del Cimento, two of Galileo's pupils made a revolutionary discovery: Evangelista Torricelli arrived at the theoretical conclusion that air had a weight, and Vincenzo Viviani set up the experimental device to verify it. The instrument was called the "barometer," which measured the "weight" of the air column. The earliest barometers consisted of a vertical glass tube closed on the top, filled with mercury and immersed in a vessel that acted as an open, fixed cistern (Fig. 7.2a). The wheel barometer, invented by Robert Hooke in 1665, used a float in a bowl of mercury to drive a pulley attached to a pointer on a circular scale (Fig. 7.2b). Wheel barometers were decorative and easy to use. However, the friction between the mechanical parts, the capillary attraction of the mercury, and the influence of temperature on the float, thread, and pulley all reduced its accuracy.[12] In 1844, Lucien Vidi invented the aneroid barometer using a capsule that drives a pointer. It, too, was easy to use but not very precise.[13] Nevertheless, the barometer (or "weather glass") soon proved essential in forecasting storms.

These early mercury barometer readings require several corrections to produce accurate standardized measurements. These include corrections for (1) the influence of temperature on the density of mercury; (2) the effects of altitude; (3) the influence of latitude on gravity; and (4) capillary depression of the mercury column in thin tubes. Early corrections began by 1830, but they remained missing or incomplete until the *International Meteorological Tables*

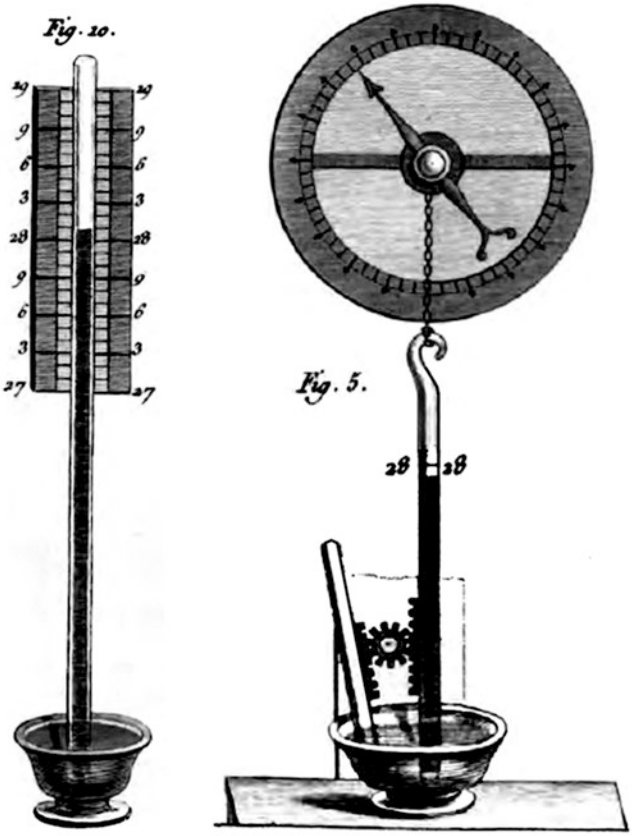

Fig. 7.2 (**a**) Early barometer, Torricelli type, consisting of a glass tube filled with mercury and a vessel acting as a cistern. (**b**) Wheel barometer invented by Hooke[14]

(1890) provided corrections related to the acceleration of gravity, altitude, and temperature.[15]

7.4 Early Precipitation Observations

Rain gauges have been used since antiquity in the Near East and India, and since at least 1440 in Korea. However, these instruments remained practically unknown in Europe until Father Benedetto (born Antonio) Castelli's 1639 rain gauge, a simple vessel with an open top exposed to the sky. Early rain gauges varied greatly in design and quality, and as they aged their readings suffered. For more than a century, they remained essentially storage vessels topped by a poor collecting funnel (Fig. 7.3). The rim of the collecting funnel lacked the sharp edge needed to collect raindrops blown at tilted or grazing angles and to retain splashing drops or snowflakes.

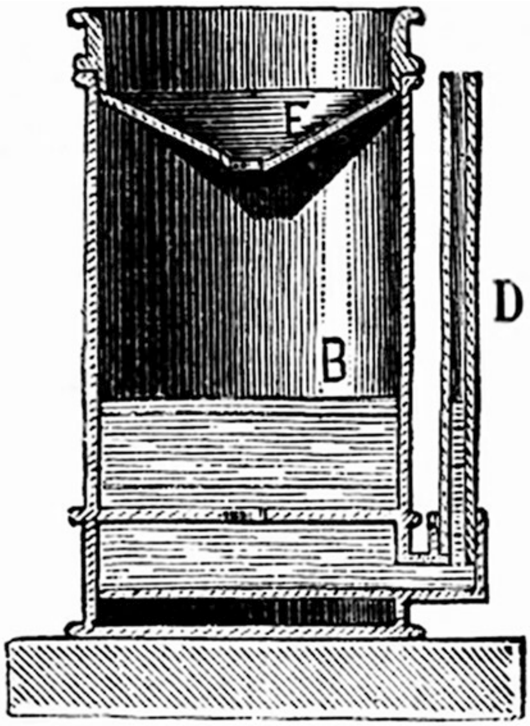

Fig. 7.3 Rain gauge of the mid-nineteenth century, composed of a collecting funnel (F), a storage can (B), and an external graduated glass tube (D) to measure the amount of precipitated water[16]

Once or twice a day, or after rain showers, the observer measured the collected water. Multiple readings to reduce evaporation losses remained uncommon, so the time of daily readings introduced considerable irregularities. Location, height, and exposure were not standardized. Up to the second half of the eighteenth century, rain gauges were normally sited on roofs, chimneys, or walls, or in closed courtyards and gardens; but only rarely in real open spaces free from obstructions. Long rain gauge measurement series usually have to combine several shorter subseries of observations in different locations, at different heights, facing different obstructions—factors that complicate the homogenization and comparison of records (see Chap. 9).[17]

Early instruments used various methods to measure the collected water. Some had the vessel fixed to the building frame and were emptied through a tap at the bottom, while others were turned upside down. Some used a graduated dip rod to measure the water level, others a side tube. They might measure by level, by weight, or by volume. Various factors add to the uncertainties and errors of early rain gauge measurements.[18] Vessels were inadequately shielded, causing evaporation losses. Instruments were not properly located to minimize obstruction from buildings and trees. Instruments might lose water when they were emptied for readings, or leftover water could affect subsequent measurements. Users also failed to take measures against frost.

7.5 Early Meteorological Networks

The Grand Duke of Tuscany organized the first network of regular meteorological observations, the Rete Medicea (Medici Network), from 1654 to 1670. Its stations were Florence, Vallombrosa, Pisa, Cutigliano, Bologna, Parma, Milan, Innsbruck, Warsaw, Osnabrück, and Paris. At each station, readings were taken using identical instruments and following the same protocols. Each station had two identical thermometers, one hung on a north-facing wall and the other on a south-facing wall, to evaluate air temperature in the shade and the sun. Readings were performed every three to four hours day and night. The Florence and Vallombrosa stations operated continuously; the others were secondary and operated for some years in winter and summer. The 1654–70 observations of the Medici Network constitute the earliest known instrumental temperature observations.[19]

The Wrocław (Breslau) network of temperature, pressure, and precipitation measurements was established in eastern Slovakia in 1717–30. Its main stations were Kezmarok and Presov (which used a little Florentine thermometer).[20] The next successful international meteorological network was established in 1723 by James Jurin, secretary of the Royal Society of London. He set precise norms for its instruments (thermometer, barometer, rain gauge) and operations, following the guidelines of Robert Hooke. These recommended temperature readings in north-facing unheated rooms, for instance. The network was active from 1724 to 1735 and observations were published in the *Philosophical Transactions*. It initiated a number of regular instrumental observations, some of them still ongoing.[21]

Several short-lived national and international networks followed. The Bern meteorological network, active 1760–62, comprised six stations in Switzerland: Bern, Lausanne, Orbe, Cottens, Vevey, and St. Cergue.[22] In 1776, to supply the newly established Societé Royale de Médecine with meteorological data, Vicq d'Azyr promoted a correspondence network of instrumental readings.[23] In 1781 the Prince Elector Karl Theodor von Pfalz and his secretary John Jacob Hemmer founded the Societas Meteorologica Palatina in Mannheim. This international network, active in the period 1781–92, included thirty-nine sites across Europe, except for England and the Iberian Peninsula. Hemmer established an operational methodology and schedule of observations. The network also distributed instruments and specified their characteristics. Its observations were published in the *Ephemerides Societatis Meteorologicae Palatinae* from 1783 to 1795.[24] Following the plea of these international networks, several local and regional instrumental series were launched: a selection of the most famous is given in Table 7.1.

The eighteenth century witnessed technological improvements in instruments. For instance, thermometers and scales were weatherproofed so that it was possible to resume outdoor observations. During the nineteenth century, meteorology became a mature, technologically advanced discipline carried out by trained professionals. With this professionalization came a shift

Table 7.1 Long regular meteorological observations in Europe

Location	*Start*	*Reference quoted therein*
Central England	1659	Manley, 1974; Parker et al., 1992
De Bilt	1706	Koopmans et al., 2015
Paris	1676	Rousseau, 2009, 2013
Berlin	1701	Brumme, 1981
Bologna	1715	Camuffo et al., 2010, 2016, 2017
Padua	1716	Camuffo and Jones, 2002; Camuffo et al., 2006
Uppsala	1722	Bergström and Moberg, 2002
St. Petersburg	1743	Camuffo and Jones, 2002
Stockholm	1756	Camuffo and Jones, 2002
Milan	1763	Camuffo and Jones, 2002
Prague	1775	Brázdil, 2012
Barcelona	1780	Rodríguez et al., 2001
Budapest	1780	Csernus-Molnár and Kiss, 2011
Timişoara	1780	Csernus-Molnár et al., 2014
Rome	1782	Colacino and Rovelli, 2010; Colacino and Purini, 1986
Lisbon	1783	Taborda et al., 2004
Cadiz	1787	Camuffo and Jones, 2002; Gallego et al., 2007
Palermo	1791	Chinnici et al., 2000

from local to national and finally international organization. The International Meteorological Committee and the World Meteorological Organization established common protocols in observations, and members' countries improved their national weather services accordingly. To use long instrumental series dating before these improvements requires careful correction and homogenization of the results based on analysis of both the data and the metadata (see Chap. 9).[25]

7.6 Conclusion

Early instrumental measurements provide crucial information about past weather and climate, particularly in seventeenth- and eighteenth-century Europe. However, using this information properly requires a critical analysis of the instruments, calibration, exposure, and operational protocols. Understanding the history of these instruments and observation networks not only has significant cultural value but also helps us correct and homogenize their readings in order to better reconstruct and analyze past climate.

Notes

1. Middleton, 1964, 1966; Goodison, 1968; Frisinger, 1977; Landsberg, 1985; Borchi et al., 1990; Borchi and Macii, 1997; Kingston, 1997; Camuffo and Jones, 2002; Brázdil et al., 2005; Brázdil, 2012; Przybylak et al., 2010.
2. Negretti and Zambra, 1864; Scott, 1875.

3. WMO, 2006.
4. Magalotti, 1667.
5. Camuffo and Bertolin, 2012.
6. Camuffo and Jones, 2002; Camuffo and Bertolin, 2012.
7. Middleton, 1966; Camuffo and Jones, 2002.
8. On Newton's linseed oil themometer, see Camuffo and della Valle, 2017; on spirit thermometers, see Camuffo and della Valle, 2016.
9. Manley, 1974; Parker et al., 1992.
10. Camuffo and Jones, 2002.
11. Böhm et al., 2010.
12. Goodison, 1968.
13. Middleton, 1964.
14. Cotte, 1774.
15. Middleton, 1964.
16. Ganot, 1854.
17. Groisman et al., 1996.
18. Strangeways, 2010.
19. Camuffo and Bertolin, 2012.
20. Brázdil et al., 2008.
21. Camuffo and Jones, 2002.
22. Pfister, 2008.
23. Borel, 2005.
24. Cassidy, 1985.
25. Camuffo and Jones, 2002.

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CHAPTER 8

Evidence from the Archives of Societies: Historical Sources in Glaciology

Samuel U. Nussbaumer and Heinz J. Zumbühl

Glaciers have been recognized as key indicators of climate change. As such, changes in glaciers not only have relevance for climate policy but also affect popular global perceptions of climate change.[1] To assess the current decline in glaciers worldwide, their changes must be compared with the natural glacier fluctuations since the end of the last ice age.

Various methods with varying temporal resolution and accuracy allow researchers to reconstruct glacier fluctuations throughout the Holocene (ca. 9700 BCE–present). To reconstruct glacier changes over recent centuries, including the Little Ice Age (LIA) (see Chap. 23), historical methods have proven especially valuable. Where sufficient in quality and quantity, pictorial documents (drawings, paintings, prints, and photographs); cartographical documents (maps, cadastral plans, and reliefs); and written accounts (chronicles, church registers, land sale contracts, travel descriptions, early scientific works on Alpine research, etc.) can provide a detailed picture of glacier fluctuations, in particular frontal length changes. Using these data, we can achieve a resolution of decades or in some cases even individual years of ice margin positions.[2]

To reconstruct past glacier movements, researchers must handle historical data carefully and take local circumstances into account. In particular, the

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evaluation of pictorial sources has to fulfill certain conditions in order to obtain reliable results concerning the former extents of glaciers (Fig. 8.1):

- First, the date of the document has to be known or reconstructed. That is, researchers have to know the exact date when the artist was visiting the glacier and making travel sketches or studies. Oil paintings might have been done on site, but they were quite often finished later, usually in the artist's studio.[3] Prints of artworks often bear a different date than their originals. Dating early glacier photographs can be especially difficult and often includes time-consuming archival work.
- Second, the glacier and its surroundings have to be represented in a manner that is realistic and topographically correct, something that requires particular skills of the artist. Some artists liked to compose motifs of their own in the foreground or omit unaesthetic frontal moraines, features that could obscure the true position of glaciers.
- In addition, the artist's topographic position should be known. The presence of prominent features in the glacier's surroundings such as rock steps, hills, or mountain peaks can facilitate the evaluation of historical documentary data.[4]

Iconic depictions of glaciers appear in the works of famous artists such as Caspar Wolf (1735–1783), Jean-Antoine Linck (1766–1843), Samuel Birmann (1793–1847), and Thomas Ender (1793–1875). Their outstanding drawings and paintings have allowed the reconstruction of LIA glacier fluctuations in the European Alps in a uniquely precise way.[5]

Prior to 1800, the abundance of historical material in Europe depended mainly on the elevation of LIA glacier tongues and the threat that glacier advances posed to settlements and cultivated land.[6] Probably the earliest known representation of a glacier in the Alps is that of Vernagtferner (Ötztal, eastern Alps) in 1601: the drawing shows a dangerous glacial lake dammed by the advancing glacier.[7] Two emblematic glaciers with a wealth of historical (pictorial) documents are the Lower Grindelwald Glacier (Bernese Oberland, Switzerland) and the Mer de Glace (Mont Blanc area, France). Using historical data, researchers have reconstructed series of cumulative length changes for these glaciers that extend back to the sixteenth century. Those reconstructions show main glacier maxima around 1600 and 1640 and again around 1820 and 1850, as well as several smaller intermediate advances.[8] Reconstructions based on dendrochronology and radiocarbon dating confirm these pulses; moreover, they indicate a third LIA peak in the second half of the fourteenth century.[9] From the late 1840s, a rapidly increasing number of photographs depict the onset of glacier retreat, marking the end of the LIA in the European Alps.[10] In southern Norway and Iceland, historical evidence and instrumental measurements show a distinct glacier asynchrony when compared with the European Alps, with LIA maxima around 1750 and at the end of the nineteenth century, respectively.[11]

Fig. 8.1 The Mer de Glace seen from the viewpoint of La Flégère, overlooking the valley of Chamonix (Mont Blanc). Left: Drawing (watercolour, pencil) by Samuel Birmann from 1823 (Kunstmuseum Basel, Kupferstichkabinett, reproduction by H.J. Zumbühl). Middle: Photograph taken by Henri Plaut in the 1850s (collection of R. Wolf, reproduction by S.U. Nussbaumer). Right: Current view with reconstructed glacier extents in 1644 (grey, largest extension), 1821 (black), and 1895 (white) (photograph by S.U. Nussbaumer)

Outside Europe, historical sources (before the late nineteenth century) are less abundant.[12] Nevertheless, resources exist for other regions, including southern South America and New Zealand.[13] Systematic worldwide observations of glacier fluctuations (regarding length, mass, volume) began at the end of the nineteenth century. Corresponding data are available from the World Glacier Monitoring Service. They deliver clear evidence that centennial glacier retreat is a global phenomenon, and that rates of early twenty-first-century mass loss are without precedent on a global scale—at least for the time period observed, but probably also for recorded history as indicated by historical sources.[14]

Notes

1. Orlove et al., 2008; Carey, 2010.
2. Zumbühl, 1980; Nussbaumer et al., 2007; Holzhauser, 2010.
3. An illustrative example is the exact oil painting of the Lower Grindelwald Glacier by Joseph Anton Koch, signed and dated in 1823. This artwork was initially misinterpreted, but Zumbühl (1980) could provide evidence that it is based on an original watercolour, drawn by Koch in the field in 1794. The oil painting, made twenty-nine years later in Rome, shows the glacier extent from 1794 (a reduced extent compared with 1823, when the glacier was strongly advancing), but in the foreground we can identify Mediterranean vegetation.
4. Zumbühl and Holzhauser, 1988.
5. Zumbühl, 2009; Nussbaumer et al., 2012.
6. Le Roy Ladurie, 1967.
7. Nicolussi, 1990.
8. Zumbühl, 1980; Zumbühl et al., 1983; Nussbaumer et al., 2007.
9. Holzhauser et al., 2005; Le Roy et al., 2015.
10. Zumbühl et al., 2016.
11. Nussbaumer et al., 2011; Hannesdóttir et al., 2015.
12. Grove, 2004.
13. Araneda et al., 2009; Purdie et al., 2014.
14. WGMS, 2017.

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CHAPTER 9

Analysis and Interpretation: Homogenization of Instrumental Data

Ingeborg Auer

9.1 Why Do We Need to Homogenize Instrumental Data?

Experts depend on instrumental measurements to explore past climate change and to analyze climatic trends and variability. But are long-term instrumental series always reliable? And when can we trust the displayed trends?

Early meteorological measurements, even those following the best practices of the period, remain incomparable with instrumental measurements using today's standards. The longer a series is, the greater the risk that it will be biased by one or more inhomogeneities. The reasons for such inhomogeneities are many—for example, station relocations, instrument or observer changes, and even the improved precision of measurements. Network regulations—such as observation hours, formulae for mean calculation, measurement units, and new types of instrument—can all change over the course of time. Sudden alterations in a station's environment, from the erection of a nearby housing block to the clearance of a nearby forest, may bias the time series. Growing heat islands of growing cities introduce artificial warming trends into the series; growing trees casting growing shadows introduce artificial cooling.

The historical climatologists' challenge is to detect these inhomogeneities and correct them enough to distinguish the real trends in a series and remove its artificial breaks and biases. *Homogenization is an appropriate and even necessary procedure to detect non-climatological breaks or trends in a series and remove them as best as possible. A perfectly homogenized series will be free of any artificial influences and reflect only natural climate variability.*

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Our longest instrumental weather series date back to the seventeenth and eighteenth centuries. At that time, instruments were not as precise as today, and observers lacked experience in how and even where to take measurements. Individuals began performing meteorological measurements with no coordinated networks or national weather service to help out. Uncoordinated measurements led to unstandardized results among stations. For instance, one of the longest series in the Alpine region, Kremsmünster, went through thirteen documented changes of observation hours during its 250 years of existence, twelve of them in the very early period.[1] By the end of the twentieth century the very early daily records of air temperature and pressure from a number of sites across Europe—Padua and Milan (Italy), San Fernando/Cadiz (Spain), Brussels/Uccle (Belgium), Uppsala and Stockholm (Sweden), and St. Petersburg (Russia)—have been quality controlled and homogenized during the IMPROVE project.[2] All the original data and metadata, and the final corrected, validated, and homogenized series, have been made available on CD-ROM, along with a detailed explanation of all the steps that were necessary to get from the original registers to the final series.

Station and network history (the so-called metadata that explain the conditions within which data has been produced) give a first impression about the quality and homogeneity of data.[3] Ideally these will provide useful information such as changes in geographical coordinates, altitude, and the types of instrument and their mountings, supported by maps, photos, written communications, and other helpful contents. This kind of metadata helps determine the exact break dates in the series. However, nobody should trust the metadata to provide complete information. Statistical tests (homogeneity tests) should also be applied in order to assess the reliability of any series.

9.2 The Practice of Homogenization

There is no generally valid recipe for calculating the "perfect series" with all artificial breaks or trends removed. Nevertheless, any successful homogenization should use both statistics and station history. Parallel measurements can also be helpful in understanding the consequences—that is, the statistical properties—of a break in more detail. A homogenized series provides not the "truth" but rather a best indicator. (Historical) climatologists should preferably base any calculations on already homogenized series. Nevertheless, while the number of homogenized series has increased considerably in recent years, much work remains to be done.

Numerous homogeneity tests have been developed for the detection and correction of breaks and trends, most of them designed to improve the quality and reliability of monthly temperature and precipitation series. There has been and still is an ongoing discussion about the best tool for homogenization. In 2007–11, COST action (Advances in homogenisation methods of climate series: an integrated approach HOME) was launched to compare various homogenization procedures and test their efficiency in a blind experiment with unknown perturbations.

Many good tests can be downloaded free of charge, and it is advisable to use this open-source software. For instance, HOMER (homogenization software in R; available at http://www.homogenisation.org/) is useful for monthly data and includes a tool for separating out urban warming effects. HOM/SPLIDHOM is useful for daily data.[4] An extensive list of tests and web addresses is available at http://www.meteobal.com/climatol/DARE/. As a general rule one can say that relative homogeneity tests perform better than absolute homogeneity tests. The latter should only be used in exceptional cases when all other possibilities have been exhausted. Relative tests objectively check the probability of a break in the candidate series by using a couple of reference stations of a network, or one (weighted) reference series built up from several stations, as a comparison.

In general, to remove inhomogeneities in monthly (or seasonal, or annual) mean temperature or precipitation series it is sufficient to calculate the monthly (or seasonal, or annual) adjustment factors for the period in question. Working with daily values means that such a correction has to be applied to every day's measurement; thus daily data correction requires both more data and more time. The simplest methods derive these correction coefficients from monthly adjustments while more complex methods take the whole frequency distribution into account.[5] Regardless of the method chosen, it is important to assess uncertainties in the adjusted data by using different samplings and by varying the reference stations (Fig. 9.1).

Fully automatic homogenization procedures, such as ACMANT (http://www.c3.urv.cat/members/softpeter.html), work without any user interaction. These methods are recommended for analyzing large networks. The results will be the same for all users. Semiautomatic methods require some user interaction during the homogenization process. The results may be different from different users, and well-trained homogenizers will probably produce better results.

It is advisable to take metadata into account when carrying out homogenization, since there will be cases where statistics alone will not be able to detect breaks. This is particularly the case when inhomogeneities occur across the whole network at the same time—for instance, when there are changes in the time of observations or in the number of observations per day for calculating daily or monthly means, or when a network changes its equipment within a short period. In such cases all series will be affected at the same time, and the inhomogeneities will go undetected by relative homogeneity tests. (For more information about early instrumental measurements and networks, see Chap. 7.)

So far, homogenization activities have focused mainly on monthly temperature and precipitation totals. Other crucial climate measurements—including air pressure, cloudiness, radiation, snow cover, and wind speed and direction—have all received less attention. Even more neglected are the daily data series, given the greater demands on network density and spatial correlation. The homogenization of short-term extreme values remains unsolved, even though more scientific evidence about these events would be an important step forward in understanding climate change.

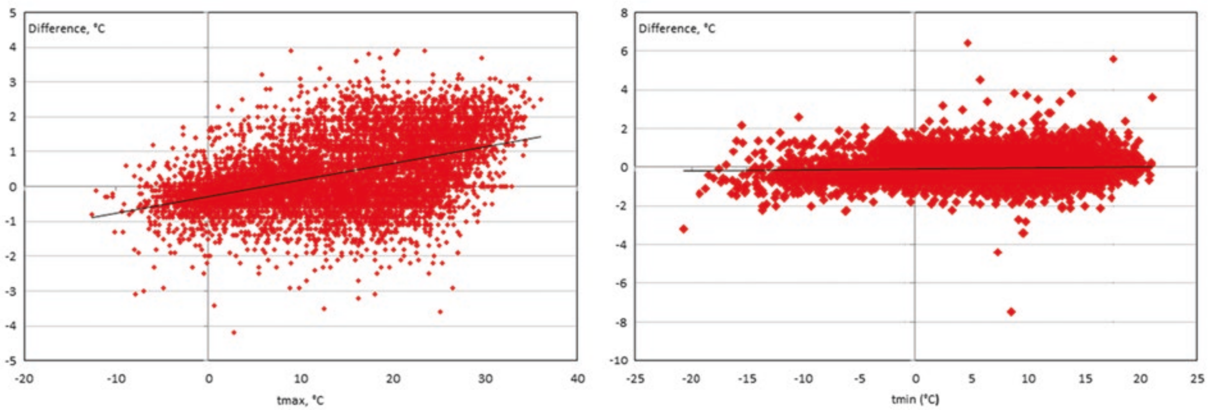

Fig. 9.1 Differences between automatically and manually measured temperatures with respect to automatically measured daily maximum (t_{max}—left) and minimum (t_{min}—right) temperatures at the Kremsmünster station from June 1988 to December 2008. In this example, only t_{max} measurements will require temperature-dependent corrections

Finally, we have to be aware that a series once homogenized will not stay homogeneous forever. It may look different after some years because it had to be "rehomogenized." Why? On the one hand, future inhomogeneities (unavoidable relocations, improved techniques, extension of built-up areas, etc.) might disturb the series, making it a candidate for homogenization all over again. On the other hand, more advanced tools for homogenization or more and better reference stations might become available. Whenever rehomogenization becomes necessary, one should start over from the original—not the homogenized—data. Homogenization must be transparent and understandable, and so one should preserve documentation of the processes used at all stages.

9.3 An Example from the European Alpine Region

As an example, Fig. 9.2 shows HOMER plots that visualize the homogenization of the temperature series from the mountain station Patscherkofel in Austria. The figure displays the test results from raw data (upper part) and homogenized data (lower part). The Patscherkofel data has been compared with that of several other stations. Here only test results for the comparison with Rudolfshütte, Säntis (Switzerland), and Kredarica (Slovenia) are shown. A dataset of homogenized long-term series of mean temperature, precipitation, air pressure, and sunshine duration for the European Greater Alpine Region can be freely downloaded for climate research purposes from http://www.zamg.ac.at/histalp.

More than 500 such series have been homogenized.[6] It turned out that none of the series was free of breaks or artificial trends once it exceeded a certain length. On average, a temperature or precipitation series experiences a break every twenty-three years. The distribution and size of breaks is not random, and this means that any spatially averaged trend for larger regions will give biased results, so long as it relies on inhomogeneous series.

As mentioned above, systemic changes in the history of networks dramatically influence the homogeneity of their measurements. Very early measurements (before 1850) demand particular attention. In this example, the very early precipitation measurements at the beginning of the nineteenth century were performed with rain gauges installed on roofs or other open locations. As a result of higher wind speeds in these open positions, the specific precipitation loss in the instrumental measurements was greater than in today's shielded exposures. Moreover, Stevenson screens did not come into use until about 1850, so before then, incoming or reflected radiation could bias temperature measurements (see Chap. 7).[7] The scarcity of early instrumental stations, and the rather sudden introduction of weather shelters, means that statistical tests alone would not have spotted and corrected these inhomogeneities. Only metadata and parallel measurements with modern equipment made it possible to correct the early data.

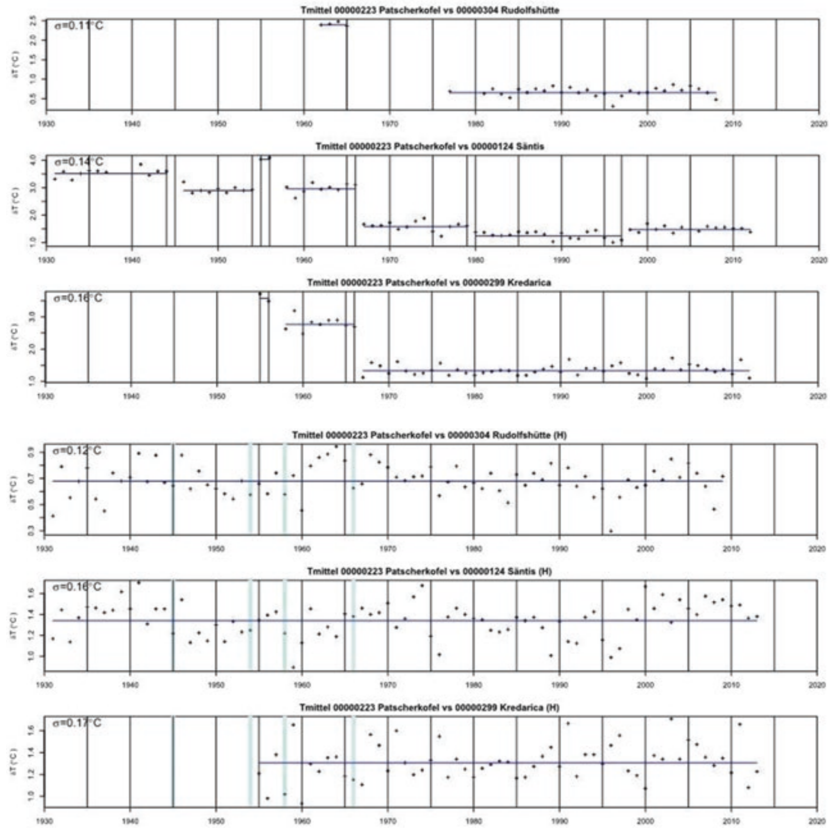

Fig. 9.2 HOMER plots visualizing the homogenization of the temperature series at the mountain station Patscherkofel in Austria. This shows the test results of raw data and of homogenized data. In this case the Patscherkofel series was compared with those of Rudolfshütte (AT), Säntis (CH), Kredarica (SI), Schmittenhöhe (AT), Villacher Alpe (AT), Zugspitze (GE), Feuerkogel (AT), Jungfraujoch (CH), Sonnblick (AT), Großer St. Bernhard (CH), Schöckl (AT), Mooserboden (AT), and Lago Gabiet (IT). Only the test results for the comparison with Rudolfshütte (AT), Säntis (CH), and Kredarica (SI) are shown here. Credit: reproduced by permission of Barbara Chimani.
Note: AT = Austria; CH = Switzerland; SI = Slovenia; IT = Italy; GE = Germany

Urban development, bringing a gradual increase of built-up areas and a reduction in grassland or forests, also obscured the natural climate variability by introducing an "urban trend." However, it was not enough to correct the data simply by estimating the surplus warming for the city as a whole: the urban trend depended on the location of stations within cities. For instance, Reinhard Böhm has shown that early instrumental stations erected in Vienna's historic city center—already a densely built-up area—did not experience the same urban warming trend as those erected in suburban districts, where former green areas were later developed.[8]

9.4 Conclusion

Homogenization of instrumental data frees biased time series from detectable inhomogeneities introduced by artificial breaks or trends. The procedures are based on statistics, meaning that the quality of results depends not only on the quality of the candidate series but also on the existence of suitable reference series. Although far from easy, homogenization remains a necessary procedure to ensure a best possible basis for calculating past climatic trends or cycles.

Acknowledgments I would like to thank Barbara Chimani for providing Fig. 9.2.

Notes

1. Auer, 2013.
2. Camuffo and Jones, 2002.
3. Aguilar et al., 2003.
4. Mestre et al., 2013.
5. For example, see Vincent et al. (2002) for simpler methods and Mestre et al. (2011) for more complex methods.
6. Auer et al., 2007.
7. Böhm et al., 2010.
8. Böhm, 1998.

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CHAPTER 10

Analysis and Interpretation: Calibration-Verification

Petr Dobrovolný

10.1 Introduction

Historical climatologists must work with diverse types of qualitative evidence regarding past weather and climate (see Chap. 4). Efforts to create quantitative climate reconstructions using these sources from the archives of societies present many of the same methodological challenges that paleoclimatologists face when working with physical sources such as tree rings or ice cores. In particular, documentary-based quantitative reconstructions have to bridge qualitative information from historical archives with early instrumental measurements. The most important step in this reconstruction procedure is calibration.

Calibration is a statistical procedure that converts direct or indirect (proxy) documentary evidence about weather and climate into meteorological units such as degrees Celsius or millimeters of precipitation. The key procedure in this process is the construction of a *transfer function*. This should translate documentary and proxy data into appropriate meteorological units. It should subsequently be verified by statistical tests and independent data.

10.2 Establishing Documentary-Based Series

The most important steps in the reconstruction procedure are summarized in Fig. 10.1. The increasing quantity and quality of databases compiled from historical archives has enabled historical climatologists to apply techniques

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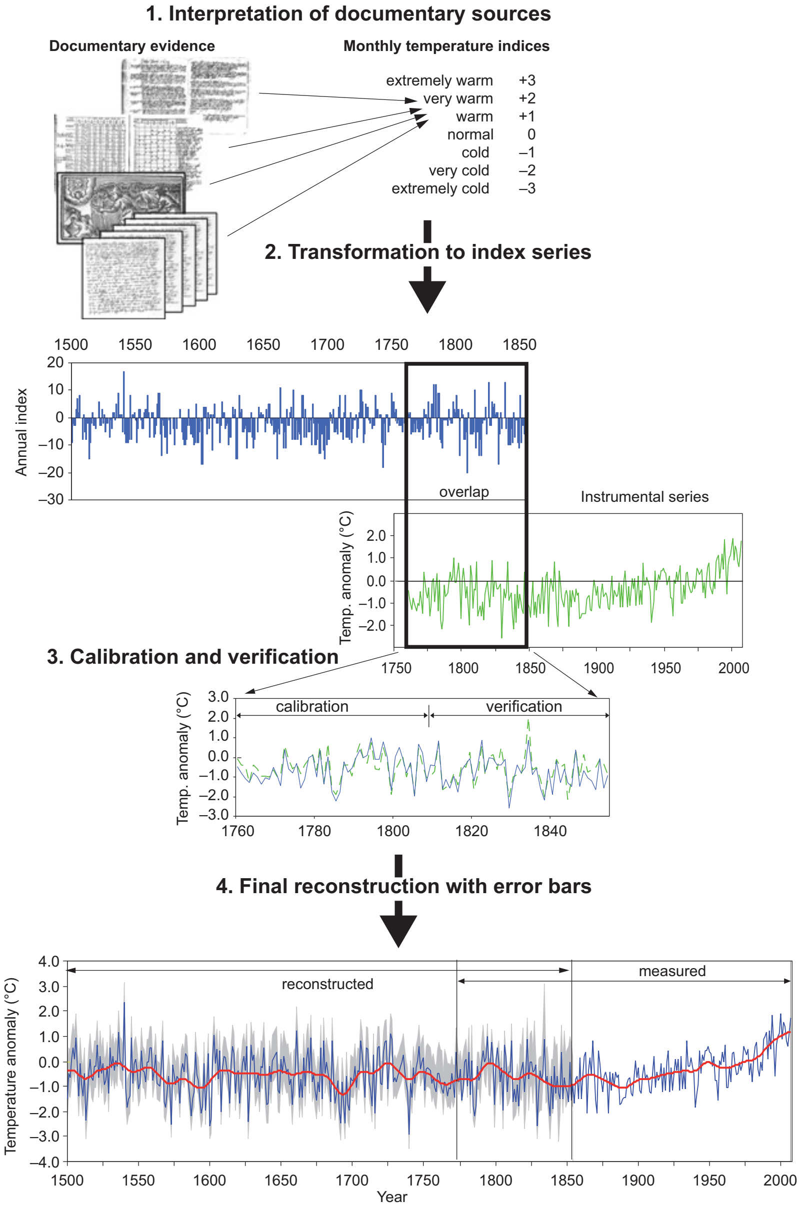

Fig. 10.1 The main steps in quantitative climate reconstruction based on temperature or precipitation indices derived from documentary evidence. Credit: Rudolf Brázdil et al., "European climate of the past 500 years: new challenges for historical climatology," *Climatic Change* 101 (2010): 7–40. Courtesy of Springer

from high-resolution paleoclimatology (e.g., dendroclimatology) to some documentary-based quantitative climate reconstructions.[1] Nevertheless, documentary data also presents some particular challenges, as described in the following paragraphs.

Historical climatologists can employ two types of documentary evidence for quantitative reconstructions. First, they can convert indirect (proxy) data—that is, biological or physical processes related to climate—into time series with annual resolution. Ideally, these series should be more or less continuous: regularly chronicled or officially regulated annual agricultural activities, such as the dates of grape and cereal harvests, are good examples.[2] In other cases, the spring opening of harbors or river and lake freezing dates can be useful.[3] Often several such series from different sources are combined into a single "chronology."[4]

Second, historical climatologists can use various reports that directly describe weather and climate. The qualitative character of this evidence requires expert interpretation and the formulation of temperature or precipitation indices before it can be converted into useful time series (see Chap. 11).[5] Compared with the proxy-based series described above, the data in these index series remains more subjective and less continuous in time and space.

When the density of data is low, the reconstruction should embrace a wider region in order to include more observations—provided, of course, that the region shares a common climate. For instance, the Central European temperature series brought together national series from Germany, Switzerland, and the Czech Republic over several centuries. Similarly, low data density can be overcome by summing up monthly indices to seasonal ones. The incompleteness of individual index series and the changing number of indices over time means that the resulting documentary-based index series used for the final reconstruction should employ variance stabilization instead of simple arithmetic averaging to combine the different indices.[6]

10.3 The Practice of Calibration

The most common method of calibration requires a sufficient overlap between the proxy or index series and instrumental measurements. Certain types of documentary evidence became rare from the 1800s onwards as these observations were replaced by instrumental measurements; therefore, index series usually end in the early nineteenth century. This means that the period of overlap used for calibration and verification usually covers the late 1700s to early 1800s—the same period when systematic temperature and precipitation measurements began in much of Europe. Both this relatively short period of overlap and the peculiarities of early instrumental data add further uncertainties to quantitative reconstructions based on index series (see Chaps. 6 and 9).[7]

As presented in Fig. 10.2, the data from the period of overlap is usually divided into early and late subperiods. The index series are calibrated to the early subperiod and then independently verified against the late subperiod. The

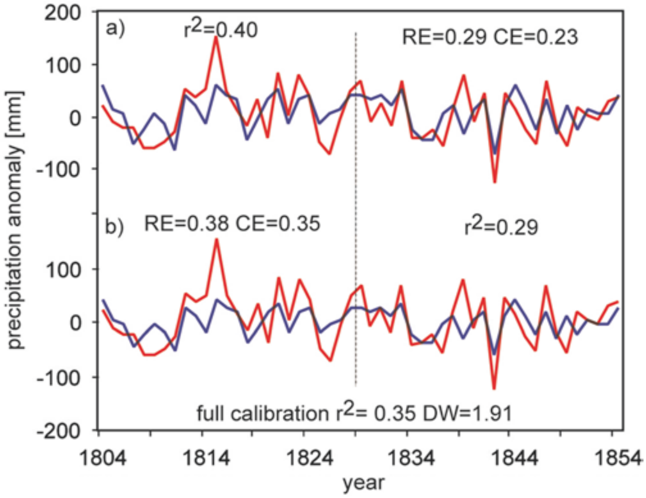

Fig. 10.2 An example of measured (red) and reconstructed (blue) mean annual precipitation anomalies (departures from the 1961–90 reference period) based on (a) early subperiod calibration (1804–29) and late subperiod verification (1830–54); and (b) late subperiod calibration (1830–54) and early subperiod verification (1804–29). Both are complemented by measures of reconstruction skill (r^2, RE, CE, and DW—see the text for explanation)[9]

whole process may then be repeated with the calibration and verification subperiods being switched. Among various approaches to calibration, the most common uses simple linear regression to estimate transfer function coefficients, and then several statistics to evaluate the quality of the calibration: the squared correlation (r^2), the standard error of estimate (SE), and the Durbin–Watson (DW) test. To verify the calibration result r^2, the reduction of error (RE), the coefficient of efficiency (CE), and the root mean square error (RMSE) may also be calculated.[8]

The r^2 quantifies the amount of temperature or precipitation variance explained by a reconstruction, while the SE measures the uncertainty in physical units. The DW tests the first-order autocorrelation within the regression residuals. Critical values of DW depend on the number of independent variables and also on the time series length, but values between 1.5 and 2.5 (with an ideal target of 2.0) are generally acceptable. DW values outside this range indicate problems with reconstructing multidecadal variations.

The RE statistic compares the mean square error (MSE) of the reconstruction to the MSE of a "reconstruction" that is constant in time with a value equal to the mean value for the measured (target) data in the calibration period. The CE instead compares the MSE of the reconstruction to a "reconstruction" that is constant and equal to the mean value of the measured data in the validation period. Both RE and CE can take values between one and negative infinity. CE is always less than, or equal to, RE. For both measures, positive values indicate that the linear regression model has some potential for reconstruction skill.

If the calibration and verification statistics provide acceptable results for both the early and the late subperiods, then the calibration is repeated for the whole overlapping period and used for the final reconstruction. One drawback of linear regression calibration is a reduction in the variance of the reconstructed values. Therefore the reconstructed values are scaled to have the same mean and variance as the target data in the full period of data overlap. This means that the reconstructed values are as close as possible to instrumental data and the side effect of the regression (reduced variability) is partly eliminated.

Some specific features of documentary evidence, such as the tendency of observers to record extreme events, have encouraged different approaches to calibration. For instance, F.S. Rodrigo has proposed a method that uses information about the frequency of extremely wet and dry months to reconstruct the low-frequency variability (i.e., long-term changes) in winter rainfall series in Andalusia, Spain.[10]

As discussed by Christian Pfister and colleagues, estimating and quantifying all the various sources of uncertainty in documentary evidence often proves problematic.[11] Some methodological approaches employed in dendroclimatology have been applied in the Central European temperature reconstruction.[12] Documentary evidence can also add valuable information regarding temperature and precipitation in climate field reconstructions that use a multiproxy approach and multivariate principal component regression, as indicated in several past studies.[13]

Numerous existing climate reconstructions based on man-made historical archives have proved that they can be, in several respects, complementary to natural proxy reconstructions. They are especially strong in the reconstruction of year-to-year variability (high-frequency signal) because documentary evidence allows precise identification of the most disastrous historical hydrometeorological extremes. Still open to question is how well they reproduce long-term changes (low-frequency signal). Thus the combination of proxies from natural and man-made archives in multiproxy reconstructions is challenging.

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Notes

1. Brázdil et al., 2005, 2010.
2. Daux et al., 2012; Možný et al., 2012; Wetter and Pfister, 2013.
3. Nordli et al., 2007; Leijonhufvud et al., 2010.

4. Leijonhufvud et al., 2010; Kiss et al., 2011.
5. Pfister and Brázdil, 1999; Brázdil et al., 2010.
6. Osborn et al., 1997.
7. Böhm et al., 2010.
8. Dobrovolný et al., 2010.
9. Dobrovolný et al., 2015.
10. Rodrigo et al., 2008.
11. Pfister et al., 2008.
12. Dobrovolný et al., 2010.
13. Luterbacher et al., 2004; Xoplaki et al., 2005; Pauling, 2006.

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CHAPTER 11

Analysis and Interpretation: Temperature and Precipitation Indices

Christian Pfister, Chantal Camenisch, and Petr Dobrovolný

11.1 Introduction

Paleoclimate research focuses mainly on the long-term, large-scale development of past climates, particularly changes in temperature. The results of this research are, however, rarely suited to understanding short-term, local impacts on economies and societies. In this respect, there is a gap between the scale on which paleoclimatologists provide information and the scale on which humans have responded—and still respond—to weather and climate, and their effects.[1] Weather provides the link between climate history and human history, as well as the raw material for the statistical reconstruction of climate. For these reasons, historical climatologists work to recover high-resolution, monthly, seasonal, and sometimes even daily data on both temperature and precipitation.

The archives of societies have left extensive descriptions and narratives about past local weather and how it affected people's daily lives (see Chap. 4). However, this information is too diverse and inconsistent to directly apply a standard statistical calibration and verification procedure (as explained in Chaps. 9 and 10). There remains the methodological challenge of making local weather information compatible with the statistical requirements of climate change research.

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One solution to this problem lies in generating ordinal-scale temperature and precipitation indices as an intermediate step between raw descriptions and climate reconstructions. The "index" approach—an original concept of historical climatology—provides an interface between individual pieces of weather information on the one hand and climate history on the other. It converts disparate documentary evidence into continuous quantitative proxy data for temperature and precipitation but without losing the ability to get back to the short-term local information for critical inspection and analysis. In a sense, this procedure resembles the way that national weather services aggregate monthly climate data from hourly and daily instrumental measurements, which nevertheless remain accessible for further research. This demanding task of index generation is accomplished by distinguishing and quantifying evidence based on human observations in a way that is compatible with the requirements of climatic time series analysis (Chap. 10).

This chapter briefly outlines the history of the index concept and then introduces the method, highlighting its strengths and weaknesses. Finally, it demonstrates how indices can contribute to large-scale climate reconstructions and to modeling relationships among climate, grain prices, and demographic variables.

11.2 History of the Index Approach

As early as the late 1800s, researchers began to develop quantitative reconstructions of warm-season temperature based on dendrochronological (tree ring) data and grape harvest dates.[2] Nevertheless, there were no comparable reconstructions of cold-season temperatures, until in 1928 Dutch journalist and amateur meteorologist Cornelis Easton developed a sophisticated winter severity index based on an extensive, well-documented compilation of narrative evidence.[3] Charles E.P. Brooks included Easton's winter severity indices in the second edition of his synthesis of climate history in 1949, although he criticized them "for being too low."[4] In 1977, one of the pioneers of climate history, Hubert H. Lamb, designed seasonal numerical three-point winter severity and summer wetness indices for Western Europe by calculating the ratio of warm to cold winter months and wet to dry summer months per decade (see Chap. 1). A decade later, in 1987, Pierre Alexandre adopted Lamb's approach for his reconstruction of medieval climate in Europe from 1000–1425. F.S. Rodrigo further developed a method to assess long-term changes in climate variability using the statistical distribution of extreme events.[5] In the meantime, F. IJnsen proposed a sophisticated nine-point temperature and precipitation index; however, apart from some Dutch colleagues, it was not adopted by other researchers.[6]

Christian Pfister came at historical climatology from a background in economic, agricultural, and glacier history, where temperature and precipitation variations make a difference. In 1981, he extended the three-point temperature and precipitation indices to all months and seasons of the year. Likewise, he devised a now widely adopted scheme of monthly seven-point ordinal-scale temperature and precipitation indices (see Table 11.1), which climate historian Franz Mauelshagen has named "Pfister Indices." The research group led by Rüdiger Glaser in Freiburg (Germany) and the research team led by Rudolf Brázdil in Brno (Czech Republic) adopted the scheme of seven-point ordinal "Pfister Indices," which have since been used in other series. For instance, documentary temperature indices have been generated for north-eastern Italy for the period 1500–1759, therefore overlapping with the long instrumental series from Padua and Bologna that starts in 1716 (albeit with many gaps). The index series was recalculated in order to have the same mean and variance as the instrumental observations.[7] Other series, from Poland (1501–1700) and the Carpathian Basin (1516–1870), have helped to create more comprehensive historical coverage of Central Europe (see Sect. 11.6).[8]

11.3 The Structure of Documentary-Based Temperature and Precipitation Indices

By their very nature, indices are simplifications, combining many details into a generalized description of weather and climate. The information in indices is "ordinal-scale," meaning it is ordered in categories ranked from lowest to highest, much like students might rate a professor's course from "1" (poor) to "5" (excellent). Note that this is not the same as "interval-scale" information that specifies the *amount of difference* between items: the categories in indices are ranked, but the difference between each rank is not necessarily known.

There are two main types of temperature and precipitation indices: the three point and the seven point. The *three-point index* is divided into three rankings or classes (−1, 0, +1) based on purely narrative observations. It distinguishes only between "cold" or "dry" anomalies (index −1) and "warm" or "wet" anomalies (index +1), disregarding any subjective emphasis given in the descriptions, such as "extremely cold" or "extremely dry." The class of 0 is

Table 11.1 The seven-point temperature and precipitation index. The average is based on the reference period. The percentile is a statistical measure indicating the value below which a given percentage of observations in a group falls

Index	*Designation*	*Assigned class (percentile)*
−3	Extremely cold/extremely dry	< 8.3%
−2	Cold/dry	8.3–25%
−1	Rather cold/rather dry	25.1–42%
0	Average (in terms of the reference period)	42.1–58%
+1	Rather warm/rather wet	58.1–75%
+2	Warm/wet	75.1–91.7%
+3	Extremely warm/extremely wet	> 91.7%

For Switzerland the reference period is 1901–60. SD: standard deviation. After Pfister, 1999, 46 used for average or unremarkable months or seasons. A three-point index does not use an (instrumental) reference period to establish a mean or standard deviation. Where there is only descriptive evidence (e.g., "a mild winter" or "a rainy November") then these indices should only use values from −1 to +1. Indices derived from descriptive evidence may be considered relative and unitless departures from "average" temperature/precipitation conditions of a given month (season).

The *seven-point index* (or "Pfister" index) is divided into seven classes (see Table 11.1). These classes, from −3 to +3, represent deviations from a designated reference period taken after the start of regular instrumental measurements but prior to the full onset of global warming, such as 1901–60. Although it is not an interval scale, and the intervals between its rankings cannot be precisely measured, the seven-point index indicates an approximate degree of difference between one ranking or class and the next, whether in temperature or precipitation values.[9]

Monthly rankings above +1 and below −1 according to the seven-point scale index should be attributed only on the basis of the analysis of proxy data such as plant-phenological evidence (see Chap. 6). Table 11.2 distinguishes between criteria obtained from the statistical analysis of institutional sources (in italics) and those for which analyses are still lacking, such as the monthly duration of snow cover, but which are nevertheless meteorologically significant.

Table 11.2 Criteria for generating seven-point temperature indices of +/2 and +/−3 for Switzerland

Month	*"Cold" (indices ≤ −2)*	*"Warm" (indices ≥ +2)*
Dec, Jan, Feb	Uninterrupted snow cover *Freezing of lakes*	Scarce snow cover Early vegetation activity
March	Long duration of snow cover Frequent snowfalls	Early sweet cherry flowering No snowfall
April	Several days of snow cover Frequent snowfalls	*Beech tree leaf emergence* *Early vine flower*
May	*Late grain and grape harvest* *Late vine flower*	*Early grain and grape harvest* *Start of barley harvest*
June	*Late vine flower* Several low altitude snowfalls	*Early grain and grape harvest* *High vine yields*
July	*Low vine yields* Snowfalls at higher altitudes	*High vine yields*
Aug	*Low tree ring density* Low sugar content of vine Snowfalls at higher altitudes	*High tree ring density* High sugar content of vine
Sep	Low sugar content of vine Snowfalls at higher altitudes	High sugar content of vine
Oct	Snowfalls, snow cover	Second flowering of spring plants
Nov	Long duration of snow cover	Second flowering of spring plants No snowfall

Italics: Ranking criteria grounded in statistical analyses. After Pfister, 1992, 33

Table 11.3 Criteria for generating seasonal temperature and precipitation indices (seven-point index scale) for the Low Countries, based on the available fifteenth-century evidence for winter (altitude 5 to 100 m a.s.l.)

Index	*Designation*	*Applied criteria*
3	Extremely warm	No frost or very few frost days, vegetation extremely advanced, at least two months "very warm"
2	Warm	Very short frost period, vegetation advanced one month "very warm"
1	Rather warm	Short frost periods, mainly rainfall instead of snowfall
0	"Average"	Longer frost period, short snow-cover, a few days with drift ice
−1	Rather cold	Several periods with frost and drift ice; longer period with snow cover
−2	Cold	Frost for about a month, ponds and small rivers ice bound, persistent snow cover
−3	Extremely cold	Large rivers and lakes ice bound. Frost for at least two months, frost impacts on crops, trees or/and vines

Table adapted from Chantal Camenisch, "Endless Cold: A Seasonal Reconstruction of Temperature and Precipitation in the Burgundian Low Countries during the 15th Century Based on Documentary Evidence," *Climate of the Past* 11 (2015): 1049–66, under a CC-BY 3.0 license: https://creativecommons.org/licenses/by/3.0/

Chantal Camenisch has applied a seven-point scale to seasonal temperature and precipitation indices for the Low Countries based on the available fifteenth-century evidence. Table 11.3 presents the criteria for winter. Seasonal indices are a sum of the corresponding monthly values (winter: DJF, spring: MAM, summer: JJA, autumn: SON), and therefore range from −7 to +7 on the three-point index scale and from −12 to +12 on the seven-point index scale, respectively. Seasonal sums on the basis of the seven-point index scale might also be divided by three, resulting in seasonal indices with one decimal place, such as 2.3 or −1.7, which can be classified according to the monthly scheme. Narrative descriptions of whole seasons—rather than more precise daily, weekly, or monthly observations—are considered secondary evidence and should be marked accordingly.[10]

Statistics obtained from the analysis of weather diaries, such as the number of precipitation days, cannot be classified according to the scheme described above. In these cases, it is more straightforward to work with duodecile statistics. Duodeciles are threshold values that—in the case of indices—arrange a set of values that have been sorted in descending order (from highest to lowest) into twelve classes of equal size, each containing ~8.33% of the total. Let us illustrate the procedure from a set of sixty monthly sums of precipitation assuming a threshold value of 5.2 precipitation days for the lowest duodecile. This entails that the eight lowest values, being between 0 and 5, receive a score of −3, or "extremely dry" (see Table 11.4).

Table 11.4 The seven-point precipitation index based on duodecile statistics. As in Table 11.1, the average is based on the reference period, and the percentile is a statistical measure indicating the value below which a given percentage of observations in a group fall

Index	*Duodecile*	*%*	*Designation*
+3	>11	> 91.7%	Extremely wet
+2	>9	75.1–91.7%	Wet
+1	>7	58.1–75%	Rather wet
0	>5	42.1–58%	Average
−1	>3	25.1–42%	Rather dry
−2	>1	8.3–25%	Dry
−3	<1	< 8.3%	Extremely dry

Source: Pfister, 1999

11.4 Guidelines for Generating Indices

Researchers have developed the following guidelines as best practices for generating monthly and seasonal indices from collections of historical evidence (both narrative and proxy):[11]

1. Researchers should choose an appropriate temporal resolution (monthly, seasonal, or annual) based on the number and quality of available records. For example, Chantal Camenisch has reconstructed temperature and precipitation indices for the Low Countries (present-day Belgium, the Netherlands, and Luxembourg) in the fifteenth century. She selected a seasonal resolution, because the density and quality of the evidence was not sufficient for generating monthly indices.[12]
2. Whether to generate three-point or seven-point indices depends on the types of available records (subjective and objective or only subjective sources).
3. Records should be *sorted chronologically* in descending order according to year, month, and season. Indices are then generated stepwise for each month and for each season. It is preferable to *begin by indexing the most recent period*, which is usually the best documented, and then *work backward* to periods where the evidence is less reliable and less complete. This procedure, named "weather hindcasting," has the important advantage that researchers become familiar with well-documented anomalies within the instrumental period prior to analyzing analogous cases (months or seasons) in the pre-instrumental past.[13]
4. Indices should use collections of records that overlap with a *climatically defined region*. Such a region might not coincide with the borders of a modern political unit.
5. Indices should be generated using *several independent contemporary records* that complement and corroborate each other. If weather within a large region is documented with just a single contemporary record,

this evidence should usually be excluded in order to enhance the validity of the reconstruction.

6. If *both* objective (statistically defined) *and* subjective (purely narrative) records are available for a regional and temporally defined aggregate of records, then the two types of record may be combined in order to derive additional monthly seven-point indices. Relatively objective proxy data such as plant-phenological observations always relate to temperatures over two or more months, which can include quite diverse and even contrasting monthly temperature patterns. For example, the full flowering of vines in open vineyards situated in the Swiss Mittelland (~430 m above sea level) is tied to May *and* June temperatures.[14] An advanced flowering at the end of May might occur after an exceptional heat wave in April followed by average conditions in May, or average or even cool weather in April followed by an unusually warm spell in May. Only detailed narrative evidence can enable us to assess which of those monthly patterns actually occurred. Of course, this problem only adds to the uncertainty already inherent in the correlation between, in this case, plant-phenological proxy data and May–June temperatures. This example shows how subjective and objective records must complement each other to create monthly indices. Only the combination of monthly weather narratives with plant-phenological, ice-phenological, or hydrological data makes it possible to apply the seven-point ordinal scale to monthly temperature or precipitation indices.
7. Researchers should *repeat the classification procedure several times* in order to reduce inhomogeneity.
8. *Periods without records should be clearly labeled* so that they are not included in statistical analyses. Marking periods without records as "0" will give misleading results, and so those periods need to be removed from the series altogether.
9. The entire procedure should be *fully transparent and open to critical re-evaluation* by disclosing both the indices and the underlying evidence (narrative texts and proxy data). This disclosure enables the reviewing and crosschecking of different types of records often originating from different regions of the country.[15]
10. As new evidence becomes available, indices should be revised.[16] No index can ever be regarded as "final." Rather, an index represents only an approximation—open to refinement and correction—of an underlying climatic reality.
11. For generating indices, researchers should have a basic understanding of (regional) meteorology and a good understanding of the strengths and weaknesses of their evidence. In any case, a high degree of expertise is essential to minimize subjectivity in the process of transforming the information in narrative accounts to numbers on a scale.[17]

11.5 Shortcomings and Uncertainties

Index generation inevitably suffers from several shortcomings. First, while the procedure performs well in periods with extensive high-quality proxy coverage, it shows deficiencies in periods where climate indicators are sparse, poor, or missing.

Second, ordinal indices underestimate climate variability. On the one hand, they suppress small variations from the mean.[18] On the other hand, since the highest and lowest classes are open ended, they cannot adequately reproduce outstanding extreme events such as winters with months-long river and lake freezes or heat-ridden summers like those of 2003 and 2015 in Western and Central Europe, which should rank −4 and +4 instead of −3 and +3. Moreover, months or seasons assigned values of −1 or +1, because only descriptive evidence was available (see the discussion of seven-point indices above), might suppress much larger anomalies. In short, the procedure is designed to err on the side of caution, underestimating rather than overestimating deviations.

These shortcomings are reflected in changes in low-frequency variability (or long-term trends), as found over the course of the Central European Temperature Series (CEUT), discussed in Sect. 11.6.[19] Every time series can be broken down into frequencies of different length, of which longer ones may represent secular changes such as the Little Ice Age (LIA), and shorter ones multiannual or annual departures from this trend. The first part of the CEUT (1500–1759), which is based on documentary indices, indicates much weaker low-frequency variability than the second part of the CEUT (1760–2007), which is based on instrumental measurements. On the other hand, the Stockholm temperature series, based on objective institutional ice-phenological data (see Chap. 6), shows a pronounced low-frequency component.[20] It is hypothesized that the smaller variability of the index-based part of the CEUT is mainly related to the time period prior to 1650, which relies particularly on three-point indices based on subjective (narrative) data. Nevertheless, this shortcoming should not be overestimated. Glaser and Riemann showed from their thousand-year temperature reconstruction for "Germany" that "in principle [there is] a strong capability of indices to describe long-term variations. Even with reduction to a 3-point scale and subsequent calibration back to temperature, thereby losing information, it is possible to keep the low-frequency signal as shown by the 11-year mean temperatures."[21]

Third, in order to create quantitative temperature and precipitation reconstructions based on indices, and to evaluate those reconstructions, the indices need to undergo the same calibration and verification procedures as would natural proxies, such as tree ring measurements (see Chaps. 3 and 10). However, unlike proxy evidence from the archives of nature, which usually continue to the present, older types of narrative sources for weather history, including weather diaries and chronicles, fade away with the onset of scientific meteorology during the nineteenth century. The First International Meteorological Congress in Vienna in 1873 banished all kinds of "soft" narrative weather information from being published in official yearbooks, reducing climate to bare numerical measurements. This tunnel vision of some early climatologists even affected weather reports in the press. This decline of published documentary evidence is an important reason why there is often no overlap period between series of documentary evidence and instrumental data long enough for calibration and verification.

11.6 Evaluations and Results

Several recent studies have reviewed the available evidence for constructing indices, the statistical strength of indices, and the validity of their results.[22] In 2010, Petr Dobrovolný and colleagues carried out the most comprehensive evaluation of documentary-based index series for past climate reconstruction. They selected series from Germany, Switzerland, the Czech lands, the Low Countries, Poland, and the Carpathian Basin (including present-day Hungary and parts of Serbia, Croatia, Slovakia, and Romania).[23]

To overcome problems of missing values and poorly documented periods, the Czech, German, and Swiss index series were merged into one main series. Moreover, the longest homogenized instrumental series for the region were merged into a single instrumental "Central European Temperature Series" (CEUT) covering 1760–2007. The authors then reconstructed monthly mean temperatures from 1500 to 1759 by calibrating and verifying the index series against the instrumental CEUT (1760–2000).

The study arrived at the following results:

- The values in all of the index series did not differ significantly from a normal (Gaussian) distribution (i.e., a "bell curve"). Neither the instrumental data nor the indices deviate from a normal distribution if applying a statistical test.
- The documentary evidence provided a similar level of data coverage for the Czech lands, Germany, and Switzerland from 1500 to 1854—that is, 70–90% of all months and seasons had sufficient observations to assign an index value. The Polish and the Carpathian series had considerably less coverage.
- High and statistically significant correlations were consistently found between the main index series (averaging the seven countries and regions) and the single Czech, German, and Swiss series, but the values were lower for the Polish and the Carpathian series. This result reflects both data quality and the spatial coherence of temperature variability.
- It turned out that the documentary evidence explains a large fraction of temperature variability, varying according to season (from 73% in autumn (SON) to 83% in winter (DJF), and according to month, from 56% in September to 86% in January).
- A spatial field reconstruction (see Chap. 12) of January to April temperatures in the whole of Europe in combination with model runs yielded the result that the CEUT is significantly correlated to 91% of all grid cells in the entire European and northern Mediterranean temperature field.[24] This result implies that this series is also representative of temperatures outside the Central European core area (and so can aid climatic impact research in surrounding regions that lack adequate climate records). Monthly temperature estimates from 1500 onwards will further improve the robustness of current gridded temperature reconstructions for the last 500 years.

Table 11.5 Reconstruction of seasonal temperature and precipitation in the Low Countries, 1400–99 (percentage of reconstructed seasons)

Season	*Temp (%)*	*Prec (%)*
Winter	83	42
Spring	47	32
Summer	50	60
Autumn	32	39

Indices cf. Chantal Camenisch, "Endless Cold: A Seasonal Reconstruction of Temperature and Precipitation in the Burgundian Low Countries during the 15th Century Based on Documentary Evidence," *Climate of the Past* 11 (2015): 1049–66, under a CC-BY 3.0 license: https://creativecommons.org/licenses/by/3.0/

There are substantially fewer valid instrumental precipitation series than temperature series for early modern Europe, and the spatial coherence of precipitation patterns is much smaller than that of temperature patterns (see Chap. 23). A Czech team centered around Petr Dobrovolný has succeeded in generating seasonal precipitation estimates for the Czech lands from 1501 to 2010 based on precipitation indices and instrumental measurements.[25] Andreas Pauling and colleagues have attempted a continental-scale reconstruction of European precipitation from 1500 to 2000 incorporating documentary-based indices.[26] Chantal Camenisch has also succeeded in generating a set of both seasonal temperature and seasonal precipitation indices based on multiple observations for each season covered.[27] However, the data coverage varied with the time of year and measurement type (see Table 11.5).

11.7 Applications

Documentary-based indices and climate reconstructions were devised in the late twentieth century to become an interface between climate history and weather-related human history. Climate indices based on human archives can also provide longer coverage than instrumental records, and at a higher level of spatial and temporal resolution than most proxies from the archives of nature. They capture the exceptional events and extremes typically missing from reconstructions created by and for climatologists. Consequently, they can offer new insights into climate patterns and trends, and particularly the human consequences of past climate. Therefore, the last section of the chapter reviews some key findings for climate history and then for human history.

The large comprehensive study by the multiauthor Pages 2k Consortium on global temperature fluctuations over the last 2000 years is supported by eleven annually resolved tree ring width and density series together with documentary records from ten European locations (including the CEUT).[28] This series (together with tree ring records) was also used to assess European mean summer temperatures over the last half-millennium.[29] The findings revealed a previously unobserved long-term decrease in temperature variability over the last five centuries during winter, spring, and summer. Purely documentary records may in themselves represent the spatial structure of some climatic elements. In particular, they can act as a reliable guide for reconstructing sea-level pressure patterns for anomalously cold winters for periods when no instrumental information is available.[30]

Documentary-based indices also enable researchers to build numerical models exploring the relations between climate and factors such as crop yields and prices. Pfister developed a model of climatic factors accounting for variations in the production of grain, vine-must, and dairy products in Switzerland, which is also valid for other parts of Central Europe. The numerical model that ultimately corresponded best to the grain price curve, for instance, comprised several seasonal "biophysical impact factors," including adverse temperatures or untimely precipitation in autumn, spring, and summer but particularly cold springs and wet midsummers.[31]

A study has calculated biophysical impact factors for the Czech lands and Switzerland from 1750–1800, in order to focus on the European subsistence crisis of the early 1770s (see Chap. 23). The course of the weather in these regions was similar in many respects. Chilly springs and wet midsummers were noted in 1769 and 1770 in both countries, leading to two harvest failures. The situation in 1771 improved somewhat in Switzerland, where high atmospheric pressure brought a warm and dry July; however, the Czech lands suffered again from persistent midsummer rains, leading to a third consecutive harvest failure. Given the high social and economic vulnerability of the region—rigid feudal structures, inhibitive mercantile policies, inefficient bureaucracies, and late adoption of the potato—the famine that followed resulted in a 10% loss of population, attributable to the adverse climate and harvest failures (Fig. 11.1).[32]

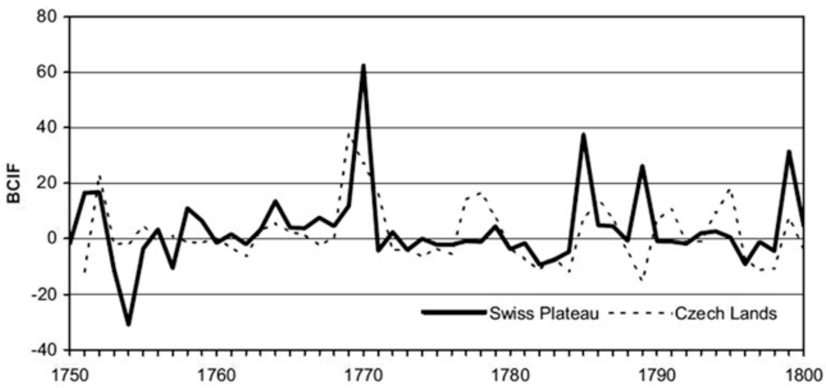
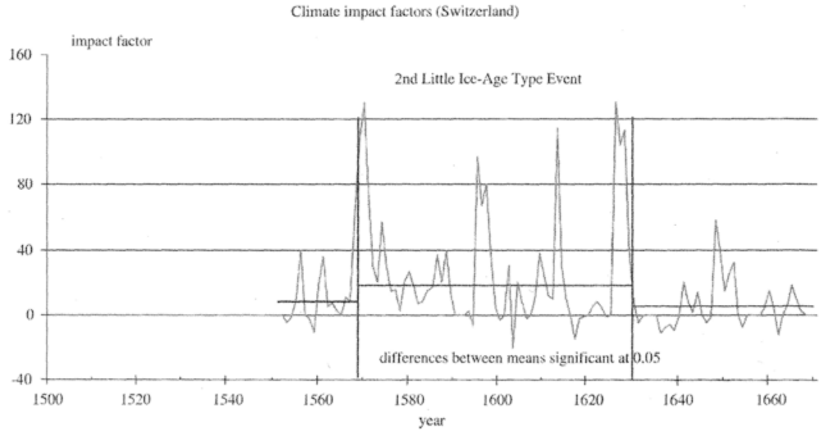


Fig. 11.1 Biophysical Climate Impact Factors computed from documentary-based indices for Switzerland and for the Czech lands over the period 1750–1800. (Image reproduced without changes from C. Pfister and R. Brázdil, "Social Vulnerability to Climate in the 'Little Ice Age': An Example from Central Europe in the Early 1770s," *Climate of the Past* 2 (2006): 115–29, under a CC-BY 3.0 license: https://creativecommons.org/licenses/by/3.0/)



Data-basis: Pfister 1988.

Fig. 11.2 Little Ice Age-type impacts in South-Central Europe 1560–1670 (Reproduced from Christian Pfister, "Climatic Extremes, Recurrent Crises and Witch Hunts: Strategies of European Societies in Coping with Exogenous Shocks in the Late Sixteenth and Early Seventeenth Centuries." *Medieval History Journal* 10 (2007): 33–73. https://doi.org/10.1177/097194580701000202, a SAGE publication)

A longer-term analysis of biophysical impact factors for Switzerland revealed that negative effects were unevenly distributed over time. Some periods displayed more frequent biophysical impact factors—also named "Little Ice Age-type impacts"—and therefore brought higher levels of climatic stress (see Chaps. 23 and 27). The six decades from 1568 to 1630 stand out as climatically the most adverse since 1500, contributing to higher average prices for grain (Fig. 11.2).[33] The seasonal temperature and precipitation indices developed for the Low Countries during the fifteenth century (see Table 11.3) were also used to investigate the relationship between climatic parameters and rye prices in Antwerp. It turned out that variations in prices are significantly correlated with indices for winter precipitation, as well as summer precipitation and temperatures.[34]

Surprisingly, this model also indicated that a classical subsistence crisis in Switzerland (and in neighboring countries) occurred during the latter half of World War I, between 1916 and 1918. It was caused by an LIA-type impact occurring under the stress of the Allied blockade of the Central Powers, which impeded adequate imports of food and forage.[35]

In conclusion, documentary-based indices and climate reconstructions have passed the test in both fields: Anthropogenic observations can significantly contribute to large-scale climate reconstructions. Climatologist Jürg Luterbacher has concluded that, under the right conditions, early instrumental sources and non-instrumental documentary sources "can be treated as one in terms of providing temporally continuous and homogeneous series."[36] Furthermore, socioeconomic modeling built on documentary-based indices has turned out to be a powerful instrument to assess climate impacts in human history, although this research requires further demonstration.

Notes

1. Oreskes et al., 2010, 1023.
2. Speer, 2010 (and references therein); Dufour, 1870; Angot, 1883.
3. Easton, 1928.
4. Brooks, 1949.
5. Lamb, 1977; Alexandre, 1987; Rodrigo, 2008.
6. IJnsen and Schmidt, 1974; Engelen et al., 2001 used it for temperature reconstruction of the warm and the cold season (excluding April and October) in the last millennium.
7. Mauelshagen, 2010, 55; Camuffo et al., 2010.
8. Bokwa et al., 2001; Dobrovolný et al., 2010.
9. Pfister, 1992, 133.
10. Dobrovolný et al., 2010.
11. See also Brázdil et al., 2010.
12. Camenisch, 2015a, 2015b.
13. Pfister, 1999, 38–39.
14. Pfister, 1984, 104.
15. Pfister and Rohr, 2015.
16. Brázdil et al., 2010.
17. Brázdil et al., 2010.
18. Glaser and Riemann, 2009.
19. Dobrovolný et al., 2010.
20. Brázdil et al., 2010.
21. Glaser and Riemann, 2009, 442.
22. See, e.g., Brázdil et al., 2010.
23. This paragraph follows the discussion by Dobrovolný et al. (2010) and references quoted therein unless stated otherwise.
24. Luterbacher et al., 2010.
25. Dobrovolný et al., 2015.
26. Pauling et al., 2006.
27. Camenisch, 2015a.
28. PAGES 2k Consortium, 2013.
29. Luterbacher et al., 2016.
30. Luterbacher et al., 2010.
31. Pfister, 1988; Pfister and Brázdil, 2006.
32. Pfister and Brázdil, 2006.
33. Pfister, 2005, 61.
34. Camenisch, 2015a.
35. Pfister, 2016.
36. Luterbacher et al., 2010.

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CHAPTER 12

Analysis and Interpretation: Spatial Climate Field Reconstructions

Jürg Luterbacher and Eduardo Zorita

12.1 Introduction

This contribution gives a short overview of spatial climate field reconstructions (CFR), the technique of employing different statistical methods to reconstruct climate (such as temperature, precipitation, drought, and air pressure) over larger geographical areas based on data from climate proxies. CFR methods have been applied both to filling spatial gaps in early instrumental climate datasets and to the problem of reconstructing past climate patterns from natural and documentary-based proxy data.

12.2 Concepts

Studies of long-term climate change require long time series of information. There are various initiatives that undertake and facilitate the recovery of historical instrumental surface terrestrial and marine global weather observations to underpin three-dimensional weather reconstructions (re-analyses) spanning the last 200–250 years for climate applications, such as the international Atmospheric Circulation Reconstructions over the Earth (ACRE).[1] To reconstruct climate change for the pre-instrumental periods, researchers must use climatically sensitive natural proxies, such as tree rings, corals, ice cores, speleo-

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thems, and sediments, as well as information from documentary evidence (see Chap. 3). If they can establish a sufficient overlap between the proxy and instrumental records, they can then calibrate the proxy measurements to the instrumental measurements in order to reconstruct pre-instrumental climate (see Chap. 10).

By contrast, statistical spatial CFR techniques attempt to reconstruct a climate field—such as surface air temperature, pressure, precipitation, or drought—over a wide area, including regions where there may not be local proxy data. They accomplish this by using a spatial network of proxy indicators. They then perform a multivariate calibration of the large-scale information in the proxy data network against the available instrumental data (Fig. 12.1). The large-scale climate field is simultaneously calibrated against the entire information in the proxy network. Therefore, the statistical model is not based on a one-to-one link between the proxy indicator and the local climate variable (although this link has to exist). Rather, it searches for statistical connections between the local proxies and each part of the geographical area to be reconstructed.

All statistical models that offer the best fit between proxy climate data and the most probable state of large-scale climate should, however, respond to some aspect of local climate during some season of the year. This so-called "upscaling" involves developing statistical models that offer the best fit between proxy climate data and the most probable state of large-scale climate (step 1 in Fig. 12.1). Model fitting is based on the period of overlap between the proxy and the instrumental data, which is usually split into a calibration and a verification period (steps 1, 2, and 3 in Fig. 12.1). The statistical connections that were derived from the period of overlap within the instrumental era are then applied to the entire period to be reconstructed (step 4 in Fig. 12.1). This step assumes that the statistical relationships throughout the reconstruction period are stable—an assumption known as the "principle of stationarity."

12.3 Applications

Since proxy records only provide a collection of measurements at particular points in space, a CFR necessarily involves some type of spatial interpolation. Fortunately, climate patterns are usually coherent over larger regions (except for precipitation), and this spatial coherency can be used to "scale up" the localized information taken from proxies to a wider area. All CFR methods use the tendency of climate fields, such as temperature, to be correlated over long distances. For instance, temperature in a particular winter tends to be colder or warmer than normal over the whole of Northern Europe, and in those winters, Greenland tends to display the opposite temperature anomalies.[2] This large-scale spatial relation can be exploited to extrapolate (and interpolate) the local information provided by a network comprising a few proxy records in order to reconstruct spatially resolved temperature over larger areas.

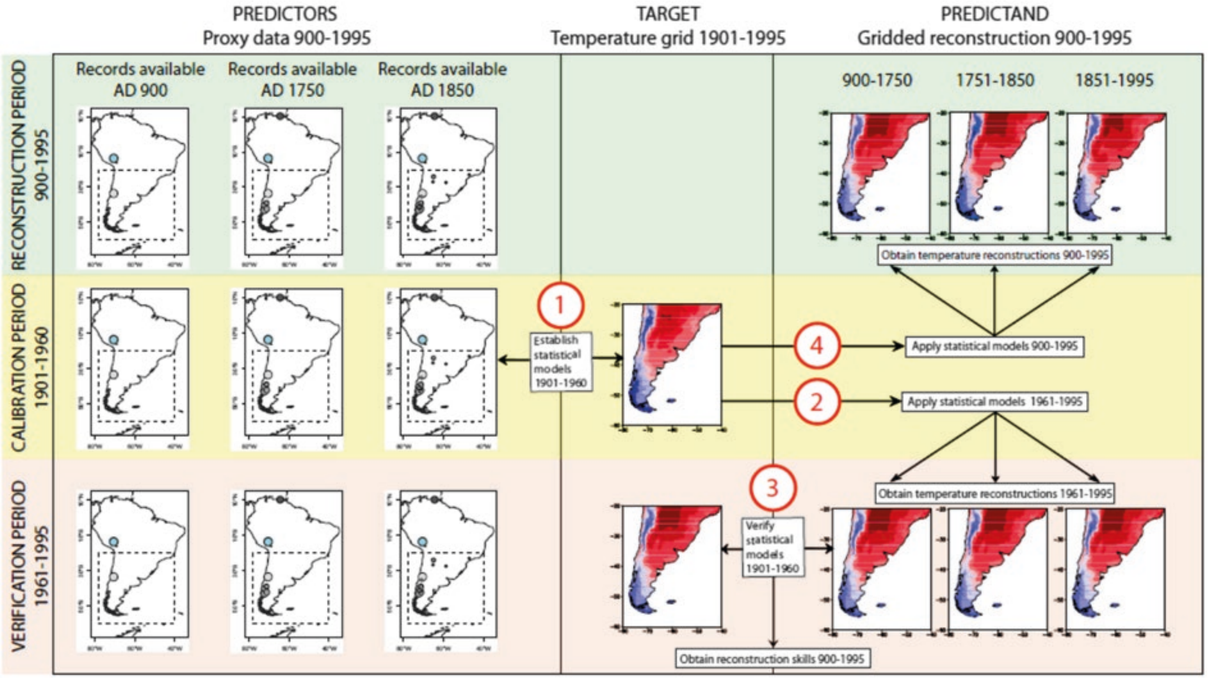

Fig. 12.1 Schematic diagram for climate field reconstructions (from Neukom 2010)

CFR commonly employs a number of statistical methods in order to help scale up localized proxy measurements to a reconstruction over a wide area. These methods (which are too complex to explain in a short chapter) include point-by-point regression, multivariate principal components regression, canonical correlation analysis, iterative covariance-based missing data imputation techniques such as regularized expectation maximization, neuronal networks, and Gaussian graphical models.[3] Furthermore, the analogue method retrieves the spatial structures from climate model simulations and then uses proxy records to potentially produce a full three-dimensional reconstruction.[4]

In addition to filling in spatial gaps in early instrumental climate datasets, these statistical methods have been used for temperature, pressure, precipitation, and Palmer Drought Severity Index reconstructions.[5] Figure 12.2 shows as an example one warm and one cold European summer CFR from the fifteenth century using tree ring information and applying a statistical approach known as Bayesian Hierarchical Modelling.[6]

CFR provides a distinct advantage over averaged climate reconstructions when, for instance, trying to understand the response of climate in a region to some external forcing, such as a large tropical volcanic eruption. In CFR, we can see for instance how the generally cool and wet mean summer conditions in Europe one to three years after the eruption are distributed over the various regions,[7] the late winter temperature response in temperate western North America,[8] the volcanic response in the Asian monsoon region[9] and in European summer droughts.[10] Thus, proxy-based CFR reconstructions provide spatially resolved climate fields at regional to global scales and can offer critical insights into the range and geographic characteristics of historical climate variability.

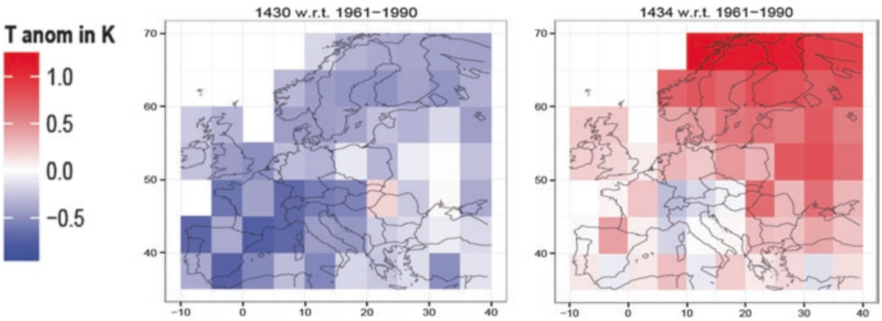

Fig. 12.2 Bayesian hierarchical model-based temperature CFR for a cold and warm European summer in the 1430s. The anomalies are shown as departures from the 1961–90 period. The reconstruction uses only tree ring information reconstructions. (Credit: Reproduced from J. Luterbacher et al., "European Summer Temperatures since Roman Times." *Environmental Research Letters* 11 (2016): 024001 under a CC BY 3.0 License: https://creativecommons.org/licenses/by/3.0/)

CFR can also contribute to analyzing the causes and processes of past climate variability and therefore the impact of weather on past societies. Proxy-based reconstructions of spatially resolved climate fields at regional to global scales can offer critical insights into the range and geographic characteristics of historical climate variability. Their comparison with climate model runs also provides an important test bed for understanding multidecadal to centennial climate variability and climate sensitivity to external forcing, while providing an extended context for anthropogenic warming prior to the instrumental era.[11]

12.4 Uncertainties

In performing CFR, researchers have to make decisions that will ultimately affect the reliability of the reconstruction. These include decisions driven by scientific needs and by methodological concerns (i.e., the choice of season, climate variable, and target field; the calibration data and calibration time interval; the spatial and temporal sampling of the proxy network; and the actual climate–proxy connection of each proxy record used for the reconstruction).[12]

A leading challenge in producing climate reconstructions is the assessment of their uncertainties. The uncertainty of a real-world reconstruction comes from two main sources: first, the imperfections of the proxy and instrumental data; and second, the uncertainties associated with the statistical methodologies. While proxies are sensitive to changes in climate, there are other non-climatic factors that can leave an imprint on them. To take the case of tree rings, their width and density can be affected by insects, competition from other trees, nutrient availability, and other environmental factors besides temperature and precipitation. This "noise" needs to be filtered out from the purely climatic "signal," which makes reliable reconstruction a challenging statistical problem. Further data uncertainties include measurement errors in the proxies, sampling errors in instrumental climate fields, chronological uncertainties, and the coarse spatio-temporal coverage of proxy or instrumental measurements. Methodological uncertainties can also stem from input data (type of data, resolution, noise level, and spatio-temporal variability), as well as sensitivity to model parameters and the uncertainty associated with the choice of these parameters.[13]

12.5 CFR Methods and Climate Models

One important tool for assessing CFR reconstruction methods is millennium-length climate simulations with fully coupled general circulation models (GCMs) (see Chap. 13).[14] These simulations are obviously not equivalent to the real climate, but they are realistic enough to be used as a "laboratory" to test CFR methods in controlled conditions. The rationale is that in the real world, the true climate is, of course, not exactly known, and therefore the reliability of CFR cannot be directly addressed (if the true climate were known we would not need reconstruction methods in the first place). In the virtual world produced by climate simulations, however, the past temperature and precipitation is indeed known. In this numerical laboratory, all the procedures used in the CFR can be emulated, for instance by taking simulated local climates as pseudo-proxies and applying CFR to these pseudo-proxies. The advantage is that the output of the CFR can then be compared with the full climate field, thereby providing a measure of the uncertainties inherent in CFR. The motivation for these pseudo-reconstructions is that real-world reconstructions are derived from many different methods, calibration choices, and proxy networks, which can be tested in the controlled set-up of climate simulations.[15]

The conclusion from these tests is that there is no one CFR method that outperforms all the others. While most methods perform well in areas with good spatial coverage by proxies, all show deficiencies in areas where proxies are missing or where they do a poor job indicating the climate. Thus, there is no "one method fits all" conclusion. Rather, reconstruction quality depends on multiple non-methodological factors, including the climate variable, season, and target field of the reconstruction.[16]

Notes

1. Allan et al., 2011.
2. van Loon and Rogers, 1978.
3. Briffa et al., 2002; Mann et al., 2008; Tingley and Huybers, 2010a, 2010b; Smerdon, 2012; Dannenberg and Wise, 2013; Werner et al., 2013, 2018; Guillot et al., 2015; Wang et al., 2014.
4. Graham et al., 2011; Franke et al., 2011.
5. Schneider, 2001; Küttel et al., 2010; Luterbacher et al., 2002, 2004, 2016; Mann et al., 2008; Riedwyl et al., 2009; Wang et al., 2014; Xoplaki et al., 2005; Neukom et al., 2011; Cook et al., 2013, 2015; Pauling et al., 2006; Shi et al., 2015, 2017; Anchukaitis et al., 2017; Werner et al., 2018.
6. Luterbacher et al., 2016.
7. E.g. Briffa et al., 2002.
8. Wahl et al., 2014.
9. Anchukaitis et al., 2010.
10. Fischer et al., 2007; Gao and Gao, 2017; Rao et al., 2017.
11. Jansen et al., 2007.
12. Werner et al., 2013; Smerdon et al., 2016, 2017.
13. Wang et al., 2014.
14. Schmidt et al., 2011; PAGES 2k-PMIP3 group, 2015.
15. Mann et al., 2005; Smerdon, 2012; Wahl and Smerdon, 2012; Wahl et al., 2012; Werner et al., 2013; Gomez-Navarro et al., 2015; Steiger and Smerdon, 2017.
16. Ammann and Wahl, 2007; Tingley and Huybers, 2010b; Smerdon et al., 2010, 2011, 2016; Dannenberg and Wise, 2013; Werner et al., 2013; Wang et al., 2014.

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CHAPTER 13

Analysis and Interpretation: Modeling of Past Climates

Eduardo Zorita and Sebastian Wagner

13.1 Introduction

Computer climate models have become an essential tool to analyze past and future climate change. Since these models comprise rather complicated pieces of computer code, the interpretation of their results requires care and a basic familiarity with their structure, underlying assumptions, and implications of their results. This need becomes even more pressing when comparing paleoclimate simulations with proxy reconstructions, because they capture different spatial and temporal scales of the climate variations. For instance, whereas proxy records can represent local seasonal mean temperature (see Chap. 3), a climate model produces daily and even subdaily temperatures averaged over 10,000 km^2. This chapter introduces important topics of consideration for the interested community of paleoclimatologists and historical climatologists who may not work regularly with climate models.

13.2 How Models Work

Climatology is essentially an observational science. Most information comes from analyzing measurements, rather than purpose-built experiments. Climate models, being a computer code that can generate virtual climates in some sense similar to observed climate, provide the means to conduct *numerical experiments under controlled conditions* in order to test hypotheses, much as in a laboratory. In addition, models can provide long, comprehensive, and gap-free climatic time series that cover several millennia and share some statistical prop-

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erties with observational records. Despite the fact that present-day Earth System Models represent and simulate a large number of the climatic subcomponents, it is still important to bear in mind that they are simplifications of the real world (see Chap. 38). In the future, as we gain more understanding about the respective subsystems of climate, new processes will be incorporated into the earlier model versions. Therefore, it is important to rigorously test models with observational and paleoclimate records.

Modern climate models are basically computer codes that represent the continuous systems of the atmosphere, ocean, cryosphere, and so on, using a discrete three-dimensional grid over the Earth (see Chap. 2). They simulate, to some level of realism, the *state* of these systems. Here *state* is defined as the average conditions for a given time interval, typically thirty minutes. In modern climate models, the mesh size (that is, the size of a box in the three-dimensional grid) is typically about two degrees of longitude by two degrees of latitude, divided into fifty atmospheric levels and fifty oceanic levels of depth.

Before starting a climate simulation, the computer code requires two essential types of *drivers*. The first drivers are the *initial conditions*, or the state of the climate at the start of the simulation. These conditions are prescribed by the climate modeler independently of the computer code used to perform the simulation. Understanding this concept is essential to grasp the subtleties of comparison between climate simulations and proxy-based climate reconstructions. The second driver consists of *external climate forcings*, such as changes in Earth's orbital parameters, solar output, volcanic aerosols, and greenhouse gases in the atmosphere including carbon dioxide and methane.[1] In this case, external drivers are those constructed and implemented by the user but not modified by the computer code itself. For instance, concentrations of atmospheric carbon dioxide, as an external driver, are not modified by the model, whereas water vapor, also a greenhouse gas, is interactively simulated by the climate model according to balance of evaporation, precipitation, and advection of air masses. Once these drivers are provided, the computer code repeatedly leapfrogs forward by the specified time interval, simulating the evolution of the state of the atmosphere and ocean and other components of the Earth system at each successive interval.

Climate variability, whether real or modeled, is composed of the combination of *external variability* and *internal variability*. External variability arises from external drivers, whether natural variations such as solar activity, or anthropogenic forcings such as greenhouse gas emissions from fossil fuels. If external drivers remained constant over time, then external climate variability would be zero. Nevertheless, the climate would not remain constant: every year, every decade, every century would be different from the previous one, because internal variability would still operate. For instance, the interaction between atmosphere and oceans in the tropics gives rise to interannual and decadal variations such as ENSO (the El Niño–Southern Oscillation), even in the absence of changes in solar irradiance or in greenhouse gas concentrations (see Chap. 2).

External variability is potentially predictable since it is linked to external forcings, whose input is prescribed independently of the response from the climate system. All simulations driven by the same external forcings should theoretically produce the same external climate variability. By contrast, internal climate variability remains unpredictable beyond a certain time range, much like local weather. Even small changes in initial conditions will produce large divergences in trends among simulations. Those simulations may look the same in a statistical sense—that is, displaying the same mean, standard deviations, and covariations in results—but they will give different time trajectories.

This point is critical when comparing simulations to proxy-based climate reconstructions. We cannot know the precise initial conditions of any historical simulation—for example, the position and velocity of every molecule of water and air during the first second of the year 850 CE. Therefore, a simulated record may show the same statistical properties as the historical record, such as mean value, amplitude of variability, and so forth, but the precise evolution in time will be different. A simulation could be programed with the same external variability, but the timing of ENSO events and other climatic phenomena would still turn out different in the simulation than in the historical record. To date, there is no established method to lock in a paleoclimate simulation so that it also reproduces the timing of observed internal climate variability, as meteorologists do when predicting the weather on a given day or hour.

As a general rule, the contribution of internal variability is larger at small spatial and short temporal scales, whereas externally driven variability becomes more relevant over longer time periods and larger areas. At smaller and shorter scales—for instance, a few tens of kilometers or a few weeks—the role of weather *noise* plays a greater role than slowly changing external global drivers such as total solar irradiance. This is important to bear in mind because proxy and documentary climate usually record local climate conditions, whereas model grid cells typically represent mean conditions over large areas.

Internal climate variability also depends on the basic characteristics of different regional climates. For instance, tropical regions share a more or less homogeneous temperature regime and an annual cycle of precipitation. Studies investigating the impact of long-term solar changes on temperatures tend to find the largest signals over tropical areas because lower internal variability leads to a higher signal-to-noise ratio when measuring the effects of external forcings. In extratropical regions, by contrast, atmospheric circulation patterns and recurrent sequences of mid-latitude cyclones play a larger role in shaping variability. As stated above, the amplitude of atmospheric internal variability should diminish at longer multidecadal timescales, but it is not yet clear at which timescales external forcing begins to dominate climate variability.

Since models cannot predict the actual state of the climate at a given point in time based on initial conditions, these climate states have to be prescribed at random within a certain plausibility range. This range of choices is, however, virtually infinite. In theory, with unlimited computer resources, many simulations could be run with different initial conditions, producing a range of possible trajectories that would encompass the range of uncertainty. But in practice, this is impossible. Instead, the *ensemble size* is usually limited to a few simulations. Once the initial conditions are prescribed, the climate model is also provided with the values of the external forcings for each year (solar irradiance, atmospheric concentrations of carbon dioxide and methane, volcanic aerosols, land-use changes, etc.) through the period covered by the simulation.[2] The climate model then generates one full history (among the infinite number that would be compatible with the external forcing) of the three-dimensional "weather" at a given time resolution (typically thirty minutes) over several centuries or millennia. This process may take several months even on the best current supercomputers used in climate modeling.

13.3 Examples and Regional Simulations

Figure 13.1 presents an example of an ensemble of just three simulations of climate in the period 850–1850 CE, using the same global climate model MPI-ESM-P and driven by the same external forcings. This period was selected by the Climate Model Intercomparison Project (CMIP) and denoted as past1000. About ten other climate models have conducted past1000 simulations that are publicly available.[3] The three time series in Fig. 13.1 represent three possible trajectories of simulated winter (December–February) near-surface air temperature over Central Europe. Results are presented in thirty-year moving averages in order to better display the slowly changing evolution of mean temperature. This figure illustrates that even at these timescales (thirty years), the portion of internal regional climate variability contained in these records remains very large, and accordingly, the influence of external forcing is small. The agreement among these three records has been achieved under ideal conditions (i.e., using the same model and same estimated external forcing), and so this agreement is the best that we can expect when comparing simulations and reconstructions. Reconstructed records have been obtained with a different "model" (that is, nature itself), and real external forcings may have deviated from those in simulations.

For instance, these climate simulations do not always demonstrate the effects of known historical forcings, even large volcanic eruptions such as Samalas in 1257 and Tambora in 1815 (see Chap. 35), or else they may reflect one such event but not another. This suggests that internal climate variability is so strong that it can potentially mask the effects of even these strong eruptions. Whether or not it does so in any particular simulation remains a matter of chance and cannot be ascertained beforehand. It is plausible to believe that this also occurs in the real world—in other words, that large-scale internal climate variability often masks the pronounced effects of short-term external forcings such as major tropical eruptions.

However, certain characteristics of European climate appear in all three simulations described above, and are thus very likely caused by the external forcings prescribed in all three. Therefore, these characteristics should show up in proxy- and documentary-based reconstructions, too. The temperature drops

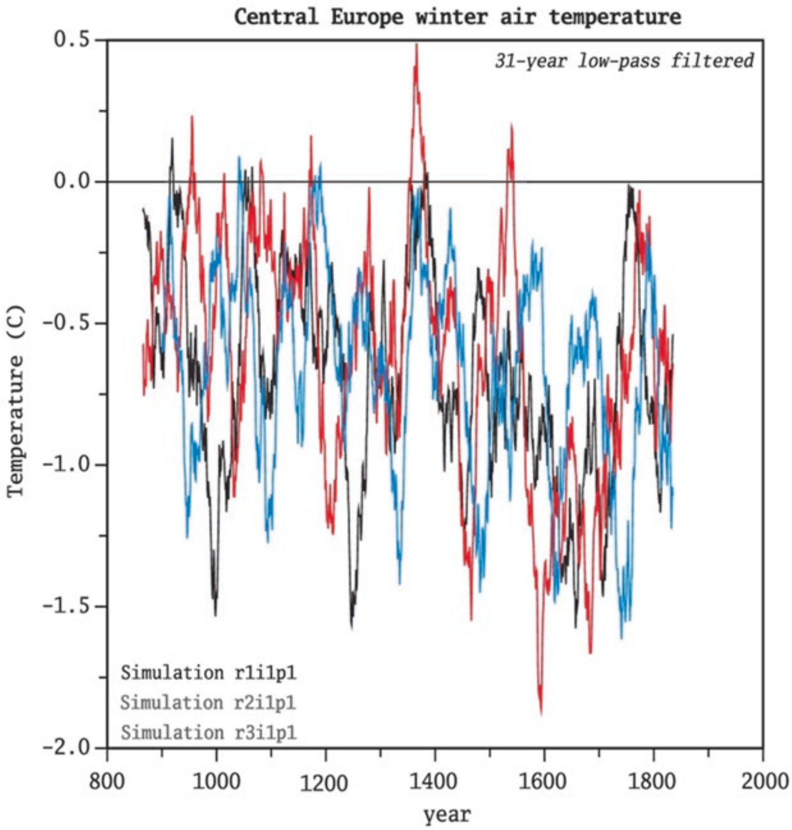

Fig. 13.1 Time series of winter (December-to-February) air temperature averaged over Central Europe (0°E–20°E; 45°N–55°N) as simulated in three simulations with the global climate model MPI-ESM-P, started with different initial conditions on January 1, 850 CE

systematically from the Medieval Climate Anomaly (MCA) (see Chap. 22) to the Little Ice Age (LIA) (see Chap. 23), although each particular simulation produces large multidecadal temperature variations around this overall cooling trend. All three simulations also produce a recovery of temperatures from around 1700 CE onward. At shorter timescales, a relatively warm period around 1400 CE also appears in all three simulations, pointing again toward the possible role of external climate forcing. However, based on the appearance of the simulated series, the reader will acknowledge that this apparent agreement may be due to chance, and thus such an interpretation must be adopted with care.

We can now focus on one of the coldest periods within the past millennium in Europe, as reflected in many proxy records and historical evidence: the Late Maunder Minimum (LMM) of 1675–1715 CE. Figure 13.2 depicts the European winter temperature differences between the LMM and the MCA in

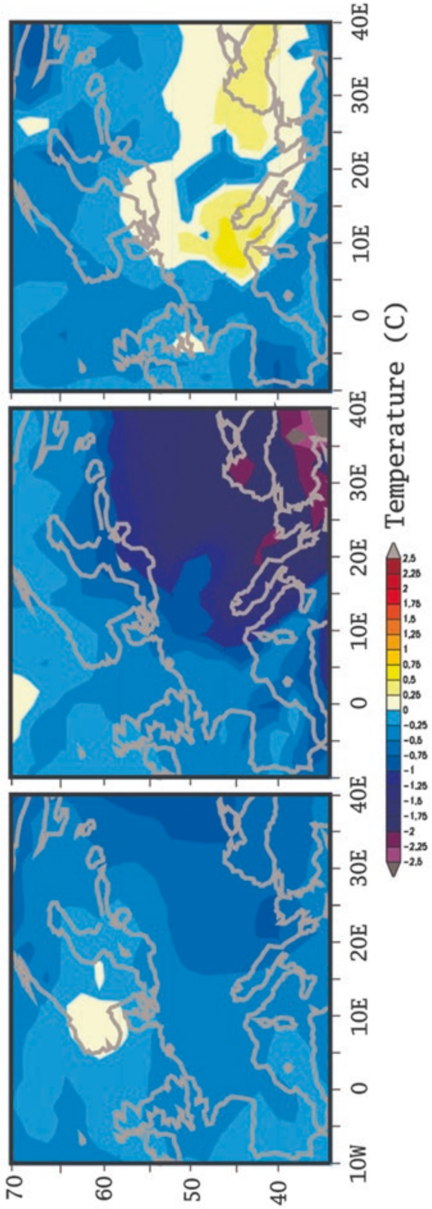

Fig. 13.2 Maps of the winter air temperature differences between the Late Maunder Minimum (1680–1710 CE) and the Medieval Climate Anomaly (1000–1200 CE) over Europe, as simulated in three global simulations with the climate model MPI-ESM-P, started with different initial conditions on January 1, 850 CE

the three simulations using model MPI-ESM-P. All three simulations produce generally colder temperatures during the LMM than during the MCA. However, the spatial structure of the temperature drop differs considerably among the simulations. The two simulations r1i1p1 and r2i1p1 simulate a stronger temperature drop in southeastern Europe than in Western Europe, with the largest temperature contrast found in r2i1p1. However, in the third simulation (r3i1p1), the cooling is more moderate and spatially more homogeneous. In this case, simulated LMM temperatures in southeastern Europe remain very similar to those of the MCA, while temperatures over the Swiss Alps actually increase slightly.

The grid cells of the model MPI-ESM are about 1.8 degrees longitude by latitude. Clearly, this resolution cannot properly represent regions with rapidly changing topography, such as the alpine region or complex coastlines. Simulations based on *regional climate models*, with higher spatial resolution for specific regions of the Earth, can help correct or at least ameliorate this problem. These models, using grid cells as small as 10 × 10 km, can better capture regional characteristics. Since regional simulations cannot cover the whole world, global climate simulations provide the data at their borders. Regional models are thus a tool to zoom in on specific regions of interest. Unfortunately, these simulations remain costly in terms of computer resources. Although they provide better regional details, their application remains too expensive to create a large ensemble of regional simulations. In time, ensembles of regional simulations could solve important outstanding questions in climatology, such as the magnitude of regional multidecadal variability for climate variables including precipitation and soil moisture.

13.4 Conclusion

Climate simulations and climate reconstructions provide two complementary tools to study past climates. Despite efforts by both climate modelers and historical climatologists, merging insights and information from these two tools remains a daunting endeavor hindered by technical hurdles.[4] Despite advances in computer technology and Earth System Models, long-term climate variability presents unresolved questions, particularly concerning the interplay between internally generated and externally forced variations. It remains of utmost importance to investigate the full set of forcing agents and evaluate their spatio-temporal variations in the context of reconstructed climate variations over the last millennium and beyond.

Notes

1. Some modern climate models include a model of the Earth's carbon cycle. In those models, the external forcing is the anthropogenic *carbon emissions*, whereas the atmospheric concentrations of carbon dioxide are interactively calculated by the model.

2. Schmidt et al., 2011.
3. Bothe et al., 2013. The external forcing prescribed in the CMIP simulations with different models is similar but not the same in all of them, since each modeling group chose different reconstructions of, e.g., solar irradiance or volcanic aerosols.
4. Brönnimann et al., 2013.

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CHAPTER 14

The Denial of Global Warming

Naomi Oreskes, Erik Conway, David J. Karoly, Joelle Gergis, Urs Neu, and Christian Pfister

14.1 Introduction

No book about the science of climate reconstruction would be complete if it did not also address the organized efforts to reject and obfuscate that science. This chapter begins with passages adapted from Naomi Oreskes and Erik M. Conway, *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming* (2010), which were kindly shared by the authors and publisher. This path-breaking work uncovered links among the tactics and agents involved in organized efforts to cast doubt and disrepute on research and researchers who have demonstrated how certain profitable enterprises have negative health and environmental externalities. Here, we have extended Oreskes and Conway's account with a discussion of global warming denial in Europe and in Australia.

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14.2 The USA (adapted from *Merchants of Doubt*)

In 2004, the US magazine *Discover* ran an article on the top science stories of the year, one of which was the emergence of a scientific consensus over the reality of global warming. *National Geographic* similarly declared 2004 the year that global warming "got respect."[1]

Many scientists felt that respect was overdue: as early as 1995, the leading international organization on climate, the Intergovernmental Panel on Climate Change (IPCC), had concluded that human activities were affecting global climate. By 2001, IPCC's Third Assessment Report stated that the evidence was strong and getting stronger, and in 2007, the Fourth Assessment called global warming "unequivocal."[2] Major scientific organizations and prominent scientists around the globe had repeatedly ratified the IPCC conclusion.[3] By the late 2000s, all but a tiny handful of climate scientists were convinced that Earth's climate was heating up, and that human activities were the dominant cause.

Yet many Americans remained skeptical. A public opinion poll reported in *Time* magazine in 2006 found that only just over half (56%) of Americans thought that average global temperatures had risen—despite the fact that virtually all climate scientists thought so.[4] An ABC News poll that year reported that 85% of Americans believed that global warming was occurring, but more than half did not think that the science was settled. Of Americans, 64% perceived "a lot of disagreement among scientists."[5]

The doubts and confusion of the American people were particularly peculiar when put into historical perspective, for scientific research on carbon dioxide and climate has been going on for 150 years. In the mid-nineteenth century, Irish experimentalist John Tyndall first established that carbon dioxide is a greenhouse gas—meaning that it traps heat and keeps it from escaping to outer space. He understood this as a fact about our planet, with no particular social or political implications. This changed in the early twentieth century, when Swedish geochemist Svante Arrhenius realized that carbon dioxide released to the atmosphere by burning fossil fuels could alter Earth's climate, and British engineer Guy Callendar compiled the first empirical evidence that the "greenhouse effect" might already be detectable. In the 1960s, American scientists started to warn their political leaders that this could be a real problem, and at least some of them—including Lyndon Johnson—heard the message. Yet they failed to act on it.[6]

One reason for the American confusion about global warming was clear: from the time that a scientific consensus emerged, a campaign to undermine that consensus and confuse the American people about it emerged as well.[7] And as the body of scientific evidence grew, the campaign to discredit and undermine it grew too.

14.3 The George C. Marshall Institute

In 1984, physicist William Nierenberg retired as director of the Scripps Institution of Oceanography and joined the Board of Directors of a newly formed think-tank in Washington, DC, the George C. Marshall Institute.

Astrophysicist Robert Jastrow had established the Institute to defend President Reagan's Strategic Defense Initiative (SDI) against critique by leading American scientists, and recruited physicist Frederick Seitz, a former President of the US National Academy of Sciences, to be its founding director. But by 1989, the justification for SDI—containing communism—had collapsed. The Berlin Wall had come down, the Soviet Union was disintegrating, and the end of the Cold War was in sight. The Institute might have disbanded—its raison d'être disappeared—but instead, the old Cold Warriors decided to fight on. The new enemy? Environmental "alarmists." In 1989—the very year the Berlin Wall fell—the Marshall Institute published its first report attacking climate science.

Their initial strategy was not to deny the fact of global warming but to blame it on the sun. They circulated an unpublished "white paper," generated by Jastrow, Seitz, and Nierenberg, entitled "Global Warming: What Does the Science Tell Us?," which claimed that the available evidence pointed to the sun as the cause of the observed rise in global temperatures.[8] The Institute's Washington office staff contacted the White House to request the opportunity to present it. Nierenberg gave the briefing to members of the Office of Cabinet Affairs, the Office of Policy Development, the Council of Economic Advisers, and the Office of Management and Budget.[9]

The briefing stopped the positive momentum that had been building in the Bush administration to act on climate change. "I was impressed with the report," said one member of the cabinet affairs office. "Everyone has read it. Everyone takes it seriously." Another ruminated, "It is well worth listening to. They are eminent scientists. I was impressed."[10] White House Chief of Staff John Sununu—a nuclear engineer by training—was particularly taken. Stanford University's Stephen Schneider lamented, "Sununu is holding the report up like a cross to a vampire, fending off greenhouse warming."[11]

The following year, the IPCC published its first assessment of the state of climate science. It reiterated the result that was by now familiar to anyone who had been following the issue: unrestricted fossil fuel use would produce a "rate of increase of global mean temperature during the next century of about 0.3 °C per decade; this is greater than that seen over the past 10,000 years."[12] Global warming from greenhouse gases would produce changes unlike what humans had ever seen before.

The IPCC explicitly rejected the Marshall Institute argument. The upper limits on solar variability, they explained, are "small compared with greenhouse forcing and even if such a change occurred over the next few decades, it would be swamped by the enhanced greenhouse effect."[13] But the IPCC's refutation did not alter the Marshall scientists' views. In 1991, they republished their report in a longer version, and in 1992 Bill Nierenberg took it "on the road" to the World Petroleum Congress in Buenos Aires, where he launched a full frontal attack on climate science. Nierenberg insisted that global temperatures would increase at most by 1 °C by the end of the twenty-first century, based on a straight linear projection of twentieth-century warming. Bert Bolin, a founder of the IPCC, confronted him directly, pointing out that greenhouse gas emissions were increasing *exponentially*, not linearly.

Add to this the time lag induced by the oceans—which meteorologist Jule Charney and others had warned about a decade earlier—and warming would accelerate over time.

In his memoir, Bolin called Nierenberg's conclusion "simply wrong."[14] A less polite man would have said something else. If Nierenberg were a journalist, one might suppose he was just confused. But Nierenberg was no journalist. He had been a brilliant scientist, and a very strategic man: one long-time associate at Scripps once said that she never knew a man who was more careful in choosing what he worked on and how he worked on it.[15]

Meanwhile, the CATO Institute—a libertarian think-tank in Washington, DC—began to circulate parts of the original Marshall Institute white paper.[16] In a February 1991 letter to the vice president of the American Petroleum Institute, Jastrow boasted about the impact they were having. "It is generally considered in the scientific community that the Marshall report was responsible for the Administration's opposition to carbon taxes and restrictions on fossil fuel consumption." Quoting *New Scientist* magazine, he described the report as "the controlling influence in the White House."[17]

At the same time, leaders of governments and NGOs were finalizing plans to convene in Rio de Janeiro for the UN Earth Summit. In June 1992, 108 heads of state, 2400 representatives of non-governmental organizations and more than 10,000 on-site journalists began to converge in the Brazilian metropole, yet it was unclear whether the US President would attend. At the last minute, George H.W. Bush flew to Rio de Janeiro to sign the United Nations Framework Convention on Climate Change (UNFCCC), which committed its signatories to preventing "dangerous anthropogenic interference with the climate system."[18] President Bush then pledged to translate the written document into "concrete action to protect the planet."[19] By March 1994, 192 countries had signed on to the Framework Convention, and it came into force.

Like the Vienna Convention on Ozone-depleting Chemicals, the Framework Convention on Climate Change had no real teeth: it set no binding limits on emissions. It was an agreement in principle not in practice. Real limits would be determined later, in a protocol that would be eventually signed in Kyoto, Japan (just as the Vienna Convention was backed up by the Montreal Protocol). With the threat that real limitations would soon be enforced, the merchants of doubt redoubled their efforts.

14.4 Discrediting Ben Santer, Derailing Rio

Despite the best efforts of Jastrow, Seitz, and Nierenberg to prevent it, the scientific debate over the detection of global warming was reaching closure. A key element was something called "detection and attribution studies." These studies work by considering how warming caused by greenhouse gases might be different from warming caused by the sun or other natural forces. These studies spoke directly to the issue of *causality*: to the social question of whether or not humans were to blame, and to the regulatory question of whether or not greenhouse gases need to be controlled. As these studies began to appear in the peer-reviewed literature, the contrarians began to challenge them.

The lead author of the IPCC chapter on detection and attribution was a young scientist named Benjamin Santer of the Program for Climate Model Diagnosis and Inter-comparison at the Lawrence Livermore National Laboratory. Santer had the good fortune to arrive at the lab not only in the middle of one of the first major model intercomparison projects but also at a time when Livermore colleagues Karl Taylor and Joyce Penner were performing an innovative set of climate model experiments that considered not only greenhouses gases, which cause warming, but also sulfate aerosol particles, which generally cause cooling. The Taylor and Penner experiments clearly showed that human influences on climate were complex: changes in carbon dioxide and sulfate aerosols had distinctly different climate fingerprints.

Fingerprinting proved to be a powerful tool for studying cause and effect relationships. Up to that point, much of the scientific argument about the causes of climate change had gone like this: if greenhouse gases increased, then you would expect temperatures to increase, too. They had. So, the prediction had come true. Textbook scientific method. The problem with the textbook method, however, is that it is logically fallacious. Just because a prediction comes true does not mean the hypothesis that generated it is correct. Other causes could produce the same effect. To prove that greenhouse gases had caused climate change, you would have to find some aspect of it that was *different* than if the cause were the sun or volcanoes. You needed a pattern that was unique.

V. Ramanathan, a prominent atmospheric scientist, had suggested one: the vertical structure of temperature.[20] If warming were caused by the sun, then you would expect the whole atmosphere to warm up. If warming were caused by greenhouse gases, however, the effect on the atmosphere would be different. Greenhouse gases trap heat in the lower atmosphere (the troposphere) so it warms up, while the reduced heat flow into the upper atmosphere causes it (the stratosphere) to *cool*. Collaborating with colleagues at the Max Planck Institute and six other research institutions around the world, Santer started to look at the vertical variation of temperature.[21] Before they had finished the work, Santer was asked to become the convening lead author for the Detection and Attribution chapter of the second IPCC assessment. Soon after, Santer submitted his results to *Nature*. The data clearly showed that the troposphere was warming but the stratosphere was not. It was the fingerprint of human-made climate change.

Santer presented this work to his IPCC colleagues in the summer of 1994.[22] The presentation electrified the audience—it was "mind-boggling," in the words of one of those present.[23] And so, the final report of the IPCC would conclude: "the balance of evidence suggests a discernible human impact" on the global climate.[24] "In an important shift of scientific judgment, experts advising the world's governments on climate change are saying for the first time that human activity is a likely cause of the warming of the global atmosphere," the *New York Times* declared on its front page.[25] This, of course, was not quite right. Scientists had been saying for a long time that human activity was a *likely* cause of warming. They were now saying that it was *demonstrated*. The *New York Times* did not get it. But the skeptics did, and they went on the attack.

The Republican majority in the US Congress launched the first strike. In a set of hearings in November, they questioned the scientific basis for concern. The star witness was another well-known contrarian, Patrick J. Michaels, who had completed his Ph.D. at the University of Wisconsin, Madison, in 1979, building models relating climate change to crop yields. In 1980, he was appointed State Climatologist of Virginia by Republican governor John Dalton (although, many years later, Michaels was forced to forgo that title when it was shown that Dalton had acted without legal authority).[26] In the 1980s, Michaels had published scientific work on the climate sensitivity of various crops and ecosystems, but by the early 1990s he was mainly known not for mainstream science but his efforts to discredit it.[27] Among other things, Michaels had previously joined with physicist Fred Singer, a colleague of Jastrow, Seitz, and Nierenberg, in publicly attacking the mainstream scientific view of ozone depletion.[28] He also produced a quarterly newsletter called the *World Climate Review*, funded at least in part by fossil fuel interests, which he now used as a platform to attack mainstream climate science. The report was circulated free to members of the Society for Environmental Journalism, ensuring that its claims got wide attention.[29] Michaels was also working as a consultant to the coal industry to promote the idea that burning fossil fuels was good, because it would lead to higher crop yields as increased atmospheric carbon dioxide led to increased photosynthesis and therefore increased agricultural productivity.[30] Republicans seeking to block action on climate turned to Michaels.

It was not exactly news by late 1995 that the Republican Congressional leadership opposed environmental protection: there had been discussion that year of repealing the Clean Water Act, one of the cornerstones of US environmental protection. So, the hearing was designed to buttress the Republican majority's claim that no action on climate was needed. Writing to Seitz after the hearing, Nierenberg said, "I doubt that Congress will do anything foolish. I can also tell you that at least one high-level corporate advisor is advising boards that the issue is politically dead. Happy holiday."[31]

The next step was an assault on the IPCC. In a letter to the journal *Science* on February 2, 1996, four months before formal release of the IPCC report, Singer claimed that the Summary for Policymakers ignored satellite data that showed "no warming at all, but actually a slight cooling." The IPCC had violated one of its "major rules" by including the fingerprinting work, because "the research had not yet, to my knowledge, appeared in the peer-reviewed literature." The panel had also ignored an "authoritative US government report" that had found the twenty-first-century warming might be as little as

0.5 °C, making global warming a non-problem. (Singer did not cite the report.) Finally, he concluded, "The mystery is why some insist in making it into a problem, a crisis, or a catastrophe—'the greatest global challenge facing mankind.'"[32]

Santer's co-author Tom Wigley responded to Singer's criticisms in March. Rejecting the "no warming" claim entirely, he simply stated: "[T]his is not supported by the data; the trend from 1946 to 1995 is 0.3°C. As shown in chapter 8 of the full report (figure 8.4) there is no inconsistency between the observed temperature record and model simulations." There were some differences between measurements made with satellites and measurements made with "radiosondes"—instruments on balloons, with radios attached to transmit the results—but climate scientists did not expect them to perfectly track each other; the reasons were explained in chapters three and eight of the IPCC work. "There are good physical reasons to expect differences between these two climate indicators," Wigley noted, because they were in different places measuring somewhat different things.

Wigley also refuted the claim that the pattern recognition studies violated the IPCC's rules. The IPCC allowed use of material from outside the peer-reviewed journals as long as it was accessible to reviewers. This was to ensure the report was "up to date" when published. Moreover, the specific work Singer referred to, "on the increasing correlation between the expected greenhouse-aerosol pattern and observed temperature changes, *is* in the peer-reviewed literature."[33] Singer was either dishonest or misinformed.

Moreover, Singer had misrepresented what the IPCC had said. "Singer refers to the [Summary for Policymakers] as saying that global warming is 'the greatest global challenge facing mankind.'" But the IPCC had *not* said that, Wigley and his co-authors explained: "We do not know the origin of this statement—it does not appear in any of the IPCC documents … [I]t is the sort of extreme statement that most involved with the IPCC would not support."[34] In short, Singer was putting words into other people's mouths, and then using those words to attempt to discredit them.

The IPCC had contracted with Cambridge University Press to publish the Working Group 1 report, scheduled to appear in the USA in June 1996. In May, Santer and Wigley presented their chapter at a briefing in the Rayburn House Office Building on Capitol Hill, organized by the American Meteorological Society (AMS) and the US Global Change Research Program. The scientists were now challenged by William O'Keefe of the Global Climate Coalition—a fossil fuel industry trade association—and by Donald Pearlman, a fossil fuel industry lobbyist and registered "foreign agent" of several oil-producing nations.[35] O'Keefe and Pearlman accused them of "secretly altering the IPCC report, suppressing dissent by other scientists, and eliminating references to scientific uncertainties."[36]

"Who made these changes to the chapter? Who authorized these changes? Why were they made?" Pearlman demanded to know. "Pearlman got up and in my face, turned beet red and [started] screaming at me," Santer recalls.

Anthony Socci, an official at the AMS, "finally separated us, but Pearlman kept following me around."[37] Santer explained that he had been *required* by IPCC procedures to make the changes in response to the government comments and author review, and the chapter had never been out of his control. But the truth did not satisfy the opposition.[38]

O'Keefe's Global Climate Coalition meanwhile had circulated a report entitled "The IPCC: Institutionalized Scientific Cleansing" to reporters, members of Congress, and some scientists. By chance, anthropologist Myanna Lahsen interviewed Nierenberg about his "skepticism" about global warming two weeks before the Working Group 1 report was published, and found that he had a copy of the Coalition report. He had evidently accepted its veracity, even though there was no way to compare its claims against the real chapter eight (since the latter had not yet been released). He quoted its claims to Lahsen, telling her that the revisions had "just altered the whole meaning of the document. Without permission of the authors." Moreover, he claimed, "Anything that would imply the current status of knowledge is so poor that you can't do anything is struck out."[39] That was preposterous: Santer's panel had included six pages of discussion of uncertainty in the final text.

Then Seitz took the attack to the national media. In a letter published in the *Wall Street Journal* on June 12, 1996, he accused Santer of fraud. "In my more than 60 years as a member of the American scientific community, including my services as president of the National Academy of Sciences and the American Physical Society, I have never witnessed a more disturbing corruption of the peer-review process than the events that led to this IPCC report." Seitz repeated the Global Climate Coalition's charges that unauthorized changes to the report had been made after its acceptance in Madrid. "Few of these changes were merely cosmetic; nearly all worked to remove hints of the skepticism with which many scientists regard claims that human activities are having a major impact on climate in general and on global warming in particular," Seitz claimed. If the IPCC could not follow its own procedures, he concluded, it should be abandoned and governments should look for "more reliable sources of advice to governments on this important question."[40]

Presumably, he meant the Marshall Institute.

Santer immediately drafted a letter to the *Journal*, which forty of the other IPCC lead authors signed. At first the *Journal* would not publish it. After three attempts, Santer finally got a reply from the *Journal*'s letters editor; the letter was finally published on June 25. Santer's letter had been heavily edited, and the names of the forty co-signers deleted.

What the *Wall Street Journal* allowed Santer to explain was that he had simply been *required* to make the changes "in response to written review comments received in October and November 1995 from governments, individual scientists, and non-government organizations during plenary sessions of the Madrid meeting." This was peer review—the very process that Seitz, as a research scientist, had been a part of all his life—only it was even more extensive and inclusive than ordinary peer review, since it included comments and queries from governments and NGOs as well as scientific experts. But the changes did not affect the "bottom line conclusion." Santer also pointed out that Seitz was not a climate scientist, had not been involved in creating the IPCC report, had not attended the meeting where the proposed changes were discussed, and had not seen the hundreds of review comments to which Santer had to respond. In other words, his claims were hearsay, at best.[41]

Bert Bolin and Sir John Houghton also responded with a long letter defending Santer and the IPCC process. "Frederick Seitz's article is completely without foundation," they replied unequivocally. "It makes serious allegations about the Intergovernmental Panel on Climate Change and about the scientists who have contributed to its work which have no basis in fact. Mr. Seitz does not state the source of his material, and we note for the record that he did not check his facts either with the IPCC officers or with any of the scientists involved."[42]

Well, that is what they had *wanted* it to say, but the *Journal* edited that statement out, too, along with three more paragraphs explaining the drafting process in some detail. The *Journal* allowed them to say only that in

> accordance with IPCC Procedures, the changes to the draft of Chapter 8 were under the full scientific control of its convening Lead Author, Benjamin Santer. No one could have been more thorough and honest in undertaking that task. As the responsible officers of the IPCC, we are completely satisfied that the changes incorporated in the revised version were made with the sole purpose of producing the best possible and most clearly explained assessment of the science and were not in any way motivated by any political or other considerations.[43]

We know exactly how the *Journal* edited the letters because Seitz's attack and the *Journal*'s weakening of the response so offended the officials of the AMS and of the University Corporation for Atmospheric Research (UCAR) that their boards agreed to publish an "Open Letter to Ben Santer" in the *Bulletin of the American Meteorological Society*. The AMS republished the letters in their entirety, showing how the *Journal* had edited them. They voiced their support of Santer and the effort it had taken all the authors to put the report together, and categorically rejected Seitz's attack as having "no place in the scientific debate about issues related to global change."[44] They began, slowly, to realize what they were up against.

> [There] "appear[ed] to be a concerted and systematic effort by some individuals to undermine and discredit the scientific process that has led many scientists working on understanding climate to conclude that there is a very real possibility that humans are modifying Earth's climate on a global scale. Rather than carrying out a legitimate scientific debate through the peer-reviewed literature, they are waging in the public media a vocal campaign against scientific results with which they disagree."[45]

But the attack was far from over. On July 11, the *Wall Street Journal* published three more letters reprising the charges, one from Fred Seitz, one from Fred Singer, and one from retired physicist Hugh Elsaesser. Singer and Seitz simply repeated the charges they had already made; Singer also took the opportunity to turn the IPCC's caution against it. The IPCC had bent over backward to be judicious, arguing at length to choose just the right, reasonable, adjective—"discernible." Singer dismissed the IPCC conclusion as "feeble," at the same time insisting paradoxically that it was being used to frighten politicians into believing that a climate catastrophe is about to happen.[46]

Santer and Bolin responded a second time to the attacks in letters that the *Journal* published July 23, prompting another attack by Singer.[47] This time, the *Journal* would not publish it; Singer circulated it by email instead. Santer responded by email, too. Singer claimed that there was no "evidence for a current warming trend." According to Singer, chapter eight had been based primarily on Santer's "unpublished work," and the panel should have included as a lead author "Professor Patrick J. Michaels, who, at the time, had published the only refereed paper on the subject" of climate fingerprinting. And he repeated the charge of "scientific cleansing." Santer rejected all of Singer's charges. Chapter eight was based on more than *130* references, not just Santer's two papers. The claim that Michaels had published the only "refereed paper on the subject" of pattern-based recognition before mid-1995 was incorrect: Hasselmann's theoretical paper on the subject had been published in 1979, and Tim Barnett and Mike Schlesinger had published a "real-world" fingerprint study as early as 1987. Michaels *had* been invited to be a contributing author to chapter eight but had refused. Finally, Santer noted, chapter eight contained several paragraphs discussing Michaels' paper, but when Wigley had approached Michaels for comments, "Prof. Michaels did not respond."[48]

Singer's claims were not only false but had been *shown* to be false. Still, he was not finished repeating them. Joined by Bill Nierenberg, Patrick Michaels, and a new ally—MIT meteorologist Richard Lindzen—Singer then attacked the AMS/UCAR Open Letter. After repeating the refuted charges of "substantial and substantive" deletions of uncertainty, Singer cast the deletions as a conspiracy that Santer was now trying to cover up. "Santer … has not been forthcoming in revealing who instructed him to make such revisions and who approved them after they were made. He has, however, told others privately that he was asked [prevailed upon?] to do so by IPCC co-chairman John Houghton." Singer continued, "You may not have seen the 15 November [1995] letter from the State Department instructing Dr. Houghton to 'prevail upon' chapter authors 'to modify their texts in an appropriate manner following discussion in Madrid.'" To Singer and his collaborators, this was evidence of political meddling in the chapter. His presentation of it as some sort of clandestine conspiracy was also absurd. By the time this letter was published in January 1997, Bolin and Houghton had already identified themselves months before as the source of Santer's instructions to revise the chapter and explained that it was a required procedure.

One might dismiss this whole story as infighting within the scientific community, except that the Marshall Institute claims were taken seriously in the Bush White House, and their claims were published in the *Wall Street Journal*, where they would have been read by millions of educated people, and influenced American public opinion. Members of Congress also took them seriously. Proposing a bill to reduce climate research funding by more than a third in 1995, Congressman Dana Rohrabacher called it "trendy science that is propped up by liberal/left politics rather than good science."[49] And in 1997, the US Senate voted 95–0 to reject the Kyoto Protocol to the United Nations Framework Convention on Climate Change.[50] Scientifically, global warming was an established fact. Politically, in the USA, global warming was dead.

14.5 How Disinformation Took Hold

Over the next twenty years, disinformation about climate science would be spread far and wide. In July 2003, Senator James Inhofe called global warming "the greatest hoax ever perpetrated on the American people."[51] In 2007, vice president Richard Cheney commented in a television interview, "Where there does not appear to be a consensus, where it begins to break down, is the extent to which that's part of a normal cycle versus the extent to which it's caused by man, greenhouse gases, et cetera," exactly the question Santer had answered a decade before.[52] And throughout the late 1990s and through the 2000s, polls consistently showed that a very large proportion of the American public—including more than half of all Republicans—thought that scientists were still arguing about the reality of human-made climate change.

How did such a small group come to have such a powerful voice?

Seitz, Jastrow, Nierenberg, and Singer had access to power—all the way to the White House—by virtue of their positions as physicists who had won the Cold War. They used this power to support their political agenda, even though it meant attacking science and their fellow scientists, and evidently believed that their larger end justified their means. Perhaps this, too, was part of their professional legacy. During the Manhattan Project and throughout the Cold War, for security reasons many scientists had to hide the true nature of their work. All weapons projects were secret, but so were many other projects that deal with rocketry, missile launching and targeting, navigation, underwater acoustics, marine geology, bathymetry, seismology, weather modification; the list goes on and on.[53] These secret projects frequently had "cover stories" that scientists could share with colleagues, friends, and families, and sometimes the cover stories were true in part. But they were not the whole truth, and sometimes they were not true at all. After the Cold War, most scientists were relieved to be freed of the burdens of secrecy and misrepresentation, but Seitz, Singer, and Nierenberg continued to misrepresent science if it served their ends. Perhaps after four decades of telling lies to serve a greater good, they had become used to it. After all, during the Cold War, it was necessary; perhaps they similarly justified it as necessary now.

But the story of American rejection of climate science goes far beyond the efforts of a small group of anti-environmentalists. During the early 1980s, anti-environmentalism had also taken root in a network of conservative and libertarian think-tanks in Washington. These think-tanks—which included the CATO Institute, the American Enterprise Institute, the Heritage Foundation, the Competitive Enterprise Institute, and, of course, the Marshall Institute—variously promoted business interests and "free market" economic policies, and the rollback of environmental, health, safety, and labor protections. They were supported by donations from businessmen, corporations, and like-minded conservative foundations.[54]

Much of the funding for these groups came from the fossil fuel industry. One of the most important of these funders was Exxon Mobil. In 2006, the UK Royal Society identified thirty-nine different organizations promoting disinformation about climate science that had received funds from the corporate giant, and wrote a letter asking them to cease and desist such funding.[55] In 2015, the non-profit news group Inside Climate News documented in fine detail that even while Exxon Mobil was casting doubt in public about the reliability of climate science, in private they were well aware of its robustness. Indeed, the reporters found that during the 1970s and into the 1980s, Exxon Mobil had funded some early but important climate change research, cooperating with scientists at the US Department of Energy and leading universities.[56] But as potential regulation of fossil fuels began to be discussed, the company shifted its emphasis toward disinformation and denial. It joined the Global Climate Coalition, and became a major donor to the think-tank network that the Royal Society would later identify, spending more than $22 million between 1998 and 2004.[57] Recipients of Exxon's largess included the Competitive Enterprise Institute, the American Enterprise Institute, and the Heritage Foundation: all economically libertarian in outlook, all promoting environmental skepticism.

This network of right-wing foundations, the corporations that fund them, and the journalists who echo their claims throughout the US media landscape created an enormous problem for US science. One academic study found that of the fifty-six "environmentally skeptical" books published in the 1990s, 92% were linked to these right-wing foundations (only thirteen were published in the 1980s, and 100% were linked to the foundations).[58] Science and scientists faced an ongoing rewriting of history that branded them as public enemies: communists, conspirators, even mass murderers.

There are many ironies in this story, but the most profound is the way in which self-appointed defenders of liberty adopted the tactics of totalitarianism. One of the great heroes of the anti-communist political right—and of the clearest, most reasoned voices against the risks of oppressive government, in general—is George Orwell, whose famous novel *1984* portrayed a government that manufactured fake histories to support its political program.[59] Orwell coined the term "memory hole" to denote a system that destroyed inconvenient facts, and "Newspeak" for a language designed to constrain thought within politically acceptable bounds. The network of US climate denial became a memory hole into which the facts of both science and history disappeared.

The mass media played a role, as well, as a wide spectrum of the media—not just unabashedly conservative newspapers like the *Washington Times* but mainstream outlets, too—felt obligated to treat the think-tanks on a par with research scientists. Journalists were pressured to grant the professional deniers equal status—and equal time and newsprint space—and they did. Eugene Linden, once an environment reporter for *Time* magazine, commented in his book *Winds of Change* that "members of the media found themselves hounded by experts who conflated scientific diffidence with scientific uncertainty, and who wrote outraged letters to the editor when a report didn't include their dissent."[60] Editors succumbed to this pressure, and reporting on climate in the USA became biased *toward* the skeptics and deniers because of it.

14.6 The Debate in Europe

In Germany (and Switzerland), the public greenhouse debate began earlier and had a different effect on politics, to conclude from a sociological analysis by Peter Weingart and colleagues in 2000.[61] A group of concerned scientists, including Wilfried Bach, Hans Oeschger, and Hermann Flohn, had already initiated discussion within the scientific community by the 1970s. Flohn in particular issued a prophetic warning published in a German scientific journal, which had little effect at the time: "The [greenhouse] problem … is not a topic for an election campaign on the short-sighted time-scale of politics. It threatens the future of the children and grandchildren on the earth as a whole."[62] A "working group on energy" in 1986 was more successful. Their public warning that "the emission of greenhouse gases should urgently be reduced to avoid a climate disaster" was picked up by the opinion-leading magazine *Der Spiegel* under the heading "Die Klimakatastrophe" ("The Climate Catastrophe"). It became the buzzword for the entire discourse in the German-speaking world for the next thirty years, and the article illustration (Fig. 14.1) became an icon. Eventually, politicians in Germany and other European countries framed policies to reduce greenhouse gases at both the national and the international levels.

In Weingart's analysis, the character of environmental risk communication differs among science, politics, and the media. In this framework, it falls to scientists to suggest options for problem-solving by producing reliable knowledge. Fearful of losing their credibility, scientists tend to emphasize uncertainties. Politicians have to frame issues as a problem that can be solved by political decision-making. However, making decisions based on uncertain scientific foundations risks losing votes and power. The media cannot effectively communicate uncertainties. In order to keep their public and their market share, they need to convert complex interrelations into simple causalities.

In both Germany and Switzerland, the political system created specific pathways of problem-solving. These focused on the role of scientific advisory bodies

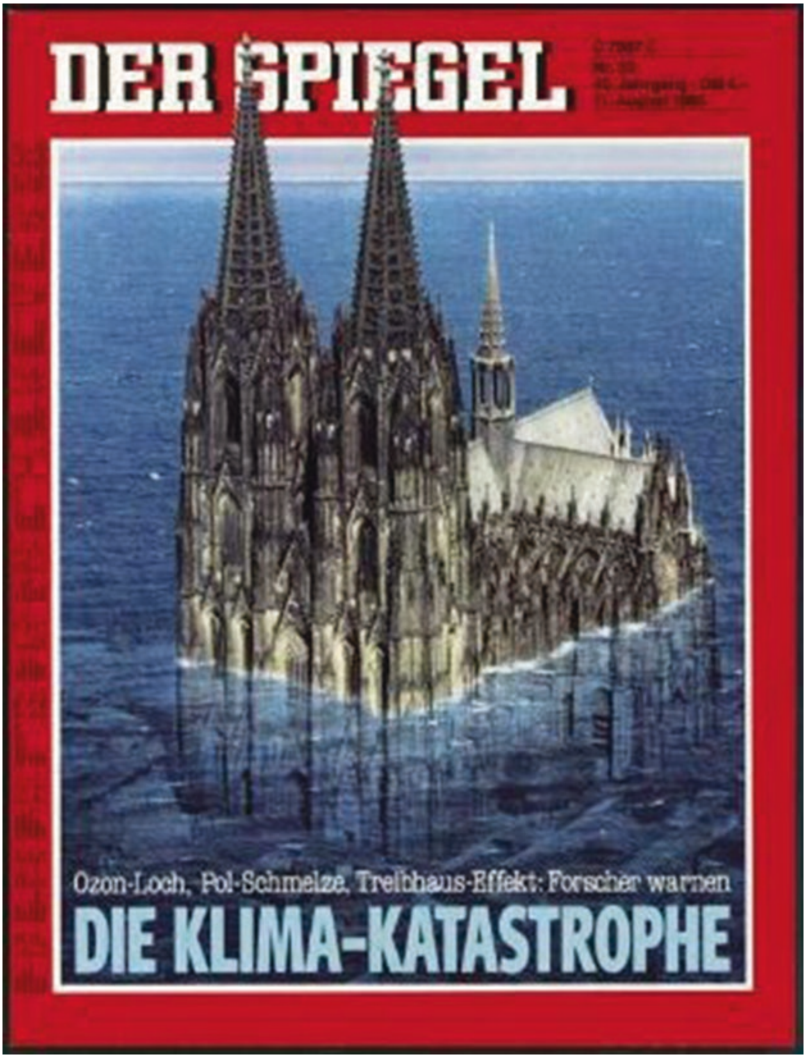

Fig. 14.1 Front cover of the magazine *Der Spiegel* 33/August 11, 1986. The photomontage shows the Cologne cathedral half under water as a result of sea-level rise. Credit: ©1986 Der Spiegel. Reproduced with permission of Der Spiegel

and the creation of institutes to study the issue from both a scientific and policy perspective. The German government founded the Potsdam Institute for Climate Impact Research in 1992 as an advisory body on climatic change; the Swiss Academy of Sciences, supported by the federal government, established an official Advisory Body on Climate Change (OCCC) in 1996, composed of a network of researchers in universities and the administration. Since 1988, this network has also set up a specific interface with the news media named Proclim. Something similar occurred in the UK, with the establishment in 2000 of the Tyndall Centre for Climate Change Research.[63]

Discussions between "skeptics" and experts fueled by popular lay books and movies were and are still waged in the (social) media. The issue of climate change is so complex and seemingly inconsistent with personal experience that many people even in Europe have turned to the kind of simplistic mono-causal explanations offered by skeptics.[64] However, the skeptics' impact on political decision-making in Europe has been marginal. Climate skepticism is not widespread in Britain.[65] Prominent American skeptics tried in vain in 1994 to influence European climate policy through the creation of a European Science and Environment Forum (ESEF), but it was ultimately dissolved in 2005.[66] Likewise, the European offices of the Nongovernmental International Panel on Climate Change (NIPCC) never achieved any political relevance.

Unlike that in the USA, climate skepticism in Europe has not relied on industry funding. Its support has come from individuals of different backgrounds—including journalists, geologists, physicists, and meteorologists—whose personal or political worldviews and interests clash with the consequences of accepting human-made climate change. One of the best-known European skeptics has been Danish statistician Björn Lomborg, who initiated many discussions on climate policy with his books *The Skeptical Environmentalist* and *Cool It*.[67] Lomborg first downplayed the importance of climate change and subsequently criticized climate policies. Yet he gradually underwent a remarkable change of opinion. In 2010, in interviews with newspapers, he admitted the importance of climate change and asked for specific actions, such as a carbon dioxide tax, investments in renewable energy, and research on geo-engineering.[68]

In Germany, the Federal Institute for Geosciences and Natural Resources even published climate skeptic reports; and German coal companies played a role in some US-based skeptical activities. These included the production in the 1990s of a film, *The Greening of Planet Earth*, which claimed that increased atmospheric carbon dioxide would be a net benefit to society because of its (alleged) positive impact on agricultural productivity.[69]

Skeptics in Europe have not organized political and media institutions like those in the USA, with the exception of the European Institute for Climate and Energy (EIKE). Lobbying by interest groups within the political process has been more effective in preventing climate action, at least in Austria.[70] Although less organized, the activities and especially the content of skeptic articles in the media—supported by skeptical or conservative journalists—are still occasionally included in political discussion by conservative politicians and parties. In France, well-known climate skeptics have acted as political advisors to conservative parties. However, even in Austria, climate skepticism has only played a minor role in public discussion, as the research project on skepticism (CONTRA) has shown; and in Germany, it appears mainly among politically inactive people.[71] In the Czech Republic, one climate skeptic (Vaclav Klaus) served as prime minister and for many years as state president, but his influence on European climate policy was negligible.

14.7 The Debate in Australia

In Australia, there have been dramatic and frequent changes in public debate and government policy on climate change over the last three decades.[72] In 1987, the government research agency CSIRO ran a major conference on the topic. The resulting book, *Greenhouse: Planning for Climate Change*, demonstrated the breadth of Australian research on climate change science and impacts.[73] In 1990, prior to the establishment of the UNFCCC, the Australian Government announced a target of reducing Australia's greenhouse gas emissions by 20% below 1988 levels by 2005, with the proviso this should be at no cost to the economy.[74] Soon after, in 1992, Australia ratified the UNFCCC.[75]

During the 1990s, developed countries faced growing expectations to commit to emission reductions under the UNFCCC. At the same time, mining industries and the business sector lobbied that any emissions reductions in Australia should not impact the economy.[76] The mining industry supported a climate change denier group, the Lavoisier Group, to question the scientific evidence on human-caused climate change. Their members included a small group of Australian scientists, including Bob Carter, Bill Kininmonth, Garth Paltridge, and Ian Plimer, all of whom regularly contributed opinion pieces to newspapers to spread doubt about the science.[77] Carter also testified in the US Congress, making the misleading claim that observed increases in carbon dioxide followed—rather than preceded—increases in temperature, and therefore could not have caused them.

In 2007, there was a change of government in Australia while a long-term drought affected the country. The new government was committed to act on climate change by introducing an emissions trading system. This commitment provoked even stronger action from industry and the media to combat the scheme, and led to the establishment of a new climate change denial group, the Galileo Movement.[78] This outfit involved the same Australian climate change deniers as the Lavoisier Group but with better funding, including support from the Heartland Foundation in the USA, and advice from American climate change deniers, including Tim Ball, Dick Lindzen, Patrick Michaels, and Fred Singer.

Despite these efforts, a national pricing mechanism on greenhouse gas emissions was eventually introduced in 2012. Rupert Murdoch's News Corp. media actively campaigned against this carbon price and for a change of government.[79] This change took place in 2013, and the carbon price was revoked. The new government strongly supported the coal industry, with Prime Minister Tony Abbott stating that coal was "good for humanity."[80]

Yet another shift in climate policy occurred in mid-2015, when Tony Abbott was removed as prime minister by his party, and a more moderate leader, Malcolm Turnbull, was elected. At the Paris UNFCCC meeting in December 2015, Turnbull committed Australia to meet an emissions reduction target of 26–28% below 2005 levels by 2030. At present, Australia is the only country to have successfully introduced a national carbon price, and then abandoned it. It remains to be seen whether it will be reintroduced.

14.8 Conclusion

In 2015, world leaders gathered once more, this time in Paris, to try to forge an effective international agreement to control the greenhouse gases that are driving disruptive climate change. The meeting resulted in an accord by nearly 200 countries to act decisively to control climate change.[81] The agreement affirms that "climate change represents an urgent and potentially irreversible threat to human societies and the planet and thus requires the widest possible cooperation by all countries, and their participation in an effective and appropriate international response, with a view to accelerating the reduction of global greenhouse gas emissions." It recognizes "that deep reductions in global emissions will be required in order to achieve the ultimate objective of the Convention," which to is to maintain climate change to below 2 °C, and to strive to keep it below 1.5 °C. But in 2017, Donald Trump was elected President of the United States, and declared the US intention to withdraw from the Paris agreement. He also appointed known climate change deniers to major government positions, including Secretary of Energy and head of the Environmental Protection Agency.

The impacts of President Trump's decisions are not yet clear. But even if the US returns to the international fold, climate change denial and resistance to action has led to significant delay in acting on the intentions expressed at Rio in 1992. And that delay has been costly. In 1988, atmospheric carbon dioxide was just about 350 parts per million—now it is over 400. Many aspects of climate change that were still just predictions in 1988 are now observed facts. The Arctic is melting at an accelerating rate; within our lifetime, there may be no summer Arctic ice. Greenland and the West Antarctic are also melting, and some scientists think that the great stores of ice in the West Antarctic are now certain to disintegrate, possibly within the foreseeable future, bringing meters—if not tens of meters—of sea-level rise. Heat waves, droughts, floods, fires, and other extreme events have worsened. Coral reefs are threatened. Many species have already changed their geographic distribution. The list of consequences is long and sobering.

Will we act to stop climate change before it brings more disasters? Will we prevent the "Klima-Katastrophe"? No one knows. But there is no question that resistance—particularly US resistance—to acting on climate change has substantially contributed to the delay in achieving meaningful global action. And because of this delay, at best, the job is going to be much harder and much costlier than it needed to be. And at worst—well, that hardly bears discussing.

Notes

1. Roach, 2004.
2. Solomon et al., 2007, 8.
3. Oreskes, 2004, 1686.
4. *Time*, March 26, 2006. Contrast this with the results of the Intergovernmental Panel on Climate Change Third Assessment Report, which states unequivocally that average global temperatures have risen. IPCC, 2001.

5. Langer, 2006. For a related poll, see also Pew Center, July 12, 2006.
6. Fleming, 1998, 2007; Weart, 2008.
7. Kerr, 1989, 1041–43.
8. Jastrow et al., 1990.
9. Roberts, 1989, 992–93.
10. Roberts, 1989, 992–93.
11. Roberts, 1989, 992–93.
12. Houghton et al., 1990; see also Weisskopf and Booth, May 26, 1990, 1.
13. Houghton et al., 1990, 63.
14. Bolin, 2007, 72; Nierenberg described the Marshall Institute's estimate as climate sensitive (1991, 10).
15. Deborah Day, personal communication with Naomi Oreskes 2008.
16. Bill Kristol to Sam Skinner et al., *Attachment—Chart B*, April 23, 1992, Jeffrey Holmstead, file "Global Warming Implications," OA/ID CF01875, Counsels Office, George H.W. Bush Presidential Library, College Station, Texas.
17. Robert Jastrow to Terry Yosle, February 22, 1991, WAN papers, Accession 2001-01, 60: file label "Marshall Institute Correspondence, 1990–1992," SIO Archives.
18. United Nations, 1992; "United Nations Framework Convention on Climate Change," UNFCC, http://unfccc.int/2860.php (accessed July 4, 2009).
19. Bush, 1993, 924–25.
20. Ramanathan, 1988, 293–99.
21. Santer et al., 1994, 267–85, 1995, 10693–726, 1996, 77–100; Santer and Taylor, 1996, 39–46.
22. Santer and Taylor, 1996, 39–46; Santer writes: "I checked on this. We submitted our paper to *Nature* in April 1995." Benjamin Santer, email communication with Naomi Oreskes, October 4, 2009; Santer, interview with Conway, February 20, 2009; Houghton, 1996.
23. Michael Oppenheimer as quoted in Stevens, 1999.
24. IPCC Second Assessment Report; Bolin, 2007.
25. Stevens, 1999; Stevens, September 10, 1995.
26. Jaquith, August 10, 2006.
27. Michaels, 1984, 143–56, 1983, 1296–303.
28. Michaels, 1991, 1992.
29. New Hope Environmental Services, http://www.nhes.com/ (accessed October 9, 2009); see discussion in Gelbspan, 1997, 41–43; Oreskes, 2011. According to Gelbspan, Michaels' publication started as World Climate Review, then became World Climate Report.
30. Oreskes, 2011.
31. Bill Nierenberg to Fred Seitz (handwritten), November 27, 1995, WAN papers, Accession 2001-01, 70: file label "Frederick Seitz, 1994–1995," SIO Archives; Schneider and Edwards, 2001, 219–96; Bolin, 2007, 113; Stevens, 1999, 229; Santer interview with Conway, February 20, 2009.
32. Singer, 1996a.
33. Wigley and Singer, 1996, 1481–82.
34. Wigley and Singer, 1996, 1481–82.
35. Gelbspan, 1997; Leggett, 2001. On Pearlman, see Gelbspan, 1997, 119–20.
36. Stevens, 1999, 231.
37. Santer interview with Conway, February 20, 2009.

38. Santer interview with Conway, February 20, 2009.
39. Lahsen, 1999, 111–36.
40. Seitz, June 12, 1996.
41. Avery et al., 1996, 1961–65.
42. Avery et al., 1996, 1963–65.
43. Avery et al., 1996, 1966.
44. Avery et al., 1996, 1961–65.
45. Avery et al., 1996, 1961; see also Bolin, 2007, 129.
46. Singer, July 11, 1996b; see also letters by Frederick Seitz and Hugh Ellsaesser in the same section.
47. Santer, July 23, 1996; see also letter by Bert Bolin and John Houghton in the same section.
48. Gelbspan reprinted this email exchange: Gelbspan, 1997, 230–36.
49. Faxed copy of statement in: Edward Frieman papers, MC 77, 123:7, SIO Archives; see also Mooney, 2005, 62–64.
50. McCright and Dunlap, 2003; *Byrd-Hagel Resolution,* July 25, 1997, The National Center for Public Policy Research, http://www.nationalcenter.org/KyotoSenate.html (accessed July 1, 2009).
51. James M. Inhofe, "Climate Change Update: Senate Floor Statement by US Senator James M. Inhofe," January 4, 2005, Floor Speeches, http://inhofe.senate.gov/pressreleases/climateupdate.htm (accessed February 19, 2007).
52. Cheney, 2007.
53. Seidel, 1995; Edwards, 1996; Sontag et al., 1998; Craven, 2001; Westwick, 2003; Oreskes, forthcoming.
54. Hays and Hays, 1987, 491. Rothman prefers to call it a backlash: Rothman, 2000, 158.
55. https://royalsociety.org/topics-policy/publications/2006/royal-society-exxonmobil/; https://royalsociety.org/~/media/Royal_Society_Content/policy/publications/2006/8257.pdf.
56. Banerjee et al., 2015.
57. http://exxonsecrets.org/em.php, accessed November 1, 2015.
58. Jacques et al., 2008, 349–85.
59. Orwell, 1949.
60. Linden, 2006, 222–23.
61. Weingart et al., 2000.
62. Flohn, 1981, 190.
63. Hulme and Turnpenny, 2004.
64. Neu, 2009.
65. Poortinga et al., 2011.
66. Rahmstorf and Schellnhuber, 2007; http://www.tobaccotactics.org/index.php/European_Science_and_Environment_Forum.
67. Lomborg, 2001, 2007.
68. Jowit, 2010.
69. Bundesanstalt für Geowissenschaften und Rohstoffe, 2004; Oreskes, 2011.
70. Brand and Pawloff, 2014.
71. CONTRA, http://projects.fas.at/CONTRA/; Engels et al., 2013.
72. Talberg et al., 2015; Hamilton, 2007.
73. Pearman, 1988.
74. Talberg et al., 2015.
75. Talberg et al., 2015.

76. Hamilton, 2007.
77. Lavoisier Group, http://www.lavoisier.com.au/index.php; Enting, 2011.
78. Galileo Movement, http://www.galileomovement.com.au/galileo_movement.php.
79. Manne, 2011.
80. Pearse et al., 2013.
81. https://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf.

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PART II

Historical Climatology: Periods and Regions

CHAPTER 15

The Holocene

John L. Brooke

15.1 Introduction

Human history has been fundamentally shaped by the climate of the Holocene, the warm interval since the last ice age. The Holocene encompasses roughly the past 12,000 years, during which human societies emerged from hunter-gatherer origins, developed agriculture, and then cities and states. On a global scale, the Holocene is divided into three broad phases: the Early Holocene (from the end of the Younger Dryas Period to *c.* 6200 BCE), the Middle Holocene (*c.* 6200–3000 BCE), and the Late Holocene (since *c.* 3000 BCE). However, European Holocene climates are traditionally broken into five periods: Preboreal (9700–8500 BCE), Boreal (8500–5700 BCE), Atlantic (5700–3700 BCE), Subboreal (3700–600 BCE), and Subatlantic (600 BCE–present). This chapter provides a general overview of origins and trajectory of Holocene climates and their role in shaping the human condition, particularly before around 3000 BCE.

15.2 The Early Holocene

The Holocene is only the most recent warm interglacial period since the Pleistocene ice ages began about 2.6 million years ago. There have been eight similar interglacials in the last 800,000 years. Patterns in the Earth's orbit around the sun—the famous Milankovitch cycles—affect the impact of solar radiation on the Earth's surface. These include cycles in the "eccentricity" (or stretch) of Earth's orbit, the "obliquity" (or tilt) of Earth's axis, and the "precession" (or wobble) of Earth's axis. Taken together, these cycles influence

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how much solar radiation the Earth receives during different seasons. Operating at multiple timescales (100,000, 41,000, and 23,000 years, respectively) and working in complex feedback loops with each other and with land-surface and atmospheric conditions, these orbital cycles have been the dominant large-scale climate forcing agents during the past million years.[1]

The warmest period of the Holocene—the "Holocene Thermal Maximum" of around 9000–5000 BCE—occurred when the Northern Hemisphere summer lined up with shortest orbital distance to the sun. However, the transition from the last ice age to the warm Early Holocene followed a complex oscillation that began around 14,000 years ago. The warming influences of orbital cycles had to overcome the cooling influences of glacial meltwater events. Huge bursts of cold fresh water from melting glaciers poured into the North Atlantic. These outbursts slowed the sinking of warm salty water that drives the Gulf Stream (the "thermohaline pump"), and with it, the entire oceanic circulation system. (Such a meltwater event, improbably sped up to take place in weeks, was featured in the movie *The Day After Tomorrow* (2004).) An initial warming known as the Bølling-Allerød (*c.* 12,700–10,900 BCE) was broken by a major meltwater event that caused a millennium of near glacial cold, the Younger Dryas period (*c.* 10,900–9700 BCE).[2]

Following the Younger Dryas, orbital patterns of obliquity and precession brought a near peak in Northern Hemisphere summer irradiance, setting conditions for the warmest period in Earth's history in the last 100,000 years. Global climatic patterns changed. During ice ages, the polar regions generated intense stormy winters reaching well toward the equator. The Intertropical Convergence Zone (ICTZ) (the band of convection and rainstorms driven by direct sunshine in the tropics) and its associated monsoon rains were weaker and never moved far from the equator. The very warm Northern Hemisphere summers of the early Holocene reversed these conditions: the ITCZ and its associated monsoon systems moved well north of the equator every summer, reaching far into the Middle East and as far as Central Asia, and turning the Sahara into a green savannah (Fig. 15.1).

A short meltwater event around 8200 BCE known as the "Preboreal Oscillation" brought a brief interruption to the warm Early Holocene. This draining of a vast glacial lake in Canada brought roughly two centuries of cold to the Northern Hemisphere. After 7000 BCE, the orbital influences of precession and obliquity and the resulting strong solar insolation began to fade, and the Northern Hemisphere very slowly began to cool. The entire suite of global climatic systems shifted south, most importantly the ITCZ and the far reach of Northern Hemisphere monsoon rains. The South Asian Monsoon gradually withdrew from the Middle East after 7500 BCE. North Atlantic winter westerlies shifted south with the advancing polar jet stream, bringing more winter rain to the Mediterranean and snow to Asia and North America.

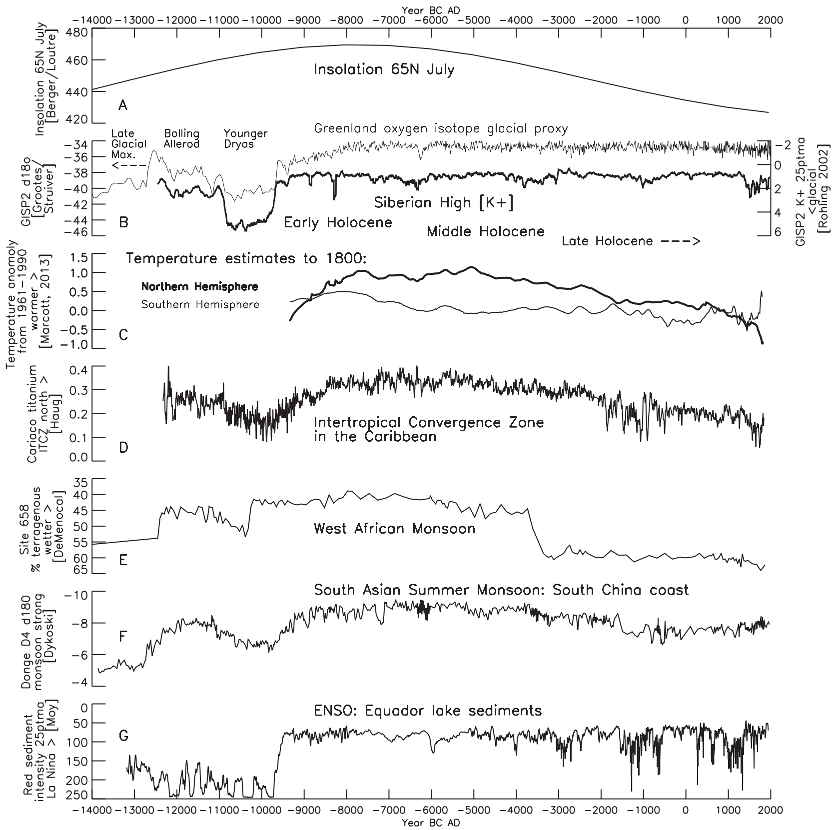

Fig. 15.1 Climate in the Holocene. The transition to Holocene climates was driven by changing patterns in the Earth's orbit, which by 18,000 years ago had begun to raise the level of solar influence, or insolation [A], on the Northern Hemisphere summer. Since the Northern Hemisphere has the bulk of the Earth's land mass, and land surface warms faster than oceans, this rising Northern Hemisphere summer insolation was the Holocene driver. This warming influence was accelerated by feedbacks with greenhouse gases and, on occasion, suddenly reversed by meltwater events [B], in which fresh glacial waters stopped the action of the salt-density pump driving ocean circulation. After 9700 BCE, these major oscillations ended, and the Early Holocene brought a general increase in Northern Hemisphere temperature [C]. This rising temperature shaped the northward movement of the Intertropical Convergence Zone [D] and the African and Asian monsoons [E, F], and encouraged La Niña conditions of the El Niño/Southern Oscillation (ENSO) [G] across the Pacific. The northern warmth was interrupted twice by short meltwater events, the Preboreal event at 8200 BCE and the Laurentine event at 6200 BCE, manifested in spikes in the GISP2 glacial and Siberian High proxies [B]. After 7000 BCE, as orbital forcing weakened Northern Hemisphere insolation [A], the entire global circulation shifted slowly south [D] and the monsoons weakened, including a sudden weakening at ~3700 BCE in the case of West Africa [E, F]. Conversely, the ENSO system shifted suddenly toward the El Niño mode around 3000 BCE [G]. Very broadly, the Middle Holocene was shaped by the waning of this peak northern warmth, running roughly from the seventh millennium to the fourth millennium BCE, followed by the Late Holocene starting in the third millennium BCE

15.3 Middle Holocene

The final collapse of the glacial Laurentine ice sheet in Canada around 6200 BCE, and the meltwater event that followed, conventionally mark the transition from the Early to the Middle Holocene. Despite the 6200 BCE meltwater crisis and the slow ongoing retreat of the monsoons, the next two millennia were still generally a global climate optimum, and Northern Hemisphere temperatures remained high until roughly 5300 BCE.

These conditions came to an end in the fourth millennium BCE, a period sometimes called the Mid-Holocene Crisis or Mid-Holocene Transition, as the declining orbital forcing of the Earth's climate system reached a tipping point toward a cooler Late Holocene world. The intensity of the North African Monsoon declined and then dropped dramatically around 3700 BCE. The climate of the Mediterranean, which had been quite humid for several thousand years, turned sharply and permanently drier. In the Americas, the El Niño system, which had been essentially switched off during the entire post-glacial period, became increasingly active from 4000 BCE and suddenly peaked around 3000 BCE, at exactly the same time as several droughts struck the Levant and East Africa. North America turned sharply cooler, and glaciers advanced throughout the world.

Dramatic evidence of the transition into the Late Holocene is now emerging as glaciers around the world melt under the impact of modern global climate change, uncovering biological material buried in ice for five millennia. At the Quelccaya glacier in the Andes, ancient plants buried under glacial advances over 5000 years ago are emerging as the ice retreats. High in the Tyrolian Alps, an even more dramatic find emerged from melting ice: a Neolithic warrior or shaman, now known as Ötzi, who died of an arrow wound sometime between 3300 and 3100 BCE.

It may well be that the Mid-Holocene cooling was shaped by the effects of both the long-term orbital shift and a millennial-scale super-minimum in solar activity. Clearly, with the transition to the Late Holocene, the direct action of solar cycles became a dominant factor in global climatic change. These solar cycles are caused by convection cycles flowing within the fluid solar dynamo, and appear on the surface of the sun as sunspots. In recorded history, grain prices have varied closely with solar cycles, and over the longer term, solar maxima and minima lasting decades and centuries correlate with periods of general prosperity and adversity in ancient populations. Volcanic eruptions have been another important source of Late Holocene climatic variability, emitting high volumes of sulfates that reflect solar radiation and cool the climate. Volcanic action generally has effects that last a year or two, but it is possible that extremely large eruptions may have triggered long-term changes in the climatic system.

15.4 Late Holocene

The final section of this chapter provides a brief overview of long-term global systems and changes, and the following chapters of this handbook will provide more detailed reconstructions for different regions and periods of Late Holocene climate. Three central elements of the global circulation system—the Pacific El Niño system, the Northern Hemisphere westerlies, and the tropical monsoons—appear to have varied in a common pattern. The warm phase of this Late Holocene pattern presents a weaker version of conditions during the Early Holocene. During warmer phases, the Northern Hemisphere summer draws the ITCZ northward, a warmer western Pacific drives stronger Asian monsoons and creates dry La Niña effects in the Americas, and finally, a stronger and north-running winter jet stream pulls strong winter westerly systems to the north. The cooler phases reverse this pattern, keeping the ITCZ to the south, weakening the Asian Monsoons as ocean heat shifts to the eastern Pacific and drives strong El Niños, and finally shifting the winter westerlies slightly to the south, which brings more winter rain and snow to otherwise arid mid latitudes.

On three occasions over the last 6000 years, powerful outbursts of extreme winter weather have dominated the Northern Hemisphere: around 4000–3000 BCE, around 1200–700 BCE, and around 1400–1700 CE (see Fig. 15.2). These "neoglacials"—manifested in extremes in the winter Siberian High, as measured by the volume of Asian dust chemistry in the Greenland ice cores—are aligned with, and appear to have been caused by, solar super-minima that are part of the Hallstatt solar cycle. Solar cycles occur on a regular pattern, but their major effects seem to have been masked during the peak orbital insolation during the Early Holocene. There are many solar cycles, the most widely known being the eleven-year cycle of solar maxima and minima. The largest and most powerful of these cycles is the 2000–2200-year Hallstatt cycle, during which the weakened solar output was manifested in a series of super-minima. While there is active debate regarding which cycle or combination of cycles had the determining forcing role on global climate, the Hallstatt cycle seems to have played a powerful role, since it is aligned with both major outbursts of the winter Siberian High and with a well-known pattern of ice-rafting in the North Atlantic known as the Bond Cycle. It is also clear that an irregular half-cycle of lesser solar minima (~2500–2100 BCE, 550–700 CE), aligned with the ice-rafting pattern but *not* the Siberian High, has also played a role in less intense episodes of global cooling. The potential cooling effects of the two Hallstatt super-minima centering at 7500 BCE and at 5400 BCE seem to have been masked by the warming effects of orbital cycles. But during the fourth millennium, orbital warming forces had declined enough for the Hallstatt solar minimum to influence global climates. Between 4000 and 3000 BCE, 1200 and 700 BCE, and 1400 and 1725 CE, deep solar minima line up with major pulses in the Siberian High, which sent cold outbursts deep into the mid latitudes.[3]

These three grand climatic reversals and their intervening optima shaped human conditions over the Late Holocene. The entire Eurasian Bronze Age, for example, took place in the inter-Hallstatt optimum of 3000 to 1200 BCE.

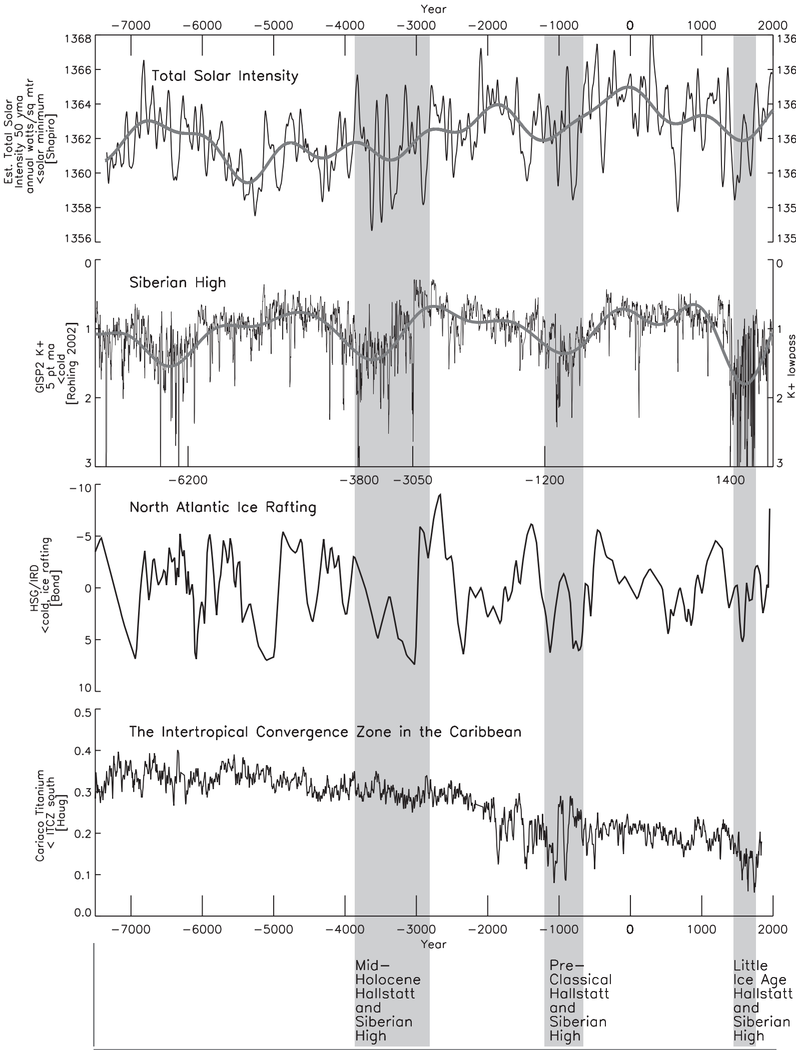

Fig. 15.2 Solar forcing in the middle to late Holocene. Orbital forcing of Northern Hemisphere insolation, punctuated by episodic meltwater crises, shaped the climatic patterns of the Early to Middle Holocene. After roughly 4000 BCE, orbital forcing reversed the high level of insolation in the northern summer, allowing cycles of solar activity to play a dominant role in the pattern of global climate change. Very broadly, the ~2200-year Hallstatt cycle, and an irregular ~1000-year half-cycle, drove three epochs of "neoglacial" cold conditions: in the fourth millennium BCE, after 1200 BCE, and after 1400 CE. These are expressed most dramatically in patterns of the winter Siberian High system [B]. Episodes of significant ice-rafting in the North Atlantic [C] correlate with numerous proxies of abrupt climatic change throughout the world; they may be associated with the irregular half-cycle of the Hallstatt cycle, such that ice-raft episodes occur with each Hallstatt minimum and with each intermediate solar downturn, most dramatically in the Dark Ages of around 500–900 CE. The gradual southward drift in the summer latitude of the Intertropical Convergence Zone [D] also reflects both impacts of the orbital shift away from the interglacial maximum and cyclical Hallstatt solar minima from 3600–2900 BCE, 1200–900 BCE, and after 1400 CE

Over the last two millennia, solar forcing reinforced by volcanic eruptions shaped several commonly recognized climatic periods:

- The Roman–Han Imperial Optimum, around 200 BCE–500 CE (solar maximum)
- The Dark Ages, around 500–950 CE (solar minina, ice-rafting)
- The Medieval Climate Anomaly, around 950–1300 CE (solar maximum)
- The Little Ice Age, around 1300–1800 CE (Hallstatt cycle solar minima, ice-rafting, Siberian High outbreaks)

While it is generally agreed that the periodicity of Late Holocene climate change is shaped by solar patterns, questions remain about the trend and intensity of these changes. Some have argued that the Little Ice Age cold shift was stronger than the previous two Hallstatt cold epochs, and that it may have been the coldest period since the Younger Dryas. If it indeed was—and this is by no means settled—these conditions might have been shaped by the ongoing influence of orbital forcing. It is widely accepted that orbital shifts shaped the Mid-Holocene transition by reducing Northern Hemisphere insolation. Work is ongoing to determine whether orbital forcing has driven a general cooling trend in the Late Holocene, a cooling trend dramatically reversed by the forces of anthropogenic global warming in the past century.[4]

Notes

1. Bradley, 2015, 36–46; Cronin, 2010, 113–47.
2. Roberts, 2014, 96–107; Cronin, 2010, 185–214.
3. Rohling et al., 2002; Nussbaumer et al., 2011; Brooke, 2014, 166–82, 276–78. For important reviews of Mid- to Late Holocene climates, see Wanner et al., 2015, and Mayewski et al., 2004.
4. Esper et al., 2012.

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CHAPTER 16

Mediterranean Antiquity

Peregrine Horden

16.1 Introduction

"If a man were called to fix the period in the history of the world, during which the condition of the human race was most happy and prosperous, he would, without hesitation, name that which elapsed from the death of [Emperor] Domitian [96 CE] to the accession of [Emperor] Commodus [180 CE]." The famous verdict of the historian Edward Gibbon (1737–1794) on the age of the Antonine emperors in the third chapter of the *Decline and Fall of the Roman Empire* (1781), however qualified or ironic, finds some endorsement from a surprising new direction, the history of ancient climate. Various new sources of information have taken scholars of the ancient world well beyond the literary texts—and beyond inscriptions, papyri, and familiar types of archeology. Data from climate proxies could potentially surpass all these in sheer quantity and attain great significance for our general understanding of antiquity. This chapter attempts first to convey the least controversial narrative of climate history that this data supports, and second to review some of the problems any such narrative presents.

16.2 Narrative

The first question is when does antiquity begin? The recognizably Mediterranean climate of hot dry summers and cold wetter winters, along with the general desertification of the Sahara, was established by the end of the third millennium BCE, and that millennium closed with an especially arid phase (see Chap. 15).[1] The supposed "4.2kya event" (2200 BCE), the beginning of a period of global cooling and drying, is evident in only some records and, strikingly, does

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not seem to coincide with any macro-historical development in the Mediterranean.[2] The collapse of palace states around the Aegean has sometimes been attributed directly to another lengthy period of drought beginning around 1200 BCE. The evidence for famine relief in that period is, however, perhaps more a sign of burgeoning connectivity and of disaster averted, than of catastrophe itself, and the patchy texts that gave rise to that misleading nineteenth-century construct, the Sea Peoples, point in the same direction. The eastern Mediterranean was becoming more integrated, and the older palace states could no longer control this enhanced mobility, a mobility to which climate change was only one among several stimuli.[3]

More plausibly, climate has been brought into the narrative of the beginnings of archaic Greece from the eighth century BCE onward. The period from the eighth to fifth centuries seems to have been one of wetter and cooler weather in the Mediterranean than before, thus friendlier to farming, demographic growth, and (it is suggested) to those cultural and political developments, including the first stirrings of Greek colonization, that seem to bring us firmly into the ancient world. Possibly the largest solar minimum (absence of sunspots) of the last 3000 years is datable to around 765 BCE. This has been linked to a long phase of cooler weather in the ninth to eighth centuries BCE, known to prehistorians of Europe as the Iron Age Cold Period. In much of the Mediterranean, precipitation increased in the aftermath of the minimum, encouraging longer and more productive growing seasons.[4] Very little can be determined about Greek climate between that early phase and around 200 BCE. In the Levant, a short dry period around 600 was followed by a more humid period until about 200 BCE.[5]

From Greece we turn to Rome. What might be labeled the long Roman period is currently the most intensely and thoughtfully studied period of premodern climatic history apart from the Little Ice Age.[6] This period sits within a millennium of relative solar stability (between minima of *c.* 360 BCE and *c.* 685 CE). It contains an unusually stable and climatically favorable period from around 200 BCE to 135 CE: the Roman Climate Optimum or Roman Warm Period, perhaps "the most humid by far of the past 4000 years."[7] Here is the unexpected vindication of Gibbon's view of the age of the Antonine emperors. Alpine glaciers retreated; according to Spanish speleothems, 150 to 50 BCE was a peak warm period with stable rainfall; and volcanoes (even Vesuvius) were exceptionally quiet from around 40 BCE to 150 CE. Improved conditions were widespread. Greenland ice cores suggest temperatures as warm as at the end of the second millennium CE, and possibly warmer than the Medieval Climate Anomaly. Rainfall across northeast France was stable and beneficial for agriculture until about 250 CE; viticulture spread across Roman Britain. Crucial to the grain supply of Rome, Nile floods of the right timing and volume generated propitious agricultural conditions in Egypt from around 30 BCE to 155 CE. Particularly good floods came on average once every five years.[8]

Of course, the benefits within the Greco-Roman world were not universal. At the least, we must allow for the well-known East–West contrast in the

Mediterranean region. For example, the oxygen isotope record from Lake Van in eastern Turkey indicates aridity from the end of the third millennium BCE through to a peak in about 110 BCE, followed by a moister and cooler phase and then a trend toward dryness again from the first century CE onward.[9] Some other studies have shown that the aridity persisted for centuries to come, while the southern Levant may have become moister.[10]

In contrast to the four centuries of (broadly) agriculturally favorable climatic stability that mark out the Roman optimum, Late Antiquity presents itself in surprisingly clear relief. The distinguishable phases are shorter and, overall, less favorable. Spanish data suggests continued moistness in the third century, but elsewhere there seems to have been a change to drier conditions across Central and parts of Southern Europe and across the eastern Mediterranean generally.[11] The period 250–550 CE is described as one of "exceptional climatic variability" across Europe.[12] There was a sharp downturn in solar activity around 200–260, which was then reversed. Nile floods were favorable less than once a decade.

The fourth century saw far greater regional divergence than for many centuries previously. Central European tree rings indicate cooling and increased precipitation. However, readings from Austria and northern Spain imply warming, reaching a peak at the end of the century. Anatolia continued to be dry, but the southern Levant was wetter and cooler, especially toward the end of the century. Solar activity was high from about 300 CE until about 370, when there began an overall downward trend, with reversals and plateaus, toward a minimum in 685 CE.

The mid- to late fifth century saw Central Europe becoming a little drier and warmer, and at least parts of Anatolia and the southern Levant turning wetter. The first half of the sixth century was markedly colder and very much drier in Central Europe—the driest period there for centuries. Several, but not all, data-yielding sites in Anatolia became wetter, while the southern Levant by contrast turned drier. This phase is cut off by one or perhaps two very large volcanic eruptions in 535/6 and 539/40, producing "years without summer," and, probably, a run of harvest failures (see Chap. 32).[13] There followed a long and unusually cool period overall, reaching into the mid-seventh century, which has been likened to the worst of the Little Ice Age (see Chap. 23). In environmental and climatic terms, it is tempting to see antiquity as ending with a bang.

16.3 Problems and Conclusion

A narrative of this sort smooths away numerous problems. First, much of the data is contradictory. Perhaps it has not been read accurately: many new and exciting techniques have still to be refined and made reliable. Moreover, information on ancient Mediterranean climates often relies on extrapolation from neighboring regions. A climatic regime inferred from, say, a Greenland ice core can have different consequences in the eastern than the western Mediterranean or in the Near East or Northern Europe. Highly localized anthropogenic effects on climate cannot be ruled out for any of the period under review.[14] Many of the chronologies proposed are very imprecise, making it hard to match one kind of climatic data with another or to match climatic and historical evidence without risking circularity of argument.

The greatest challenges, however, come from the problem of climate determinism and the related question of what history to bring into the picture. The ancient world has an environmental history now, with climate as a major part of it. The proponents of that climatic history want their efforts to be seen as an essential element in any general view of the period. So, they relate a phase of cooling to the expansion of the Celts across Europe or periods of intense drought on the Eurasian steppes to the irruptions of Huns and Avars onto the European and Mediterranean stages.[15] On the other hand, they do not want to be accused of simplistic climatic determinism. Thus, the role of climate is left vaguely as a "contributing factor."

Climate historians also tend to focus on periods of environmental decline or disaster, since superficially they align with the course of human affairs. The climatic vagaries of Late Antiquity, for example, loosely correlate with the collapse of the (Western) Roman Empire, the turbulence of early "barbarian" Europe, and major shifts in the economic landscape.[16] But of course, correlation is not explanation, and some of the major relevant climatic phenomena began earlier, in the third century BCE. As for the Eastern Empire, the sixth century and especially the age of Justinian can be seen as one of transition from late Rome to the very different world of Byzantium and early Islam. That it can also be seen as a disaster-prone period, politically as well as environmentally, does not prove that a deteriorating climate was the primary cause of change.[17]

The Roman Climate Optimum provides a great counter-example to this preoccupation with climatic stress, and shows how much is left out by merely correlating climatic affairs and the fortunes of empires. A strong supply of grain from Egypt was clearly significant for Roman governments and armies. Yet how exactly did a climatic regime favorable to agriculture further Roman imperialism? Would the Romans have made little headway in a climatic downturn in the Mediterranean? The counter-factual is worth exploring to test current thinking about the role of the Roman Optimum in Roman history.

Still more desirable is the integration of climate, not into a rather old-fashioned historiography that divides up the past according to the waxing and waning of empires, but into a comparative ecological historiography of primary production. For instance, if Horden and Purcell are right that Mediterranean farmers and pastoralists characteristically handled their changing micro-ecologies to insure against the risk of bad years,[18] then Mediterranean populations should have been more resilient to climatic change, whether positive or negative, than those in neighboring regions of Europe or the Near East. Technology could also mitigate environmental pressures, especially the provision of water in arid locations. Much remains to be investigated, not only on the side of climate science but also on the side of human economic and cultural history.

Notes

1. Broodbank, 2013, 601.
2. Finné et al., 2011, 3154.
3. Broodbank, 2013, 459, 470–1; Cline, 2014, 142–7; Kaniewski et al., 2015.
4. Manning, 2013, 112–14, 132.
5. Issar, 2003, 24.
6. McCormick et al., 2012; McCormick, 2013; Manning, 2013.
7. Nieto-Moreno et al., 2011, 1404–5.
8. McCormick, 2013, 78.
9. Manning, 2013, 158, 163.
10. Manning, 2013, 160, 163.
11. Manning, 2013, 163–5.
12. Büntgen et al., 2011, 580.
13. Gunn, 2000.
14. Manning, 2013, 106, n. 3.
15. Büntgen et al., 2011, 580; Cook, 2013.
16. Cheyette, 2008.
17. Meier, 2003.
18. Horden and Purcell, 2000.

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CHAPTER 17

China: 2000 Years of Climate Reconstruction from Historical Documents

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17.1 Introduction

Modern China stretches over ~9,600,000 km^2, an area roughly equal to that of Europe or the USA. Today, the country comprises twenty-two provinces and a dozen autonomous regions, municipalities, and special administrative units. Geographically, these vary from rugged mountains to fertile plains, from arid deserts to humid forests, and from cold continental climates in the north to subtropical monsoon climates in the south. Historically, the land settled by Han Chinese and ruled by Chinese imperial dynasties has changed over time. The center of population and agriculture shifted from the Yellow River to the Yangtze River valley during the first millennium CE.

While China's earliest dynastic history dates back more than four millennia, China was united for the first time in 221–207 BCE under the Qin Dynasty (for a list of dynasties, see Table 17.1). From that time on, successive imperial administrations left an increasing number of written records about past weather and climate. Because written Chinese has not fundamentally changed since the Qin period, present-day scholars with some training in paleography may still read and understand texts written several hundred years ago.

This chapter explains the variety and uses of historical documentary evidence for climate reconstruction in imperial China. This evidence includes both institutional and personal sources, both climate proxies and qualitative descriptions (see Chap. 4). The chapter concludes with a brief discussion of research on historical climate impacts in China.

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Table 17.1 The dynasties of imperial China

Xia (*c.* 2070–1600 BCE)
Shang (*c.* 1600–1300 BCE)
Zhou (1046–256 BCE)
"Spring and Autumn" period (770–476 BCE)
Warring States period (475–221 BCE)
Qin (221–207 BCE)
Han (207 BCE–220 CE)
Three Kingdoms (220–280 CE)
Jin (265–420 CE)
Northern and Southern Dynasties (420–589 CE)
Sui (581–618 CE)
Tang (618–907 CE)
"Five Dynasties and Ten States" period (907–60 CE)
Song (960–1279 CE)
Yuan (1271–1368 CE)
Ming (1368–1644 CE)
Qing (1644–1911 CE)

17.2 Sources of Documentary Evidence

With respect to sources, the documentary evidence on weather and climate can be broken down into four types: classical literature, local gazettes, documents of the central administration, and private diaries. Apart from private personal diaries, these documents are mostly institutional records (see Chap. 6). They were commissioned by emperors eager to learn about local conditions and local history, and compiled by knowledgeable grand secretariats. Therefore, most of the records are of high quality and relatively objective and reliable.

Classical literature, called *Jing Shi Zi Ji* in Chinese, includes the canonical texts of history, philosophy, science, and medicine. Of the forty-four categories of classical literature compiled in the *Si Ku Quan Shu* ("The Complete Collection in the Four Branches of Literature") published in 1787, twenty-eight categories representing 1531 books contain some climatic information, including indications of temperature, precipitation, droughts and flood, and other meteorological events.

The relevant volumes covering the period 30 BCE–1470 CE have been found to contain 22,567 items providing climatic information with definite times and locations (see Fig. 17.1).[1] In addition, the *Ming Shi Lu* ("Veritable Records of the Ming Dynasty") and *Qing Shi Lu* ("Veritable Records of the Qing Dynasty"), compiled during the Ming and Qing dynastic periods respectively, recorded important political and social affairs, as well as natural disasters and abnormal climatic events. The *Qing Shi Gao* ("Manuscript of History of the Qing Dynasty"), compiled during the early republican period, also contains much information about climate.

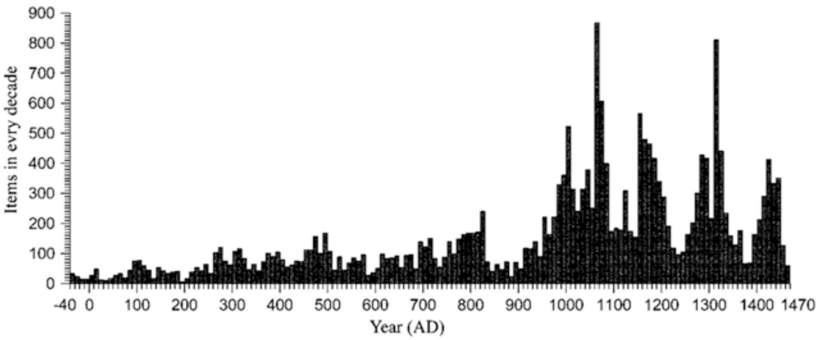

Fig. 17.1 The number of records in Chinese documents containing climate information for each decade (30 BCE–1470 CE). Reproduced from Q.-S. Ge et al., "Coherence of Climatic Reconstruction from Historical Documents in China by Different Studies," *International Journal of Climatology* 28 (2008): 1007–24, with permission from John Wiley & Sons

Local gazettes are official histories reporting both the natural and human events of a particular administrative unit (county, prefecture, or province). Gazettes first appeared during the Zhou and Qin Dynasties; they became standardized during the Song Dynasty (960–1279 CE); and they reached their peak in the Ming and Qing dynasties, when they were edited and revised almost every thirty years. According to statistics in the *United Catalogue of China's Local Gazettes*, some 8264 local gazettes have survived since around 960 CE, including 5685 from the Qing Dynasty alone, and they represent almost every county in China.[2]

Their climatic information focuses on droughts and flood, frosts and snow cover, severe cold, plant and ice phenology, agricultural conditions, changes in river systems, and natural disasters such as plagues and locusts. The times and locations of climatic events were clearly recorded and their impacts were described in detail (Fig. 17.2). We estimate that there may be more than 200,000 items of accurately located and dated climatic information contained in China's local gazettes for the past millennium.

Archives of the Qing Dynasty and the Republic of China. There are about 10 million files of Qing Dynasty archives in the Chinese First Historical Archive in the Beijing Palace Museum. These include ~600,000 files of *Zou Zhe* (memorials) with written comments by the emperors, and more than 2 million other memorials; ~400,000 files of the Royal Family Office; ~2.2 million files of the Palace Internal Affairs Office; ~1.5 million folders belonging to the six major government ministries; and ~2 million files concerning imperial decrees and other important government affairs.

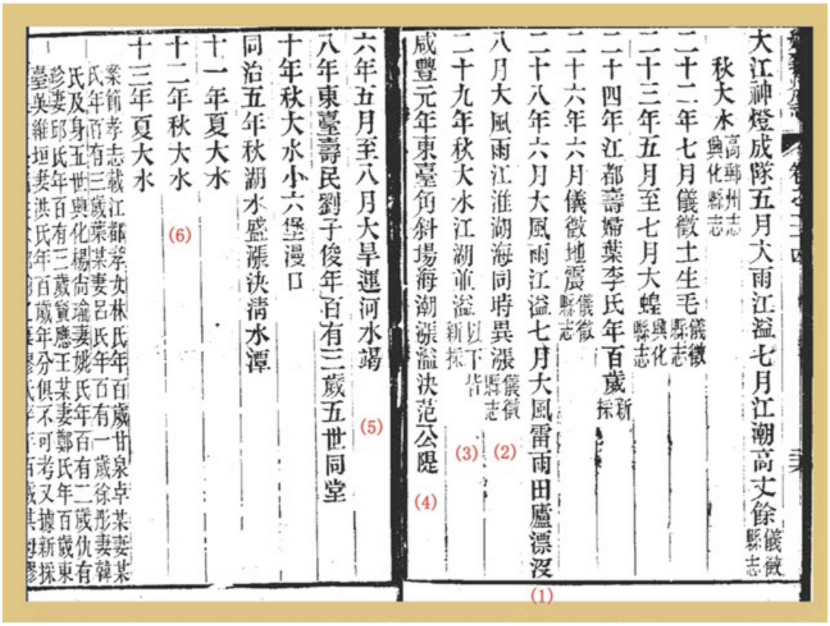
大江神燈成隊五月大雨江溢七月江潮高丈餘儀徵縣志
秋大水高郵州志 興化縣志
二十二年七月儀徵土生毛儀徵縣志
二十三年五月至七月大蝗興化縣志
二十四年江都壽婦葉李氏年百歲新採
二十六年六月儀徵地震儀徵縣志
二十八年六月大風雨江溢七月大風雷雨田廬漂沒 (1)
八月大風雨江淮湖海同時異漲儀徵縣志 (2)
二十九年秋大水江湖並溢以下皆新採 (3)
咸豐元年東臺角斜場海潮漲溢決范公隄 (4)
六年五月至八月大旱運河水竭 (5)
八年東臺壽民劉子俊年百有三歲五世同堂
十年秋大水小六堡漫口
同治五年秋湖水盛漲決清水潭
十一年夏大水
十二年秋大水 (6)
十三年夏大水

Fig. 17.2 An example of climatic information recorded in a local gazette (from *Gazettes of Yangzhou Prefecture*, published in 1874). The two pages list disasters and abnormal events in the region for the period 1842–74 (from right to left), dated in the Chinese lunar calendar. The numbers in brackets indicate descriptions of disasters. For example, [1] indicates that in the sixth (lunar) month of the twenty-eighth year (of Daoguang—that is, 1848), there were strong winds and heavy rain, and the Yangtze River overflowed; in the seventh month, there were strong winds and thunderstorms, leaving fields and houses submerged. Reproduced from Q.-S. Ge et al., "Coherence of Climatic Reconstruction from Historical Documents in China by Different Studies," *International Journal of Climatology* 28 (2008): 1007–24, with permission of John Wiley & Sons

Two series are particularly important for climate reconstruction. The Records of Sunny or Rainy Days (*Qing Yu Lu*) provide daily observations about the state of the sky, wind direction, and the type, intensity, and duration of precipitation events (e.g., clear skies, light rain, snow, etc.). For Beijing, these observations have been preserved for the period 1724–1903 with only six missing years, and the records have proven consistent with the instrumental meteorological record that began in 1841. Besides Beijing, officials in Nanjing (1723–98), Suzhou (1736–1806), and Hangzhou (1723–73) all reported daily weather to the central administration.

The Records on Rainfall Infiltration and Snowfall (*Yu Xue Fen Cun*) contain measurements on how deep each precipitation event infiltrated into the soil. These measurements followed standard criteria in all eighteen provinces down to the level of prefectures, from 1693 to the end of the Qing Dynasty in 1911. Local officials recorded them in the Chinese units of *fen* (≈3.2 mm) and *cun* (≈3.2 cm), and submitted them directly to the emperor (see Fig. 17.3).[3]

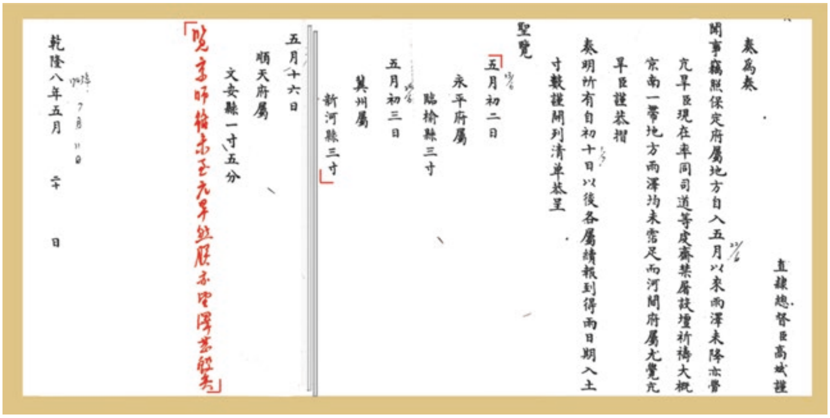
直隸總督臣高斌謹
奏為奏
聞事竊照保定府屬地方自入五月以來雨澤未降亦暫
亢旱臣現在率同司道等虔齋禁屠設壇祈禱大概
京南一帶地方雨澤均未霑足而河間府屬尤覺亢
旱臣謹恭摺
奏明所有自初十日以後各屬續報到得雨日期入土
寸數謹開列清單恭呈
聖覽
五月初二日
永平府屬
臨榆縣三寸
五月初三日
冀州屬
新河縣三寸
五月十六日
順天府屬
文安縣一寸五分
乾隆八年五月 二十 日

Fig. 17.3 This example from the Records on Rainfall Infiltration and Snowfall (*Yu Xue Fen Cun*) contains the first and last pages (right to left) of an original twelve-page memo prepared by Gao Bin, Governor of Zhili Province (near Beijing) dated on the twentieth day of the fifth (lunar) month of the eighth year of the Qianlong Reign (July 11, 1743). Reproduced from Q.-S. Ge et al., "Coherence of Climatic Reconstruction from Historical Documents in China by Different Studies," *International Journal of Climatology* 28 (2008): 1007–24, with permission from John Wiley & Sons

Private diaries. As of 2016, researchers had located about 200 private diaries containing records of everyday weather conditions or weather-related natural phenomena. The *Diary of Gengzi-Xinchou* (1180–1181 CE) by Lü Zuqian (1137–1181 CE) is among the earliest. These diaries often made clear and detailed descriptions of the timing, location, and conditions of climate events, which could be used for reconstruction.[4]

17.3 Types of Documentary Evidence

With respect to content, these records can be further divided into two categories:

The first category consists of more or less objective observations of natural proxies, particularly plant-phenological observations and ice- and snow-phenological data (see Chap. 4). The former includes observations on the development of wild and domesticated plants; the distribution and northern boundary of subtropical cash crops, such as sugar; and the dates of agricultural activities, which in China includes the location and timing of double (twice-yearly) rice crops. The latter comprises records of the dates of the first and last frosts and snowfalls; the duration of frost and snow; and the freeze and thaw dates of rivers, lakes, and seas.

The second category of documentary evidence consists of qualitative descriptions of weather and discussions of weather and society, particularly the impacts of extremes and meteorological disasters. This evidence provides information especially about relative changes in temperature (e.g., that a particular season was "rather cold," or a particular location enjoyed a "warm winter").[5]

Since the 1970s, researchers have undertaken several reconstructions of Chinese historical climate using documentary sources.[6] These studies have quantified documentary information into annual or seasonal indices, then calibrated it to modern instrumental data in order to establish a statistical relationship and thereby to reconstruct temperature and precipitation at different temporal and spatial resolutions (see Chap. 11). Based on these results, this chapter outlines the main variations in temperature and precipitation in eastern China during the last 2000 years.

17.4 Temperature Reconstructions

In 1973, Chu created the first temperature series from historical documents, covering the past five millennia. The series provided an approximate temperature change profile, indicating that the temperatures were ~2 °C higher around 3000–1000 BCE than in the 1950s reference period, and that temperatures showed 2–3 °C amplitude since around 1000 BCE. Three remarkable cold periods were centered at about 400, 1200, and 1700 CE, while the period around 500–1000 CE was generally warm. Following this pioneering work, researchers found more and more climate-related information and developed statistical methods to convert the many qualitative descriptions into quantitative series. Based on the described intensity of frosts, snows, and rains, the dates of the river and lake freezings, cold-related disasters, and other information, R. Wang and S. Wang reconstructed the winter temperatures in eastern China (25–35°N, 115–120°E) during the 1470s–1970s CE.[7] They identified two cold stages, during the 1450s–1690s and 1790s–1890s CE. Later, S.-L. Wang and collaborators reconstructed a decadal temperature series beginning in the 1380s for each of ten regions across China. This study identified three cold periods—the 1450s–1510s, 1560s–1690s, and 1790s–1890s CE—covering most of the Little Ice Age (LIA) (see Chap. 23).[8]

Other studies during the 1990s reconstructed decadal winter temperatures in southern China and Shandong Province during the 1470s–1970s, as well as the Taihu Basin (around modern Shanghai) during the 1100s–1970s, by calculating the frequency of cold and warm years recorded in historical documents.[9] In 2000, Wang and Gong catalogued historical records of abnormal meteorological and hydrological phenomena, and reconstructed a winter cold index series for every fifty-year period in eastern China during 800–2000 CE.[10]

In 2003, Ge and colleagues reconstructed winter half-year (October–April) temperatures for the past 2000 years in the central region of eastern China (25–40°N, 110–120°E) at a resolution of ten to thirty years. Their reconstruction was based on the frequency and intensity of cold and warm events revealed by plant- and ice-phenological evidence in Chinese historical documents. From the beginning of the Common Era, average temperatures fell at a rate of 0.17 °C per century; then the winter half-year abruptly warmed up from the 570s to the 1310s at a rate of 0.04 °C per century. After that decade, temperatures dropped at a rate of 0.1 °C per century, a change that coincides with the onset of the LIA in the Northern Hemisphere. Since the start of the twentieth century, and particularly since the 1980s, temperatures in the winter half-year have increased.[11]

More recently, researchers have used historical documents to create temperature series with an annual resolution. In 2012, Hao and colleagues reconstructed mean annual winter (December–February) temperatures over the middle and lower reaches of the Yangtze River (24°N–34°N, 108°E–123°E) extending back to 1736, based on information regarding snowfall days in the Records on Rainfall Infiltration and Snowfall (*Yu Xue Fen Cun*) archive (see Sect. 17.2). They found that the eighteenth century was 0.76 °C colder and the nineteenth century 1.18 °C colder than the reference period of 1951–2007. However, since the twentieth century, winter temperatures have been increasing.[12]

In spite of this considerable effort to reconstruct China's historical temperatures at high resolution, researchers sometimes produced different results even when using similar documents. In a 2008 review, Ge and colleagues compared various temperature series and found that a thirty-year temporal resolution might be reasonable for studying temperature changes using Chinese documentary data. They also found that the spatial patterns among the different time series showed high coherence.[13]

Building on these studies and other proxy climate data, subsequent studies investigated the general characteristics of climate changes, regional differences, and uncertainties in Chinese climate reconstruction over the past 2000 years (see Fig. 17.4).[14] Relative to 1851–1950 mean values, the climate in China during the Common Era showed four warm intervals—roughly 1–200 CE, 551–760, 951–1320, and after 1921—and four cold intervals—201–350, 441–530, 781–950, and 1321–1920 (covering the entire LIA period). Temperatures from 981 to 1100 and again from 1201 to 1270 were comparable to those of the present warm period but with an uncertainty of ±0.28 °C to ±0.42 °C at the 95% confidence interval. Since 1000 CE—the period covering the Medieval Climate Anomaly (MCA), LIA, and the present warm period—temperature variations over China have typically been in phase with those of the Northern Hemisphere as a whole. In contrast, the warm period in China during 541–740 CE has not been found elsewhere.

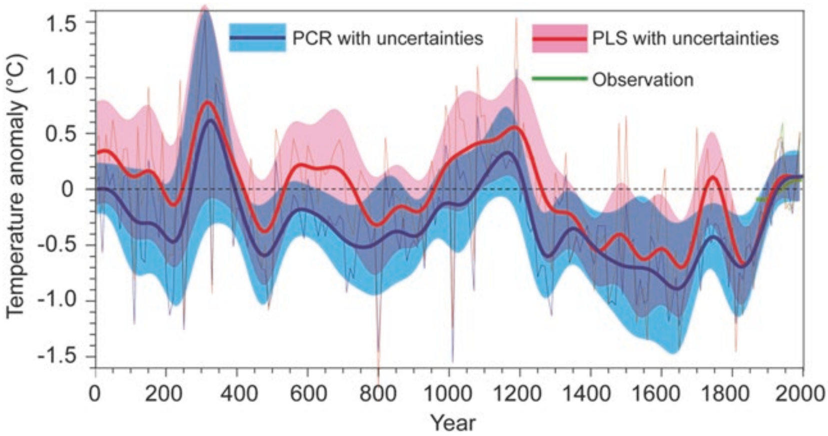

Fig. 17.4 An ensemble of temperature reconstructions based on partial least squares (red lines) and principal components regression (blue lines) methods at decadal (thin lines) and centennial timescales (solid lines; smoothed by a five-point fast Fourier transform filter), along with the 95% confidence interval (shading). The reference value is the mean temperature from 1851 to 1950. The green line indicates the observed average air temperature. Image reproduced without changes from Q. Ge et al., "Temperature Changes Over the Past 2000 Yr in China and Comparison with the Northern Hemisphere," *Climate of the Past* 9 (2013): 1153–60, doi:10.5194/cp-9-1153-2013, under a CC-BY 3.0 license: https://creativecommons.org/licenses/by/3.0/

17.5 Precipitation Reconstructions

China possesses a rich legacy of documents describing drought and flood disasters with direct impacts on agriculture and society, particularly for the last two millennia. In 1981, these documents were used to reconstruct annual precipitation since 1470, by converting the qualitative descriptions found in historical sources for each of 120 stations into a quantitative grade from 1 (wetness) to 5 (dryness).[15] Using this dataset, a 2006 study reconstructed an annual Pacific Decadal Oscillation (PDO) series for the pre-instrumental period.[16]

So far, the longest drought/flood proxy dataset drawn from Chinese historical documents covers sixty-three stations from 137 BCE to 1469 CE using 22,567 written descriptions.[17] Employing the two above-mentioned datasets, Zheng analyzed the severity, duration, and spatial patterns of droughts and floods from 101–1900 CE, and reconstructed a 1500-year regional dry/wet index series for the North China Plain (approximately 34–40°N), the Jianghuai area (approximately 31–34°N), and the Jiangnan area (approximately 25–31°N).[18] The results show extended droughts in eastern China from the twelfth to fourteenth centuries; however, since the middle of the seventeenth century, eastern China has been more subject to flooding. Flood severity during the twentieth century was comparable to that of historical times, but the droughts were usually less severe.

Nevertheless, strong regional differences should not be overlooked, such as opposite trends in the Jiangnan and Jianghuai areas during the eleventh–thirteenth centuries or in the North China Plain and Jiangnan area since the sixteenth century. Hao studied the spatial patterns of precipitation anomalies in eastern China during both warm and cold periods over the past 2000 years.[19] This study showed that there has been no one fixed spatial pattern of precipitation anomalies during either cold or warm periods. During most of China's warm periods, a coherent spatial pattern of dry conditions only occurred north of the Yangtze River. Precipitation during cold periods showed various spatial patterns; similarities were only present during the seventeenth and nineteenth centuries, when there was a meridional (north–south) gradient in precipitation. Compared with the warm twentieth century, the period 440–540 demonstrated an opposite spatial pattern of precipitation, but the seventeenth and nineteenth centuries both showed similar patterns (see Fig. 17.5).

Since 2005, the Records on Rainfall Infiltration and Snowfall (*Yu Xue Fen Cun*) archive has also been used in precipitation reconstructions. A study by Q.-S. Ge and colleagues combined these records with modern field measurements that followed the same ancient methods.[20] Starting with experiments at Shijiazhuang—which demonstrated the potential for high-resolution reconstruction back to the early eighteenth century—they followed up with an expanded field measurement program in eastern China, and developed models fitting the relationship between rainfall infiltrations recorded in the *Yu Xue Fen Cun* and observed precipitation at each site. A subsequent study by Zheng and colleagues used this method to create a precipitation series for the middle and lower reaches of the Yellow River during the period 1736–1910.[21] Further research has reconstructed the initial/final dates and duration of the *meiyu* (the East Asian June–July rainy season) for the middle and lower reaches of the Yangtze River, as well as the northwestern part of the East Asian Summer Monsoon.[22]

17.6 Extreme Events

Historical climatologists have also employed documentary evidence to reconstruct extreme events. For example, a 2012 study identified fifty extremely cold winters during 1650–1949, based on 4000 pieces of verifiable information extracted from local gazettes in southern China. The authors' criterion was winters in the coldest tenth percentile of the probability density function. These were seasons characterized by the freezing of lakes and rivers, snow and ice storms, or widespread damage to subtropical crops from the cold. The study found that the frequency of extreme winters has varied since 1650. The most frequent occurrences came during the late seventeenth and the nineteenth centuries (including the Maunder and Dalton sunspot minima) when extreme winters were twice as common as in 1950–2000. By contrast, extreme winters during the eighteenth century were almost as rare as in the second half

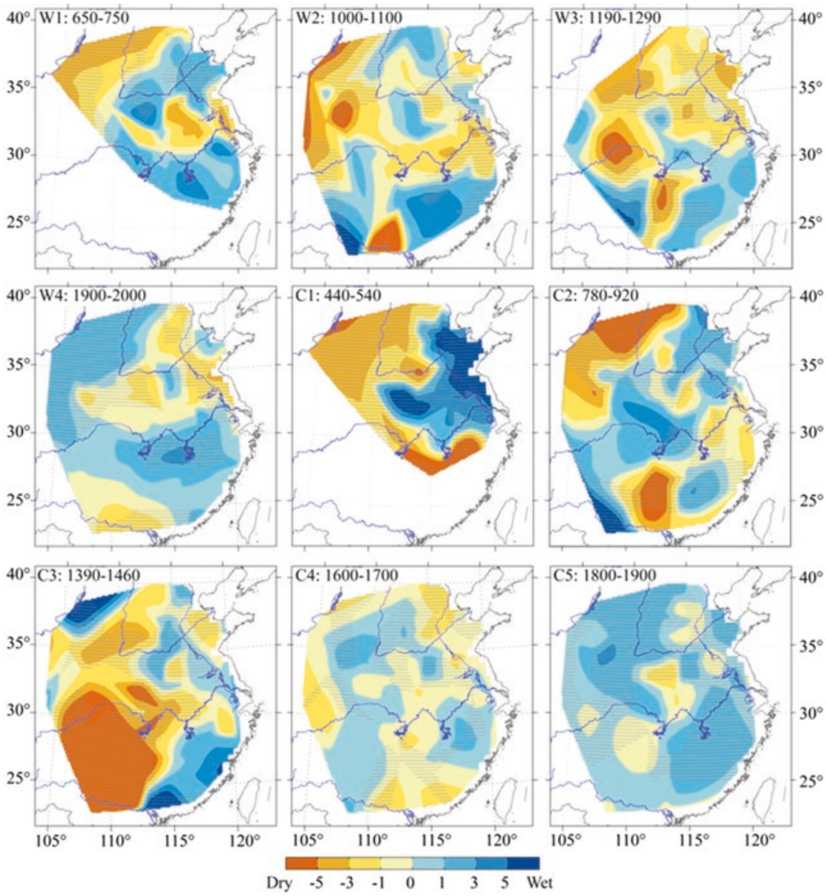

Fig. 17.5 Spatial patterns of precipitation anomalies over eastern China (with reference to the average values of the past 2000 years) during the four warm ("W") and cold ("C") periods, on a centennial timescale. The shaded area exceeds the 90% significance level based on a chi-square test. Reproduced from Z. Hao, J. Zheng, X. Zhang, H. Liu, M. Li, and Q.-S. Ge. "Spatial Patterns of Precipitation Anomalies in Eastern China during Centennial Cold and Warm Periods of the Past 2000 Years." *International Journal of Climatology* 36 (2015): 467–75 with permission of John Wiley & Sons

of the twentieth century. The intensities of some historical cold events, as in 1653–54, 1670, 1690, 1861, 1892, and 1929, exceeded those of the coldest winter events since 1951.[23]

Based on annual precipitation indices derived from historical sources, as well as the reconstructed wet/dry index series for eastern China, historical climatologists have identified extreme drought and flood events during the past two millennia in three regions of the North China Plain (34°N–40°N), as well as Jianghuai (31°N–34°N) and Jiangnan (25°N–31°N).[24] The highest frequency of extreme flood and drought events occurred during roughly 100–150, 550–650, 1050–1100, and 1850–1900 in the North China Plain; 250–450 and 1600–1850 in Jianghuai; and 350–400, 1100–1200, and 1900–50 in Jiangnan. Over the whole of eastern China, higher frequencies of extremes came during 100–150, 250–350, 750–850, 950–1000, 1050–1150, 1400–50, 1550–1650, and 1800–1950. During the late twentieth century, the frequency and intensity of extremes was close to the mean level of the past 2000 years. Furthermore, a comparison between drought/flood events and temperature series over eastern China suggests that global warming over recent decades did not bring more frequent extreme events. In addition, a 2008 study found that the anomalous precipitation events reconstructed from Chinese historical documents mainly occurred at periods of high solar forcing, active volcanic eruption, and large anthropogenic forcing (the twentieth century).[25]

17.7 Climate Change Impacts

The human element in past and present climate change remains a controversial topic, which scholars may best approach by synthesizing climate reconstruction and historical narrative and analysis. Historical climate impact research in China has so far drawn three principal conclusions:

1. Historically, climatic change impacts tended to be negative in cold periods and positive in warm ones. For example, twenty-five of the thirty-one most prosperous periods in imperial China during the past 2000 years occurred during periods of warmth or warming.
2. Long-term cooling trends often coincided with social and economic decline. Population growth and expanded land use supported by an expanded resource base during warm periods tended to increase vulnerabilities when the climate turned colder.
3. Throughout Chinese history, both the rulers and ruled adopted strategies and policies to cope with climate change, as geography and circumstances permitted. Government decisions and initiatives were often decisive in the outcome of climate-related challenges.[26]

Notes

1. Zhang, 1996.
2. Beijing Astronomical Observatory, 1985.
3. Ge et al., 2005. For examples from these series, see the study of volcanic weather and its effects in China following the Tambora eruption of 1815 (Zhang et al., 1992).
4. Gong et al., 1984; Gong and Hameed, 1991.
5. Ge et al., 2003.
6. Zhu, 1973.
7. Wang and Wang, 1990.

8. Wang et al., 1998.
9. Zhang, 1980; Zheng and Zheng, 1993; Shen and Chen, 1993.
10. Wang and Gong, 2000.
11. Ge et al., 2003.
12. Hao et al., 2012.
13. Ge, 2008.
14. Ge et al., 2010, 2013.
15. Academy of Meteorological Science of China Central Meteorological Administration, 1981.
16. Shen et al., 2006.
17. Zhang, 1996.
18. Zheng et al., 2001, 2006.
19. Hao et al., 2016.
20. Ge et al., 2005.
21. Zheng et al., 2005.
22. Ge et al., 2008, 2011.
23. Zheng et al., 2012.
24. Hao et al., 2010.
25. Shen et al., 2008.
26. Ge et al., 2014.

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CHAPTER 18

Climate History of Asia (Excluding China)

George C. D. Adamson and David J. Nash

18.1 Introduction

As the largest landmass on Earth, Asia's climatic history is of paramount importance. However, with the exception of China (see Chap. 17), research on the historical climatology of the continent remains in its infancy. Instrumental observation of weather in Asia began earlier than in many other parts of the world. In Siberia, observations date back to the formation of the Russian Central Physical Observatory in 1849, while the genesis of the Japanese Meteorological Agency began with the founding of the Tokyo Meteorological Observatory in 1875.[1] Systematic meteorological observation in India and Indonesia began shortly after the establishment in 1854 of national meteorological services in the UK and the Netherlands, the colonial countries who then governed these regions. The *Magnetisch en Meteorologisch Observatorium* in Batavia (Jakarta) was established in 1866, and the Indian Meteorological Department in 1875.

Reconstruction of climate for periods prior to the mid-nineteenth century using documentary sources is only just commencing, although it is further advanced in Japan than in other regions of the continent (excluding China). Reconstructions using tree rings are common in the Himalayas, the Mongolian steppes, northern Japan, and parts of Siberia. Coverage in tropical regions is

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much weaker due to the general absence of trees producing annual growth rings, although researchers have begun to derive climatic data from teak (*Tectona grandis*).[2]

As the climate of Asia is extremely diverse—ranging from subarctic in Siberia (Df in the Köppen classification) to tropical rainforest in Indonesia (Af)—the continent will be divided into five regions for the purposes of this chapter. These are Arabia and West Asia; the Indian subcontinent; Japan and Korea; Southeast Asia and Indonesia; and Siberia and Central Asia.

18.2 Arabia and West Asia

The documentary record of the Islamic world has been identified as a potentially fruitful source of historical climate information. Arabic (and other) language documents have been used substantially for information on historical astronomical occurrences.[3] However, climate reconstruction has as yet been either preliminary or focused on the Iberian peninsula.[4] The documents available for climate reconstruction are predominantly *ta'rikh* (history) chronicles, which require careful interpretation for climatic information. Moreover, many have been lost, existing now only in copies or abridged formats.[5] (On North Africa and the Nile Valley, see also Chaps. 20 and 34.)

Nevertheless, some reconstruction has been undertaken for the period 800–1500 CE, notably for Iraq, Syria, and Palestine. Using references to freezing conditions, Ricardo Domínguez-Castro and colleagues identified that the tenth century CE in Iraq witnessed a greater frequency of cold winters than the twentieth century. Steffen Vogt and colleagues have further demonstrated that winters from 900–50 and 1020–70 CE were particularly wet. At a coarser resolution, using documents from the late Roman Empire, Michael McCormick identified droughts in Palestine from 210–20 and 311–13 CE, a return to wetter conditions around 400 CE, and further droughts from 523–38 CE. Available information on the Arab world becomes more limited after 1500 CE, a reversal of the situation in most other parts of the world. This is likely related to a shift in the focus of the chronicles at the turn of the sixteenth century, from accounts of events to biographical data and anecdotes.[6]

The climate history of Anatolia has received somewhat more attention than that of the Arab world. Several scholars have undertaken studies assembling and mapping historical references to climatic and meteorological events during Hellenistic and Roman times.[7] Byzantine historians have compiled more extensive descriptions of climate (particularly extremes such as drought and freezing winters) from the fourth to fifteenth centuries CE. Some researchers have recently begun to integrate those descriptions with archaeological finds as well as palaeoenvironmental reconstructions, with the goal of formulating a more comprehensive interdisciplinary climate history of Byzantine Anatolia. So far, this research has identified probable periods of colder, drier climate during the fourth–fifth and late eighth–ninth centuries, and possibly warmer, wetter climate during the tenth to early eleventh centuries.[8] The Ottoman period (*c.* 1300–1923 CE) offers further potential for detailed documentary-based climate reconstruction, including, among other sources, numerous chronicles, travel narratives, records from the imperial archives in Istanbul, and European diplomatic dispatches. So far, only a handful of studies have analyzed particular episodes in Ottoman climate history, including Sam White's study of drought, rebellion, and crisis during the late sixteenth–seventeenth centuries.[9]

18.3 The Indian Subcontinent

Substantial written information on the climate of the Indian subcontinent becomes available from around 1700 CE onward. This is predominantly due to the knowledge-production project of various European colonial and missionary groups, particularly the British East India Company.[10] In recent years, scholars have begun to explore the documentary record of the East India Company to reconstruct the historical intensity of the monsoon and extreme meteorological events. The earliest reconstructions derive from records of the Royal Danish Lutheran-Protestant Mission in Tranquebar, which date from 1710.[11] In western India, the records of the East India Company have been used to reconstruct monsoon duration and intensity from 1780 to 1860.[12] These reconstructions have demonstrated a change in the average date of monsoon onset over time (Fig. 18.1), and have been used to explore the long-term relationship between the Indian monsoon and the El Niño Southern Oscillation. Using a selection of personal diaries from early nineteenth-century Bombay, George Adamson has also demonstrated that monthly maximum temperatures were then around 5 °C lower than today, likely a result of the urban heat-island effect.[13]

For the pre-colonial period, G.B. Pant and colleagues reviewed a number of different types of written source material to uncover broad-scale monsoon variability for the past ~1000 years. This work revealed a twelve-year drought between 1397 and 1408 and a random distribution of droughts from 1600 CE onwards. Recorded drought before this date was relatively low, likely due to a lack of preserved documentary evidence.[14]

18.4 Japan and Korea

Japan is one of the best-served regions for documentary climate reconstruction in Asia. Written evidence of climatic phenomena extends back to 55 CE.[15] Historical sources for climate reconstruction are reviewed in Takehiko Mikami's 2008 paper "Climatic Variations in Japan Reconstructed from Historical Documents."[16] The longest and possibly most robust record available is that of the "cherry blossom festivals," which coincided with the date of spring flowering of cherry trees at Kyoto, recorded regularly in diaries and chronicles. Flowering was found to correlate closely with average February–March temperatures, allowing springtime temperature to be reconstructed back to 801 CE.[17] Similar studies have been undertaken for Tokyo.[18] Likewise, the dates of

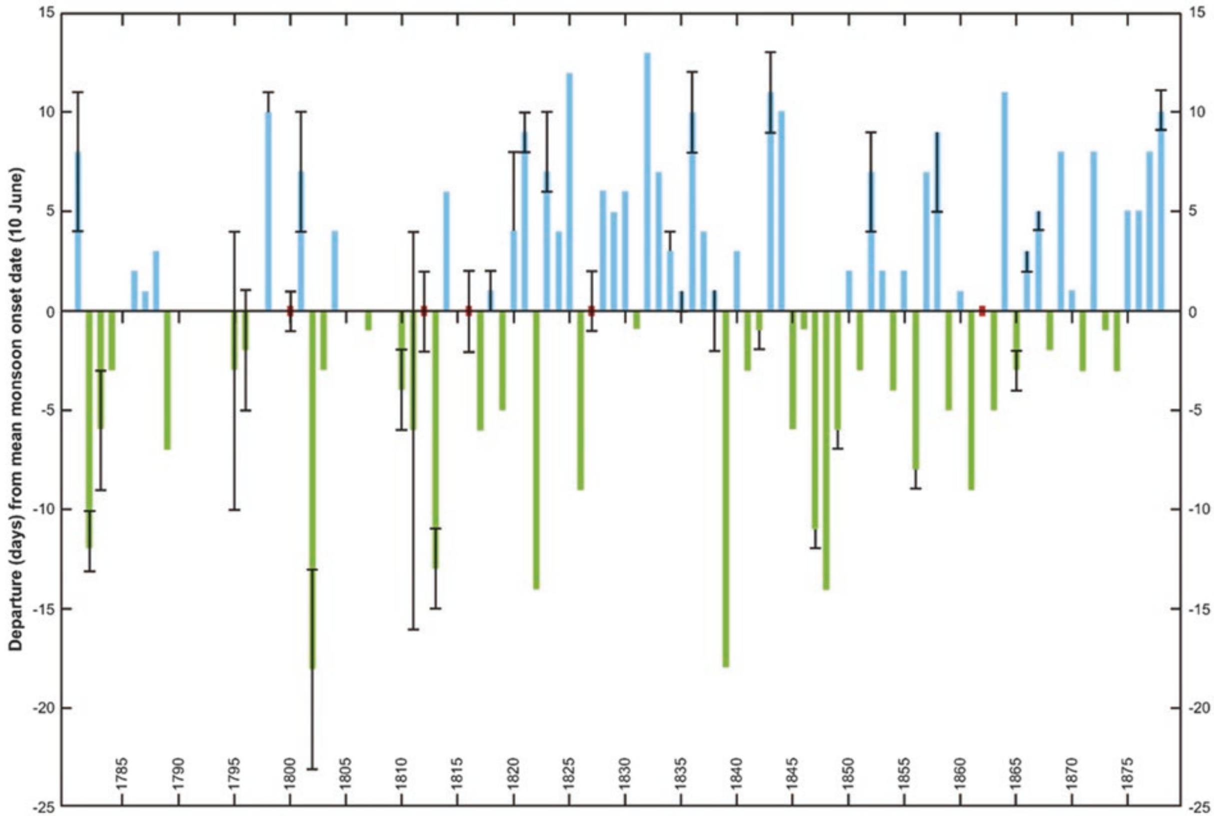

Fig. 18.1 Reconstructed date of monsoon onset over Bombay for 1781–1878 (with error bars). Positive values indicate a later date of monsoon onset. (Reproduced from George C.D. Adamson and David J. Nash, "Long-term variability in the date of monsoon onset over western India," *Climate Dynamics* 40 (2013): 2589–603. With permission of Springer)

ceremonies for the *Omiwatari* on Lake Suwa (a crack in the ice running the full length of the lake, caused by diurnal temperature variations) reach back to the fifteenth century. The date of freezing was found to be highly correlated with mean December–January temperatures, allowing reconstruction of these temperatures back to 1444 CE. A large number of weather diaries from the eighteenth century onward have been digitized in the Historical Weather Database of Japan, also enabling reconstruction of summer temperatures. These show a general increase in temperatures from around 1800 onward, although this increase is not uniform.[19] Other studies have used references to typhoons in documentary materials to reconstruct northwest Pacific typhoon frequency and tracks during the nineteenth century.[20]

Woo-Seok Kong and David Watts have undertaken a coarse-grained reconstruction of precipitation, frost, droughts, and floods for Korea using documentary evidence.[21] This reconstruction demonstrates major cold phases from 1001 to 1400 CE, dry phases during 201–600, 701–900, and 1001–1300 CE, and humid phases from 400 to 500 and 1000 CE to the present. Famine seems to have been associated with the cold phases. Gyo-Ho Lim and Tae-Hyeon Shim additionally used the Annal of the Chosun Dynasty to reconstruct extreme weather events from around 1400 CE, indicating extreme droughts around 1440, 1600, and 1680, and wet periods around 1410, 1520, and 1660.[22] The authors are unaware of any other such studies in Korea, although some may be available in the Korean language.

18.5 Southeast Asia and Indonesia

Southeast Asia and Indonesia have generally been understudied with regards to documentary climate analysis, although tree ring reconstruction has been undertaken in parts of Java and Thailand. The authors are aware of no precipitation or temperature reconstructions, despite a wealth of documentary materials available from the records of the Dutch East India Company (VOC) and Dutch colonial government, as well as in local languages. More work has been done on cyclones (typhoons), particularly in the Philippines. Ricardo García-Herrera and colleagues reconstructed landfalling typhoons over the Philippines from 1566 to 1900, particularly using records compiled by the Spanish Jesuit Miguel Selga in 1935.[23]

Research by historians not specifically designed to reconstruct climatic variability has uncovered evidence of extreme events, particularly drought. Victor Lieberman has outlined evidence for drought in Burma, Cambodia, and Vietnam during the fourteenth century, a period that saw the concurrent decline of Pagan, Angkor, and Dai Viet.[24] Brendan Buckley and colleagues reviewed evidence for climate extremes in central Vietnam from the thirteenth–eighteenth centuries using historical chronicles.[25] They note in particular a period of heavy climate-related mortality associated with the seventeenth-century "crisis."[26] In general, such analysis has been only descriptive, and systematic climate reconstruction from documentary sources in the region remains elusive.

18.6 Siberia and Central Asia

Despite the availability of a number of sources of documentary evidence, most notably historical chronicles and Russian governmental documents and grade books, documentary-based climate reconstructions in Siberia and Central Asia also remain very limited. Much of the early work on the historical climatology of the former Soviet Union east of the Urals is reviewed by Borisenkov. Of particular note are the relatively mild climate conditions reconstructed in Siberia during the early to mid-seventeenth century—at the heart of the Little Ice Age—when conditions were sufficiently favorable to allow Russian vessels to sail from the Kola Peninsula to Chukotka in northeast Siberia and through the Bering Straits, opening up a trade route to the Pacific.[27] The authors are aware, though, of no other significant studies.

18.7 Conclusion

Despite its size, Asia's climate history (outside China) remains far less studied than that of Europe or North America. The chief source for historical climate patterns in much of the continent is the Monsoon Asia Drought Atlas, deriving predominantly from tree rings.[28] However, this work is constrained by the geographical spread of the growth-ring producing trees (mostly located in the Himalayas) and has been found to be unreliable in places.[29] Documentary climate reconstruction that has been undertaken has shown the importance of such approaches for understanding long-term climate variability, and the influence of climate on social change. Other work not specifically designed for climate reconstruction has demonstrated the potential of the written record in the region, and it is hoped that the climate history of the continent will continue to be revealed in the future.

Notes

1. Fleming, 1998.
2. Cook et al., 2010.
3. Domínguez-Castro et al., 2012.
4. Grotzfeld, 1991, 1995; Bulliett, 2009; Weintritt, 2009; Vogt et al., 2011; Domínguez-Castro et al., 2012, 2014; de Miguel, 1988.
5. Domínguez-Castro et al., 2014.
6. Grotzfeld, 1995.
7. e.g., McCormick et al., 2012a, 2012b.
8. Telelis, 2008; Haldon et al., 2014; Xoplaki et al., 2016.
9. White, 2011; Xoplaki et al., 2018.
10. Grove, 1998.
11. Walsh et al., 1999.
12. Adamson and Nash, 2013, 2014.
13. Adamson et al., 2014.
14. Pant et al., 1993.

15. Ingram et al., 1981.
16. Mikami, 2008.
17. Aono and Omoto, 1994; Aono and Kazui, 2008; Aono and Saito, 2010.
18. Aono, 2015.
19. Mikami, 2008.
20. Grossman and Zaiki, 2009.
21. Kong and Watts, 1992.
22. Lim and Shim, 2002.
23. Ribera et al., 2004, 2008; García-Herrera et al., 2007.
24. Lieberman, 2011.
25. Buckley et al., 2014.
26. Reid, 1990; Boomgaard, 2001.
27. Borisenkov, 1995.
28. Cook et al., 2010.
29. Adamson and Nash, 2014.

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CHAPTER 19

Climate History in Latin America

María del Rosario Prieto and Facundo Rojas

19.1 Pre-Colonial Records

In Latin America, written information about climate and related topics begins shortly before the Spanish conquest. The Americas were previously populated by groups with different degrees of social, political, and economic integration, from bands of hunter-gatherers to urban states with a high degree of political development, social stratification, and division of labor. In Mesoamerica, the Maya and the Aztec states developed pictographic and ideographic writing systems on paper made from tree bark. The texts as we know them began with the fourth king of the Mexica, named Itzcoatl (*c.* 1380). He ordered the destruction of previous records to create a new Aztec history distinct from that of their old enemies, the Toltec people. Most historical authors are anonymous, but they were likely priests trained as scribes or *tlahcuilo*, the "artists" of the famous Aztec picture books.[1] The surviving manuscripts and ritual calendars cover a range of topics, including pictographs of natural disasters and descriptions of historic events. These codices have information on large snowfalls, frosts, droughts, and their consequences, such as epidemics, plagues, and famine, accompanied by precise dates for each event. This type of information is most abundant in the Aztec codices, which cover the twelfth through seventeenth centuries. Prehispanic codices are considerably less common than those written during the colonial period, as many of the prehispanic ones were destroyed by the Spanish conquerors. Most surviving codices were written during the early colonial period in the Valley of Mexico.[2]

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19.2 Colonial and Modern Records

Christopher Columbus arrived in the Antilles in 1492 on an expedition sponsored by the Spanish crown. This marked the beginning of Spanish voyages of exploration and conquest in the north and south of what would later be called the Americas. In 1494, Pope Alexander VI and the Treaty of Tordesillas divided the Americas between Spain and Portugal.[3] A few years later, in 1500, the Portuguese Pedro Álvares Cabral, among other Europeans, arrived on the Brazilian coast and began the conquest and colonization of those lands. Ferdinand Magellan crossed the strait that bears his name in 1520, opening a sea route to the Pacific.[4] At the same time, Hernán Cortés landed on the Mexican coast; his army and native allies overthrew the Aztec state after fierce resistance. They captured its capital Tenochtitlan in 1521 and founded Mexico City in its place. This began a period of expansion into not only Central and South America but also parts of the current southwestern USA.[5] A decade later, Francisco Pizarro led another expedition into Peru and confronted the Inca Empire, already facing a civil war. They captured and killed the emperor Atahualpa, leading to the fall of that great state. From this point on, the Iberian conquest advanced rapidly, although peripheral areas were not dominated until later.

The colonial regime saw extensive cultural and biological mixing with indigenous populations, as well as high mortality and environmental disruption from European invasive animals, plants, and microbes. Colonial governments were installed, first as governorships and later viceroyalties. The first viceroyalties were New Spain (Mexico), Peru, and New Granada (modern Ecuador, Colombia, and Venezuela), followed in 1776 by the viceroyalty of the Río de la Plata (Argentina) (see Fig. 19.1).[6]

Of the evidence left by the Spanish, the city council documents (*Actas Capitulares*) stand out. They came out of weekly city council meetings held in most cities throughout the Spanish empire until the early nineteenth century. In addition to collections of such documents preserved by national archives in Latin America, the holdings of the Archivo General de Indias (AGI) in Seville are fundamental. This archive brings together all documents sent to and received from the Americas, including correspondence on events affecting the regional economy, such as droughts, floods, and heavy rains. The Spanish colonial presence in Latin America has strongly influenced the sources used in studies of climate history. The large majority of written documents—from Spain as well as the Americas—are colored by the particularities and idiosyncrasies of those who produced them.

Of the more recent documentary sources, newspapers are especially important. Most Latin American newspapers began during the nineteenth century. Many are still in print, such as *Los Andes* in Mendoza (Argentina), founded in 1885. Since instrumental data for snowfall in the Argentine–Chilean Andes began only in 1951, M. Prieto and colleagues included information from newspapers from 1885 to 2000.[7] They were able to determine the number of annual snowfalls, the beginning and end of the annual snow cycles, and their relationship with the El Niño Southern Oscillation.

Fig. 19.1 Cities and places mentioned in the text

Climate reconstructions through the 1700s are based only on proxy data and historical documents. More objective data becomes available during the nineteenth century with the start of instrumental measurements (see Table 19.1). At the end of the eighteenth century and during the nineteenth, non-professional meteorologists began to record some data. A paradigmatic example is Francisco José de Caldas, who began to record the first systematic data on temperature and atmospheric pressure in the first decade of the 1800s in Popayán (currently in Bogotá, Colombia).[8]

Table 19.1 Starting dates for instrumental data in Latin American countries

Current country	*Start of observations*[9] (*Sporadic/* continuous)	*City*	*Person or institution recording the data*	*Source*
Colombia	*1735*	Cartagena	Juan de Ulloa	Pabón Caicedo, 2008
	1799	Popayán, Santa Fé (Bogotá)	F.J. de Caldas, Observatorio Astronómico Nacional[10]	
	1866	Bogotá	Observatorio Meteorológico Nacional	
Peru	*1753*	Lima	Cosmógrafos Mayores	Seiner Lizárraga, 2004
	1892		Observatorio Meteorológico Hipólito Unánue	Universidad Católica del Perú, 2015
Mexico	*1769*	Mexico City	José Antonio de Alzate y Ramírez	Comisión Nacional del Agua, 2012
	1877		Observatorio Meteorológico y Astronómico de México	Jáuregui Ostos, 2000
Brazil	1781	Rio de Janeiro, San Pablo	Francisco de Oliveira Barbosa and Bento Sanches Dorta	Neto and Lima, 2004; Farrona et al., 2012
	1808	Rio de Janeiro	Marinha do Brasil	Oliveira and João, 2005 Web page: Observatório Nacional (Brasil);
Cuba	*1794*	Havana	Captain Tomás Ugarte	Ramos Guadalupe, 1996
	1858[11]		Real Colegio de Belen	Udías, 2003
Argentina	*1804*	Buenos Aires	Pedro Cerviño	Prieto, 2016
	1872	Córdoba	Observatorio Meteorológico Nacional	
Ecuador	1825	Quito	Colonel Hall	Hall, 1838
	1864		Colegio Nacional de Quito	Aguilar, 1865
Chile	*1850*	Santiago, La Serena, Copiapó, Valparaiso	J.M. Gillies-I. Domeyko	Anales de la Universidad de Chile, 1851
	1868		Oficina Central Meteorológica, Universidad de Chile	Anales de la Universidad de Chile, 1870; Web page: Servicio Meteorológico de la Armada de Chile

19.3 The Development of Climate History in Latin America

The development of climate history as a discipline in Latin America began only two years after E. Le Roy Ladurie's pioneering study *Histoire du climat depuis l'an mil* (1967). Enrique Florescano's 1969 thesis became the first scientific examination of relationships between climate and society in Latin America.[12] Several studies, including a critical review of sources, have appeared since the year 2005, covering South America, Colombia, Peru, and southern Chile.[13] Usually, there is more information on the scarcity or abundance of water than on temperature, except in temperate areas where early or late freezes affected harvests.[14]

Mexico has been a country of pioneering studies in climate history. Extreme droughts predominate in Mexico, which has influenced the choice of research topics. A study by G. Garza Merodio divides Mexican researchers into two groups: on the one hand, scholars from various disciplines who emphasize climate reconstruction (the "strict climate" or "climate first" approach); on the other hand, historians and social scientists who incorporate climatic events as an explanatory factor in specific historical processes (the "case-study approach"). Generally, the latter address a specific extreme event such as an extraordinary drought or flood that is interpreted using concepts of risk, disaster, and vulnerability.[15] A two-volume compilation by García Acosta has brought together case studies covering 2000 years of Latin American history, up to the end of the nineteenth century.[16] These are landmarks in the study of Latin American climate history.

Pioneering studies such as those by G. Padilla, S. Metcalfe, and colleagues anticipated methodologies and topics that climate historians have since developed more fully.[17] Thanks to their wide-reaching compilation of data on droughts, floods, and heavy rains, they contributed to the development of long-term regional climate data series. Besides classic studies of Mexican droughts, other studies appeared in force during the 1990s, including those of D. Liverman and the already classic work by E. Florescano and S. Swan, in which the authors systematized some of the principal sources on droughts.[18] These studies are contemporaneous and follow the same approaches as O'Hara and Metcalfe, and as Tortolero.[19]

More recently, a number of new authors have gained prominence. These include G. Garza Merodio, who has looked for regional signals of the Little Ice Age and created indices for droughts in the Valley of Mexico from the end of the sixteenth to the middle of the eighteenth centuries based on an analysis of rain ceremonies (*pro pluvia*) (see Chap. 4).[20] We agree with Garza Merodio, who pointed out that long-term regional climate studies that use documentary sources to develop continuous and homogeneous data series "have been utilized very little in Mexico toward the end of the twentieth century."[21] Further studies have analyzed colonial Spanish and Nahuatl sources to reconstruct Mexican climate variability and impacts at local scales, incorporating comparative case studies and indigenous perspectives (see Chap. 30).[22]

19.4 Studies of Climate Forcings

19.4.1 El Niño Southern Oscillation, Droughts, and Floods

The northern coast of Peru and the southern coast of Ecuador are the areas most directly affected by increases in sea-surface temperature during El Niño Southern Oscillation (ENSO) events, which result in heavy precipitation. William Quinn and colleagues have written the most complete—but sometimes controversial—documentary chronology of ENSO events, based principally on secondary sources.[23] In 2000, Luc Ortlieb revised Quinn's chronology, addressing some ambiguities in Quinn's work.[24] More recently, Ricardo García Herrera and colleagues have developed a new ENSO chronology based mainly on primary sources from the municipal archive of Trujillo, Peru.[25] ENSO has also been studied in the southern Pacific Ocean through information in the ship logbooks of the Manila galleon fleet, which traveled between Acapulco (Mexico) and the Philippines.[26]

There are fewer studies of ENSO in Chile, even though its signal is clear and it brings copious rainfall. Ortlieb has connected rains in central Chile with El Niño years and has also published a detailed compilation of rains in northern Chile during the nineteenth century.[27] Further studies have traced connections between ENSO and years with increased snowfall in the Argentine–Chilean Andes and fluctuations in the flow volumes of the Mendoza River.[28] The rivers of northeastern Argentina are intimately tied to ENSO. M. Prieto examines flooding of the Paraná River during 1590–1805.[29] In terms of ENSO-related droughts, historical climatologists have reconstructed rainfall variability in the Andean puna grassland, particularly in Potosí and La Paz, and have also connected ENSO to historical droughts in central Mexico.[30] Blanca Mendoza and colleagues have studied the frequency and duration of droughts in the Valley of Mexico and been able to tie them to ENSO, the Atlantic Multidecadal Oscillation, and Southern Oscillation Index in the Yucatán Peninsula.[31]

19.4.2 Caribbean Cyclones

Climate historians in Caribbean countries have principally focused on hurricanes, given their importance in the region. Cyclone frequency has been studied through historical documents beginning with the earliest data on cyclones in 1500.[32] García Herrera and colleagues have undertaken a significant study of historical hurricanes in the Caribbean based on logs of Spanish and English ships.[33]

19.4.3 Ship Logs, Maritime Climate, and Southern Glaciers

Unlike in Europe, old drawings and paintings of glaciers are scarce in South America, and so research is based more on historical documents (cf. Chap. 8).[34] Logbooks from ships, mainly from Spain, have provided valuable information

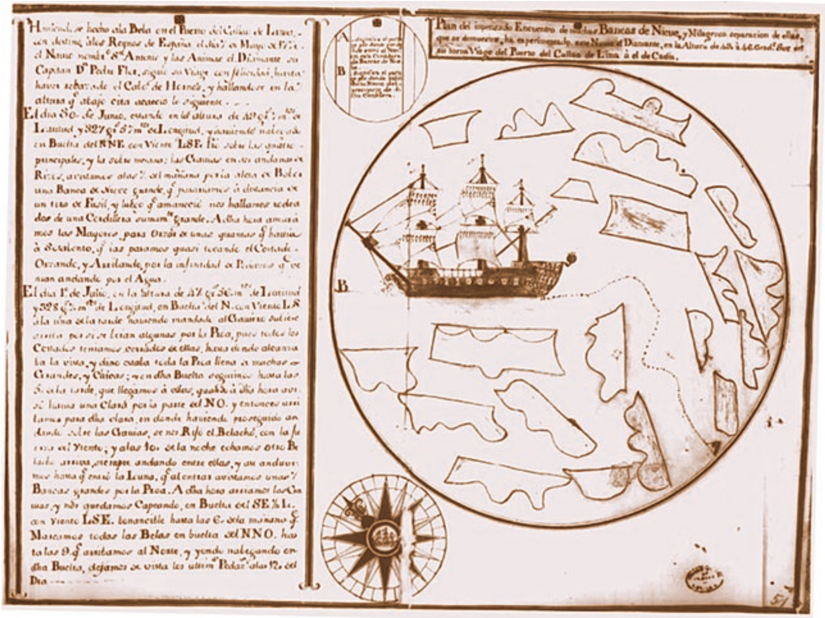

Fig. 19.2 Iceberg sightings from the *Diamante* during the voyage from Lima, Peru to Cádiz, Spain. AGI, Maps and Charts of Peru and Chile, May 1770. (Reproduced from M.R. Prieto, R. García Herrera, and E. Hernández, "Early Records of Icebergs in the South Atlantic Ocean from Spanish Documentary Sources," *Climatic Change* 66 (2004): 29–48. With permission of Springer)

on the southern maritime climate, principally in the Strait of Magellan between 1520 and 1619, in addition to descriptions of nearby glaciers.[35] For instance, Prieto and colleagues have described five sightings of iceberg clusters prior to those recorded by Captain Cook in 1772–75 (Fig. 19.2).[36]

19.4.4 Hydroclimatic Variability in South America

Researchers studying climate variability in Argentina have focused on regional precipitation and the run-off of rivers that originate in the Andes. Some have concentrated on determining fluctuations in the flow of the Mendoza River and their correlations with glacial advances in the Andes during the Little Ice Age.[37] Rivers of northern Argentina have also received attention, such as research on the flow of the Salí Dulce River, and a data series incorporating an ordinal index of very low flow (−2) to exceptional floods (2) for the Bermejo River.[38] Other studies have examined climate variability, droughts, and heavy rainfall in the same region.[39] Studies of Brazil have emphasized droughts in the northeast and their connection to social problems.[40] In Brazil, R. Araki has done a historical reconstruction to interpret the climate in São Paulo.[41]

19.5 Conclusion

Latin American historical climatology has seen significant growth in recent decades, but it remains focused on certain regions and topics. Most research covers Mexico, Argentina, and the Pacific coast of South America. A few principal themes have emerged, such as the compilation of long data series (precipitation, river flows, and ENSO events) used to verify the impact of climate variations on people and institutions. There has also been an intense amount of work directed at interpreting relationships between droughts and social processes, principally in Mexico and Brazil. We believe that there have been important advances in the discipline toward more quantitative perspectives, in tune with developments in Europe by researchers of the Pfister and Brázdil schools (see Chap. 11).[42]

Acknowledgment Thank you to Erik Marsh for translating this chapter.

Notes

1. Bethell, 1984.
2. González Álvarez, 2006.
3. Morales Padrón, 1963.
4. Pigafetta, 1954.
5. Morales Padrón, 1963.
6. See Fig. 19.1 for modern place names in the text.
7. Prieto et al., 2001.
8. Pabón Caicedo, 2008.
9. Dates refer to key times. In most cases, the first year of observations marks the beginning of a brief period of instrumental data. Continuous datasets began later, and usually were recorded by an institute of meteorology organized by the state or the Jesuits. The table does not include data from sailors from coastal areas, which in some cases was even earlier.
10. Some authors consider this to be the first meteorological station in the Americas.
11. From 1858 to 1961, discontinuous instrumental data was recorded in Havana. This is an important data series because of the early start date and because the series extends for more than 100 years.
12. This thesis studies agricultural crises (in terms of the price of corn and droughts) that led to famine, migrations, and social conflict in Mexico between 1708 and 1813; Florescano, 1969.
13. Prieto and García Herrera, 2009; Pabón Caicedo, 2008; Carcelén Reluz, 2009; Prieto et al., 2012.
14. Prieto, 1983.
15. Garza Merodio, 2007.
16. García Acosta, 1996, 1997.
17. Padilla et al., 1980; Metcalfe, 1987.
18. Liverman, 1990; Florescano and Swan, 1995.
19. O'Hara and Metcalfe, 1995; Tortolero, 1996.
20. Garza Merodio, 2002, 2007.
21. Garza Merodio, 2002, 106.
22. Endfield, 2008; Skopyk, 2010.
23. Quinn et al., 1987; Quinn, 1992.

24. Ortlieb, 2000.
25. García Herrera et al., 2008.
26. García Herrera et al., 2001.
27. Ortlieb, 1994.
28. Prieto et al., 1999, 2001.
29. Prieto, 2007.
30. Gioda and Prieto, 1999; Gioda, 1999; Mendoza et al., 2005.
31. Mendoza et al., 2005, 2007.
32. Walsh and Reading, 1991; Rappaport and Fernández-Partagás, 1997; Fernández-Partagás and Díaz, 1996; García Herrera et al., 2007.
33. García Herrera et al., 2001.
34. Guerrido et al., 2014.
35. Prieto et al., 2004; Araneda et al., 2007.
36. Prieto et al., 2004. To calibrate and verify these data series, a set of statistical calculations was used, following Neukom et al. (2009).
37. Prieto and Rojas, 2012; Gil Guirado et al., 2016.
38. Herrera et al., 2011; Prieto and Rojas, 2015.
39. Prieto et al., 2000, 2001.
40. Villa, 2000.
41. Araki, 2012.
42. Pfister et al., 2001.

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CHAPTER 20

A Multi-Century History of Drought and Wetter Conditions in Africa

Sharon E. Nicholson

20.1 Introduction

Africa contains the world's largest expanse of arid and semi-arid land. Its people have contended with its harsh conditions over millennia, developing a close relationship with the environment and climate. Droughts cause famine, economic hardship, mass migration, and death. Extraordinary rains cause dwellings to collapse, flood low-lying areas, and prevent travel and commerce. The close relationship between people and climate has figured prominently in the development of a climatic history for the continent. A nearly continuous record of the Nile extends back to the year 622 CE. Historical empires were chronicled, so that records of famine and drought exist in many parts of the continent as of the eighth century or earlier.[1] When the Portuguese began exploration of sub-Saharan Africa commencing in the fifteenth century, additional information concerning its climate history came to light. By the seventeenth century, Holland, Denmark, and Sweden had established a presence on the continent.

Africa was a hub of European activity in the nineteenth century, the focus of dozens of explorers and geographical expeditions, as various European countries fought for power. Colonies, settlements, forts, trading posts, and missions were variously established by the French, Belgians, British, Portuguese, Italians, Spanish, and Germans. Climate, especially droughts, was of great interest to them, and a wealth of meteorological information resulted. The diverse sources include maps, meteorological diaries and observations, geographical studies, missionary reports, and travelers' journals.

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Historical references to drought and wetter conditions allow for the reconstruction of climate over several centuries. In most cases, absolute certainty cannot be established. However, "convergence of evidence" from numerous sources is used to create a chronology of the most likely conditions that prevailed. By the nineteenth century, enough information was available to allow for the development of semi-quantitative annual records for the whole continent since 1800.[2]

20.2 Multi-Century Drought Chronologies

Figure 20.1 presents "drought" chronologies commencing in the sixteenth century for several African regions. These include Sahelian West Africa, the Cape Verde Islands, the Guinea Coast, Algeria, Tunisia, Morocco, coastal Angola, and the western Cape of South Africa (see also Fig. 20.2). They are constructed from documentary evidence in the early centuries, then rain gauge records beginning in the mid- to late nineteenth century.

The chronologies should be interpreted with caution, as information is not available for every year. However, historical information is plentiful enough in these regions, that the absence of mention of drought is a likely indication of adequate conditions of rainfall. Reports of very wet years appear, but references to drought are much more frequent. This contrast exists for three reasons. First, in the semi-arid regions that prevail over Africa, dry years occur more frequently than wet years. Second, drought is a broad, regional phenomenon while intense rainfall is often more localized in nature. Third, drought tends to have more human impact than wetter conditions and thus more importance may be placed upon it.

20.2.1 Equatorial Regions

Perhaps the longest and most complete equatorial chronology is that for Angola, commencing in 1550, from Miller.[3] Major droughts occurred in the 1580s, the 1610s, and the 1710s, while dry conditions were frequent in the 1640s and 1650s. There was a near absence of drought throughout most of the eighteenth century, until the mid-1780s and 1790s. Numerous dry years also occurred in the 1810s.

Historical records for the Guinea Coast derive mostly from southern Ghana, particularly from the Cape Coast castle or the Danish fort at Christiansborg (modern Accra).[4] Relatively good conditions prevailed throughout most of the eighteenth century until the late 1770s, when several dry or drought years occurred consecutively. Good rainfall returned in the 1780s and continued until at least the turn of the century. References to drought are common in the nineteenth century, except for a sequence of wet years around 1840 or 1850. Sediment cores from various equatorial lakes, particularly Lakes Bosumtwi and Kamalete, support these broad trends.[5]

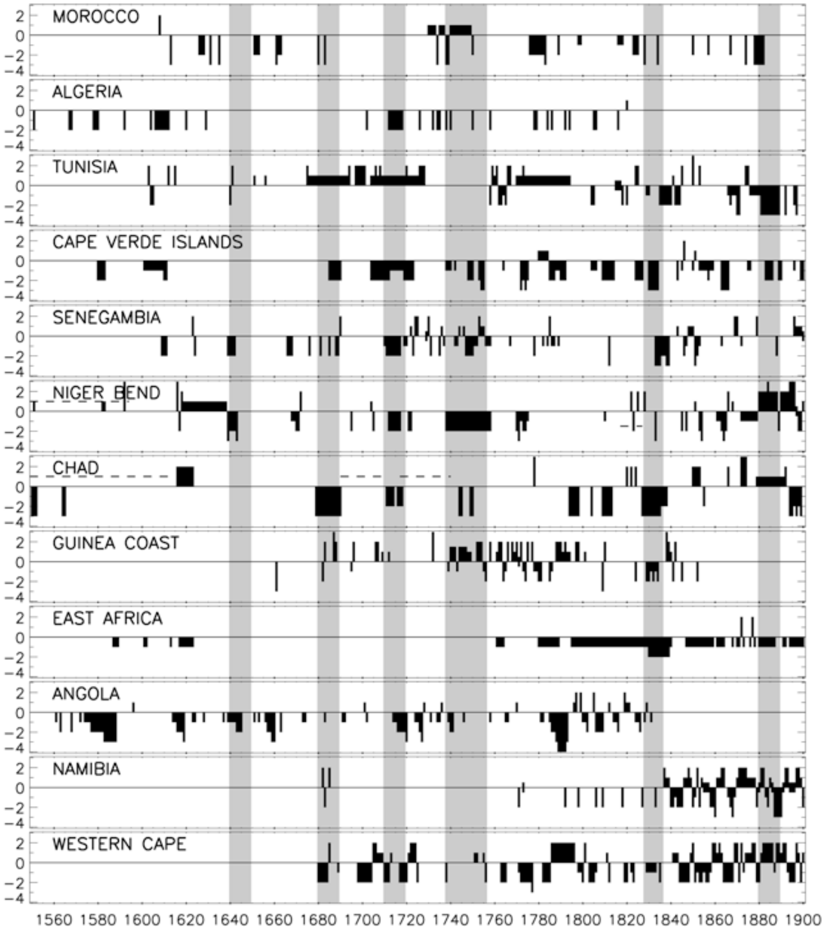

Fig. 20.1 Climatic chronologies for select regions of Africa (see Fig. 20.2 for location). Negative numbers indicate dry conditions or drought. The length of the bar is arbitrary, but −1 is generally indicative of dry conditions, −2 an actual drought, and −3 severe drought. Similarly, positive numbers indicate good to very good conditions of rainfall. The dashed horizontal lines indicate general periods of wetter or drier conditions. The chronologies for Algeria, Senegambia, the Guinea Coast, and Angola stop at the point where reliable gauge data becomes available. Widespread intervals of anomalous conditions are shaded.

For East Africa, most of the currently available information lacks good temporal resolution. The exception is the Nile flood information available for several centuries, but it is difficult to interpret in terms of annual precipitation.[6] References to drought and famine are often described as occurring during the reign of a particular ruler and are generalized.[7] Lake level information is relatively plentiful for the last few hundred years, but it generally does not have

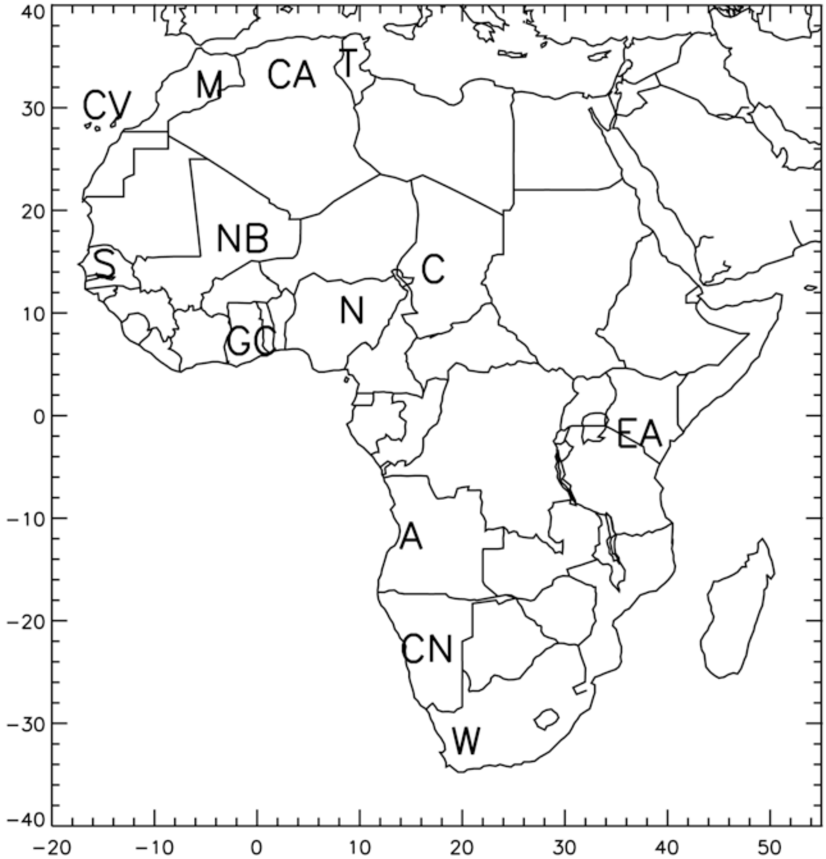

Fig. 20.2 Location of regions in Fig. 20.1: Niger Bend (NB), Senegambia (S), northern Nigeria (N), Chad (C), Cape Verde Islands (CV), Guinea Coast (GC), coastal Algeria (CA), Tunisia (T), Morocco (M), coastal Angola (A), western Cape of South Africa (W), East Africa (EA), Central Namibia (CN)

annual resolution. The lakes with useful records include Naivasha, Edward, Baringo, Tanganyika, Victoria, Malawi, Turkana, Duluti, and Challa.[8]

These tend to support the observation that the fluctuations in the eastern equatorial regions tend to be out-of-phase with those in the western. However, dry conditions at the end of the eighteenth century and the first few decades of the nineteenth century appear to have been ubiquitous. In East Africa they were calamitous, especially in the 1830s.[9] Reports from European travelers in East Africa indicated a famine had prevailed in the Pangani Valley of Tanzania and around Mombasa, Kenya for some twenty years.[10] In the mid-1830s, a Ukerewe chief had been deposed because he could not stop the multiyear drought that caused widespread starvation.[11] Lakes Chibwera and Kanyamukali in western Uganda and Baringo in central Kenya became completely desiccated in the late nineteenth and early twentieth centuries, and other lakes fell continuously during this time.[12] During the period 1785–1835, rainfall over the Lake Victoria basin was probably about 15% lower on average than during the twentieth century.[13]

20.2.2 Sahelian West Africa

In the Sahel, rainfall conditions were good throughout most of the sixteenth century to the mid-seventeenth century.[14] However, drought affected Senegambia and northern Nigeria around 1610 and Senegambia and the Niger Bend from around 1639 to 1643.[15] Prolonged and widespread drought episodes occurred in the 1680s, the 1710s, and around 1738–56.

The Cape Verde Islands, just west of the Sahel, experienced many of the same droughts as the Sahel.[16] Drought was an infrequent occurrence from the 1550s to the late seventeenth century. However, drought occurred in the early 1600s, in the 1680s, in the 1710s, and in the late 1730s to mid-1750s. Rainfall was plentiful early in the 1780s, but drought prevailed again from about 1785 to 1792.

20.2.3 Southern Africa

Some of the longest historical records from the low-latitude portions of southern Africa come from Namibia, Botswana, and South Africa.[17] Figure 20.1 shows an example of a drought chronology from Namibia, where droughts tend to occur synchronously throughout most of the country. The most extensive period of drought may have been in the 1830s and 1840s. An extended period of good rainfall prevailed in the 1870s, but a severe drought commenced in the late 1880s. Elsewhere in southern Africa, such as the Kalahari and summer-rainfall regions of South Africa, drought conditions were common in the 1820s and 1830s.[18] Extensive dry conditions in the 1840s affected the Kalahari and parts of Zimbabwe.[19]

20.2.4 Extratropical Margins

Unlike the rest of Africa, the North African coast and the Cape region of South Africa receive predominantly winter rainfall and are generally governed by mid-latitude meteorological processes. Thus, the rainfall trends in these regions show little relationship to each other or to those of the African tropics.

In Tunisia, good conditions prevailed from about 1600 to 1760. Only three drought years occurred within that period.[20] Several drought years occurred in the mid-1700s, but a stretch of good years ensued until the 1810s. From that time onward, drought occurrence was relatively frequent.

In Algeria, drought occurred frequently from the mid-1500s to the early 1600s, but from 1630 to 1700, the region appears to have been drought-free.

Drought occurred frequently from the 1710s to around 1820, after which time good conditions of rainfall set in.

In Morocco, historical records indicate that catastrophic drought and famine occurred in 1519–21, 1626–8, and 1651–3. Analysis of sediments suggests further drought episodes in the six years 1776–82 and in the three-year periods 1815–18 and 1822–5.[21] On a timescale of centuries, drought occurrence in Morocco appears to be roughly out of phase with drought occurrence in Algeria. During the mid-eighteenth-century Sahel drought, Morocco experienced good rainfall.

Historical information implies that drought episodes occurred in the winter-rainfall region of the western Cape around the 1690s and in the 1760s and 1770s.[22] Good seasons prevailed early in the eighteenth century and in the 1780s. Tree rings from the southwestern Cape confirm these wetter conditions, but not the period of drought.[23]

20.3 The Nineteenth and Twentieth Centuries

With the plentiful information available for the nineteenth century, more detailed and reliable climatic records could be constructed. Combining this material with rain gauge measurements, Nicholson and colleagues were able to construct semi-quantitative time series of annual rainfall for ninety regions of the continent from 1800 to present (Fig. 20.3).[24] The basis of the method is the use of regions that are homogeneous with respect to interannual variability. That is, important wet or dry years tend to affect the entire region.

Because so much of the available material is descriptive, a seven-class system is used to describe the "wetness" of the season. (For more on the conversion of descriptive material into quantitative indices, see Chap. 11.) The values −1 to −3 represent dry conditions, drought, and severe drought, respectively. A zero denotes normal conditions and +1 to +3 indicate a range from good rains to anomalously wet then very wet. Statistical methods were used to convert rain gauge data to these same categories and to create spatial detail.

The resultant dataset for each region and year is depicted in Fig. 20.4. The lowest region numbers commence in the northern extreme of Africa and the highest are generally for the southern extreme. However, there is no strict geographical correspondence to the numbering. The Sahel/Soudan zone includes roughly regions 9–22 and equatorial Africa is roughly regions 23–40 (see Fig. 20.3).

The most striking feature is the extensive period of aridity on a continental scale in the 1820s and 1830s. It is also evident in the two-century-long time series derived from this dataset (Fig. 20.5), in the Nile flood record, and in the sediments of numerous lakes in East and southern Africa, some of which were completely desiccated at this time.[25] The 1830s, in particular, was one of the most severe drought episodes experienced by the peoples of East Africa.[26]

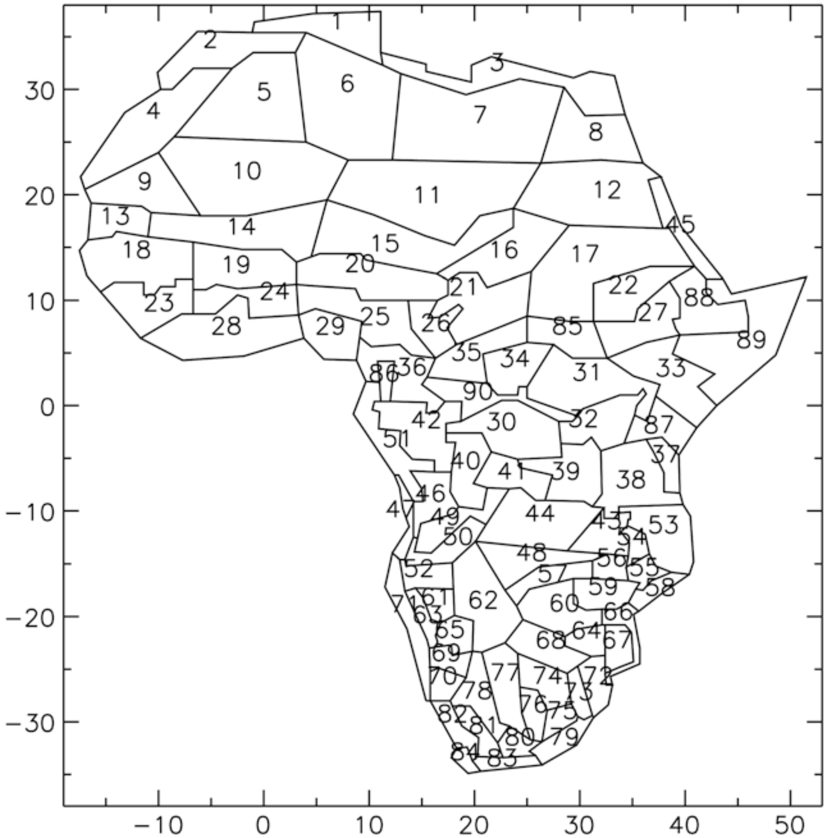

Fig. 20.3 Map of ninety regions depicted in Fig. 20.4

These conditions often provoked famine, migrations, and, in many places, decimation of the population.

Another important climatic episode occurred late in the nineteenth century (Fig. 20.4). During the 1880s, rainfall was continually good throughout the Sahel and much of the area to the north of it. Unfortunately, though, it was a period of intense drought throughout many of the equatorial regions, particularly in East Africa.[27]

20.4 Summary

From the evidence presented, two firm conclusions can be drawn. One is that major episodes of drought tend to affect large portions of the continent, thus tying them into large-scale and perhaps global patterns of climate. Examples include the 1640s, the 1680s, the 1710s, the late 1730s to the mid-1750s, and

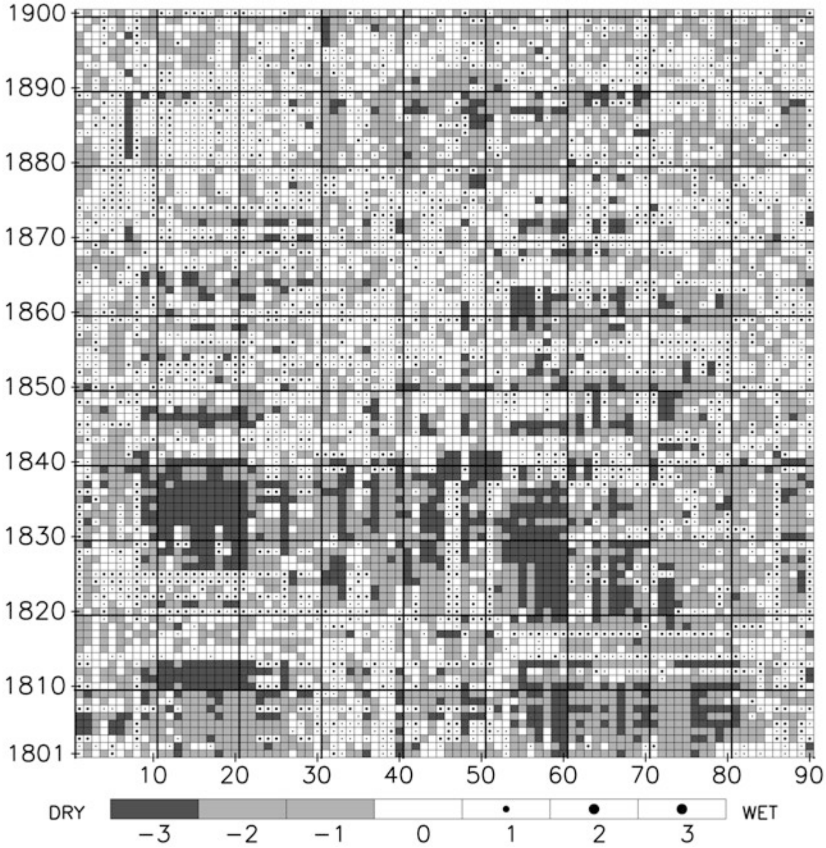

Fig. 20.4 Semi-quantitative dataset. The dataset includes several categories, indicating a range of conditions from extreme drought (−3) to very wet (+3). All wet categories are indicated by a dot.

the 1780s. The droughts of the 1680s and mid-1700s were evident across the east–west extent of the Sahel and appeared to include the Guinea Coast in many years as well.[28] The second conclusion is that a period of major aridity affected nearly the entire continent in the early nineteenth century, leaving its mark on Africa's inhabitants.

Africa, with its predominantly arid and semi-arid environments, may be the continent most affected by projected global climate change. In view of the climatic teleconnections across the continent, this could mean continent-wide impacts. Thus, future climate change could be disastrous for Africa.

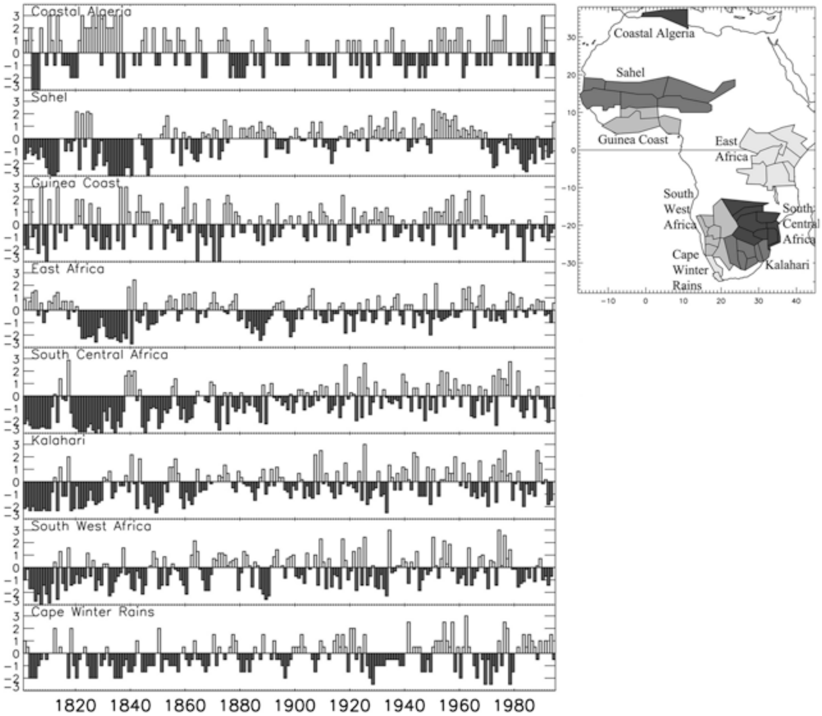

Fig. 20.5 Select regional time series based on the data in Fig. 20.4

Notes

1. Nicholson et al., 2012a.
2. Nicholson et al., 2012b.
3. Miller, 1982.
4. Norrgård, 2013; Nicholson, 1996.
5. Shanahan et al., 2009; Ngomanda et al., 2007.
6. Popper, 1951.
7. Spinage, 2012.
8. Ricketts and Johnson, 1996; Verschuren et al., 2000, 2009; Verschuren, 2004; Russell et al., 2007; Nicholson, 1998, 1999; Kiage and Liu, 2009; Wolff et al., 2011; Öberg et al., 2013; Russell and Johnson, 2005.
9. Hartwig, 1979.
10. Ajayi and Crowder, 1972.
11. Spinage, 2012.
12. Bessems et al., 2008; Nicholson, 2001.
13. Nicholson and Yin, 2001.
14. Nicholson, 1978.
15. Becker, 1985; Nicholson, 2001.
16. Almeida, 1997; Brooks, 2006; Patterson, 1988.

17. Vogel, 1989; Nash and Endfield, 2008; Nash and Grab, 2010; Kelso and Vogel, 2007; Neukom et al., 2014.
18. Nicholson et al., 2012a, 2012b.
19. Neukom et al., 2014.
20. Bois, 1944.
21. On Algeria: Marchika, 1927; on Morocco: Abdelhadi, 1987.
22. Nicholson, 1981.
23. Nicholson, 1996.
24. Nicholson et al., 2012a, 2012b.
25. Hartwig, 1979; Nicholson, 2001; Verschuren et al., 2000; Bessems et al., 2008.
26. Hartwig, 1979.
27. Hartwig, 1979.
28. Nicholson, 1980; Norrgård, 2013, 2015.

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CHAPTER 21

Recent Developments in Australian Climate History

Joëlle Gergis, Linden Ashcroft, and Don Garden

21.1 Introduction

Despite Australia being home to one of the world's oldest cultures, an understanding of its climate history is still emerging. While Australian Aboriginal culture is intricately linked to the environment and landscape, the oral nature of indigenous history means that quantitative data on interannual climate variability is limited to European arrival on the continent in 1788 (for more on climate history and indigenous peoples, see Chap. 30).[1]

The Sydney region of modern New South Wales (NSW) was Australia's only colony from 1788 until 1803, when settlement expanded to the island of Van Diemen's Land, now known as Tasmania (Fig. 21.1).[2] European settlement began in what became the modern states of Queensland (1824), Victoria (1834), and South Australia (1836), and reached most of the western and northern parts of the continent by the mid-nineteenth century.[3] As such, our understanding of early Australian climate history is predominately confined to the geographical areas of south-eastern Australia (SEA) and locations in and around the Sydney region of NSW until the middle of the nineteenth century.[4]

Early explorers and nineteenth-century polymaths were fascinated by the Australian climate, and several historical compilations of instrumental and documentary weather and climate information date back to that time.[5] Similarly,

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https://doi.org/10.1057/978-1-137-43020-5_21

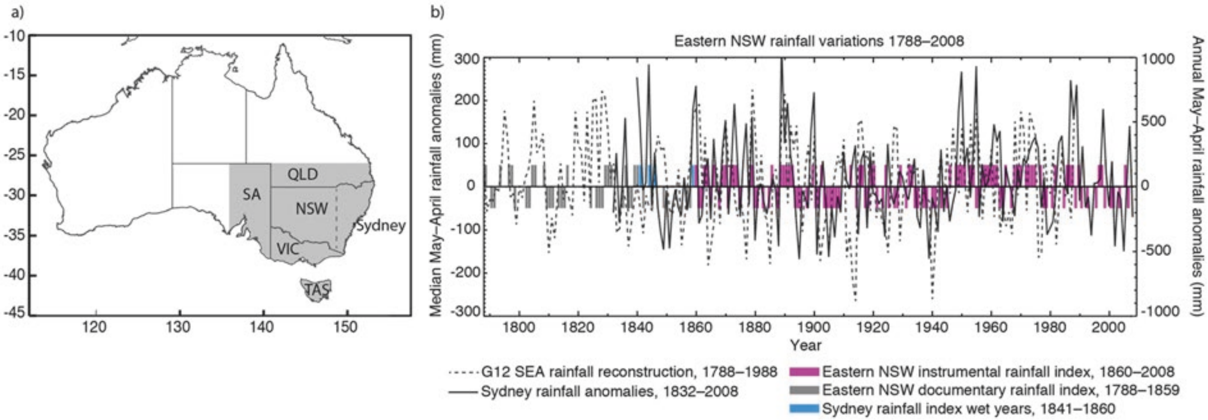

Fig. 21.1 (**a**) A map of Australia showing the south-eastern Australia (SEA) study region. The states of South Australia (SA), Victoria (VIC), New South Wales (NSW), Queensland (QLD), and Tasmania (TAS) are marked, as well as the city of Sydney and the eastern NSW region (east of the vertical dashed line). (**b**) Wet and dry years for eastern NSW identified using a nine-station instrumental rainfall network described in Gergis and Ashcroft (2013) (1860–2008, purple), the documentary chronology of Fenby and Gergis (2013) (1788–1860, grey), and historical rainfall for Sydney (1841–60, blue). The median rainfall reconstruction of Gergis et al. (2012) (G12; 1788–1988) is plotted as anomalies (mm) relative to a 1900–88 base period (dashed line), as well as long-term Sydney rainfall anomalies (1832–2008) relative to 1910–50 (solid line).

dedicated individuals recorded information on the weather and climate conditions that they experienced in the southern colony.[6] However, until recently, these Australian historical records remained virtually untapped for use in contemporary climate research. The vast majority of scientific climate studies focus on the twentieth and twenty-first centuries, once the Australian Bureau of Meteorology was formed and instrumental observations became more readily available.[7]

The climate of SEA is dominated by high rainfall variability, due in large part to the impact of the El Niño–Southern Oscillation phenomenon (ENSO).[8] Consequently, the majority of environmental history research has focused on the influence of rainfall variability and water availability on the landscape and psyche of European settlers in Australia.[9] The impacts of ENSO events have also been the focus of contributions to the fields of Australian environmental history and modern climatology.[10]

21.2 The South Eastern Australian Recent Climate History Project

Until recently, research in the fields of climate science and environmental history in Australia took place largely in isolation from one another. From 2009 to 2012, an initiative known as the South Eastern Australian Recent Climate History (SEARCH) project (www.climatehistory.com.au) addressed this lack of disciplinary interaction and engaged palaeoclimatologists, meteorologists, and historians to consolidate the region's early instrumental and documentary climate records back to first European settlement in 1788.[11]

A 2013 study by C. Fenby and J. Gergis examined twelve documentary-based rainfall chronologies for SEA comprising colonial archive reports, personal diaries, and newspaper accounts that contained detailed information about past drought, floods, and other significant weather events since first European settlement. This study identified twenty-four new drought years in SEA and seventeen previously undescribed wet periods in eastern NSW between 1788 and 1900 (Table 21.1).

This analysis was then expanded by J. Gergis and L. Ashcroft, who used recovered historical rainfall records, modern rainfall data, and the documentary compilation by Fenby and Gergis to develop an eastern NSW drought and wet year index over the 1788–2008 period. This series now represents Australia's first comprehensive drought and wet period chronology, combining an unprecedented analysis of Australian colonial documentary records with newly recovered and homogenized instrumental climate data (see Chap. 7 on early instrumental measurements and Chap. 9 on homogenization).[12]

Table 21.1 lists a total of seventy-one wet and eighty-one dry years identified for eastern New South Wales spanning the 1788–2008 period.[13] Given that the majority of Australian drought studies begin in the late nineteenth century, here we focus on highlighting a few of the more significant, largely undescribed dry and wet years experienced in eastern NSW from 1788 to 1899 (Fig. 21.1).[14]

Table 21.1 Dry and wet years for eastern NSW identified from documentary (1788–1860 for dry, 1788–1840 for wet, italic font) and instrumental rainfall records (1860–2008, plain font)

Dry years	*Wet years*
1790–1	*1788*
1798	*1793*
1802–3	*1796–7*
1809–11	*1804–5*
1813–15	*1808*
1824	*1816*
1826–8	*1829–31*
1835	*1836*
1837–8	*1839–40*
1842	1859–60
1845	1863–4
1849	1866
1857–8	1869–70
1861–2	1872–4
1865	1879
1868	1886
1871	1889–93
1875	1900
1880–1	1903
1883	1913
1885	1916–17
1888	1920–1
1894–6	1925
1898	1930
1901–2	1933–4
1904–9	1947
1915	1949–52
1918–19	1954–5
1922	1958–63
1924	1966
1926	1969–71
1928–9	1973–6
1932	1978
1935–6	1983
1938–9	1987–9
1941–2	1991
1944	1998–9
1946	2007
1956–7	
1964–5	
1968	
1979–80	
1982	
1986	
1990	
1992	
1994	
1997	
2000	
2002–3	
2005	
2008	

Adapted from Gergis and Ashcroft. Note that documentary information for the wet phase of the eastern NSW rainfall index is not available over the 1841–60 period. Instead we use instrumental rainfall data from Sydney to classify wet and dry years, as described in Gergis and Ashcroft (2013). This accounts for the inclusion of the 1859–60 wet event listed here, and its omission from Table 3 of Gergis and Ashcroft (2013).

21.3 Australian Droughts, 1788–1899

The newly developed eastern NSW drought chronology presented in Table 21.1 reveals twenty-four largely unknown drought periods during the pre-1900 period. Ten of these dry periods lasted for at least two years: 1790–1, 1802–3, 1809–11, 1813–15, 1826–8, 1837–8, 1857–8, 1861–2, 1880–1, and 1894–6.

The longest drought period in eastern NSW occurred in 1809–15, with only one average rainfall year occurring in 1812. According to the 2013 study of Fenby and Gergis, dry weather resulted in crop failures and severe water shortages. By October 1813, around 5000 cattle and 3000 sheep had died from lack of pasture and water brought by the prolonged drought conditions. The primary water storage basins of Sydney were empty for the first time since they were constructed during the first settlement drought of 1790–1.[15]

The most widespread drought, recorded across every SEA state, took place in 1837–41. According to documentary records, the period from 1835 to 1841 was dominated by drought conditions in mainland SEA, with the exception of a few periods of good rainfall.[16] Water shortages resulted in a general failure of agricultural crops in NSW and widespread loss of cattle, particularly during 1837–9.[17] In Victoria, drought conditions were recorded from 1837 to 1840, converting the landscape "into an arid waste, destitute of either grass or water".[18] Interestingly, instrumental rainfall data for western Tasmania suggests that the island state was wet during 1836–8, with drought not recorded until the early 1840s.[19] The spatial variability of the 1837–41 drought is typical of modern SEA rainfall variations, as a variety of large-scale circulation features can affect climate in the region.[20]

21.4 Australian Wet Periods, 1788–1899

Historically there has been a focus on Australian drought, with little attention paid to the impact pronounced wet periods can have on society. Table 21.1 lists seventeen previously undescribed wet events from eastern NSW that occurred during the pre-1900 period. Nine of these wet periods lasted two or more years: 1796–7, 1804–5, 1829–31, 1839–40, 1859–60, 1863–4, 1869–70, 1872–4, and 1889–93.

European settlement of NSW in the year 1788 was characterized by high rainfall that hampered efforts to establish infrastructure in the new penal colony.[21] Heavy rain and storms influenced life during the early days in Sydney Cove, making the establishment of the colony very difficult. This early period of European settlement was characterized by cool, wet conditions associated with the 1788–90 La Niña event recorded in palaeoclimate records (see Chap. 34).[22]

Early nineteenth-century records contain a number of dramatic accounts of severe flooding on the Hawkesbury River in the Sydney region. These events culminated in the "Great Flood" of March 1806, which is believed to have been the most destructive flood experienced since first settlement of Australia. During this event, flood damage is estimated to have caused severe crop losses in the colony's "food bowl" that brought the settlement to the brink of famine.[23]

The early 1830s stand out as a notable wet period in Table 21.1 and Fig. 21.1. In 1836, NSW farmers described the recent harvest as "one of the most plentiful seasons ever remembered in the Colony". The 1836–7 summer was reportedly wet, with heavy rains soaking the dry pastures typical of Australian summer conditions.[24] This prolonged pluvial is the most prominent feature of a palaeoclimate reconstruction of southern SEA rainfall developed by Gergis and colleagues. It is also captured by a range of historical rainfall data, providing independent verification of the wet period reported in the documentary record (Fig. 21.1).[25]

The late nineteenth century in eastern NSW was also dominated by very wet conditions associated with a number of La Niña events, particularly during 1869–74 and 1889–93.[26] The findings presented in Table 21.1 correspond well to other analyses of early instrumental rainfall, as well as documentary and palaeoclimate studies.[27] Together, these lines of evidence strengthen the development of a reliable historical rainfall chronology for eastern NSW.

21.5 Conclusion

The purpose of this chapter has been to highlight recent advances in the developing field of Australian climate history. Despite the geographical biases associated with the location of population settlement, it is clear that historical documentary and instrumental records play an important role in understanding pre-twentieth-century rainfall variations in the SEA region. Recent interdisciplinary research by the SEARCH project has identified twenty-four new drought events and seventeen wet periods from eastern NSW during the 1788–1899 period. It is important to note that these years have been classified for eastern NSW only, and may not reflect nuances in the wider SEA region, individual rainfall stations, or local historical documents.

This study confirms that SEA has experienced significant rainfall variability that has shaped the development of Australian societies since first European settlement in 1788. This research is the first study of its kind in the Australasian region to combine documentary, early instrumental, and modern meteorological rainfall observations using internationally comparable techniques.[28] It represents a significant advance in historical climatology for the region. The results presented in this study now provide the opportunity for Australia to be included in cross-regional drought comparisons from the Indo–Pacific regions of the Southern Hemisphere.[29]

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Notes

1. Webb, 1997.
2. Macintyre, 1999.
3. Macintyre, 1999.
4. Fenby and Gergis, 2013.
5. Strzelecki, 1845; Jevons, 1859; Russell, 1877.
6. Kingston, 1879; Foley, 1957; Nicholls, 1998; Clarke and Moyal, 2003; Ashcroft et al., 2014a.
7. Day, 2007; Jones et al., 2009.
8. McBride and Nicholls, 1983; Risbey et al., 2009.
9. Sherratt et al., 2005; Morgan, 2013; Beattie et al., 2014.
10. Nicholls, 1988; Garden, 2009.
11. Gergis et al., 2009, 2010, 2018; Ashcroft et al., 2012, 2014a, 2014b, 2015; Fenby and Gergis, 2013; Gergis and Ashcroft, 2013.
12. Ashcroft et al., 2014a.
13. Gergis and Ashcroft, 2013.
14. Murphy and Timbal, 2008; Ummenhofer et al., 2009; Verdon-Kidd and Kiem, 2009.
15. Gergis et al., 2009, 2010; Fenby and Gergis, 2013; Gergis, 2018.
16. Fenby and Gergis, 2013.
17. Fenby and Gergis, 2013.
18. Fenby and Gergis, 2013.
19. Ashcroft et al., 2014a, 2016.
20. Risbey et al., 2009.
21. Gergis et al., 2010; Gergis, 2018.
22. Gergis and Fowler, 2009; Gergis et al., 2010.
23. Fenby and Gergis, 2013.
24. Fenby and Gergis, 2013.
25. Ashcroft et al., 2014a.
26. Gergis and Fowler, 2009.
27. Timbal and Fawcett, 2013; Garden, 2009; Gergis et al., 2012.
28. Brázdil et al., 2005.
29. Nash and Endfield, 2008; Neukom et al., 2009; Nash and Grab, 2010; Gergis and Henley, 2017; Gergis, 2018.

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CHAPTER 22

European Middle Ages

Christian Rohr, Chantal Camenisch, and Kathleen Pribyl

22.1 Introduction

This chapter aims to shed light on the historical climatology of the Middle Ages in Europe. In European history, the Middle Ages are defined as the era between Late Antiquity (see Chap. 16) and the early modern period (see Chap. 23), or *c.* 500–1500 CE. The era conventionally starts with the fall of the (Western) Roman Empire (476 CE) and the Migration Period (375–568 CE). It conventionally ends with any number of events used to date the transition toward modernity: the invention of movable type print in Europe (1450s), the fall of Constantinople (1453), the expeditions of Christopher Columbus to America (1492), or the Protestant reformation (1517). Scholars tend to divide it into "early" (approximately sixth–ninth centuries), "high" (approximately tenth–twelfth centuries), and "late" (approximately thirteenth–fifteenth centuries) periods; but as this chapter will discuss, the major climatic periods do not exactly align with this historical periodization.

The Middle Ages witnessed major changes in politics, demography, economy, and society in Europe. The long-lived Byzantine Empire provides the only element of political continuity. For most of this period, it covered large parts of present-day Turkey and the southern Balkans; yet its borders and its fortunes varied considerably over the course of the centuries.[1] During the period *c.* 1300–1453, the Ottoman Empire conquered Byzantine territory and finally its

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capital Constantinople. The Frankish Empire and its successors provided the most influential polities of Central and Western Europe. Under the rule of Charlemagne (768–814) it also expanded into northern Italy, Hungary, and Croatia; and in 800 CE Charlemagne received the title of emperor from Pope Leo III. In the late ninth century this Carolingian Empire was partitioned. The western part later became the kingdom of France, and the central part would belong for much of this period to Burgundy. The eastern part developed into the so-called Holy Roman Empire, but the actual power of its emperors varied over this period, and its "federal" structure would ultimately create a patchwork of disparate polities.[2] England first saw the consolidation of a number of Anglo-Saxon kingdoms, then the Norman Conquest of 1066, which brought stronger centralized political authority. During the Hundred Years' War (1337–1453) the English kings also ruled large parts of France.[3] A number of relatively wealthy city-states emerged in northern Italy, including the Venetian Empire, which expanded into the eastern Mediterranean. The Papacy in Rome established the so-called Papal States, which ruled much of central Italy, while southern Italy was under the influence of Arab and Norman dynasties.[4] Large parts of Spain came under the rule of Arab Muslim dynasties for most of this period; and European historical climatology has not conventionally looked into Arabic (or Ottoman Turkish) source material. Christianity and literacy spread into Northern and Eastern Europe from the ninth century CE onward, through conversion and conquest. Some parts of these regions (e.g., Hungary and Iceland) contain more relevant records and research than others for this period.[5]

22.2 The State of the Field

The pioneers of modern historical climatology Emmanuel Le Roy Ladurie and Hubert Lamb both helped develop the current understanding of European climate during the Middle Ages. It was Lamb who in 1965 first described the European "Medieval Warm Epoch," or what is now commonly (and appropriately) termed the Medieval Climate Anomaly (MCA), as well as popularizing the "Little Ice Age" (LIA).[6] Two years later Le Roy Ladurie, in his pioneering book *L'histoire du climat depuis l'an mil*, presented valuable new methods and results of historical climate reconstruction, with a strong emphasis on the Middle Ages.[7] Moreover, both scholars continued their research in the field for several decades (see Chap. 1).[8]

The subsequent generations of historical climatologists have included several notable specialists on the Middle Ages. During the 1970s and 1980s, Pierre Alexandre improved reconstruction methods, particularly the use of medieval narrative sources, and delivered an excellent overview of the climate of Europe (excepting the British Isles) from 1000–1425 CE.[9] During the 1990s, Gabriela Schwarz-Zanetti studied the climate of Central Europe during the high and late Middle Ages with an emphasis on winter temperatures.[10] More recent publications that cover wide regions during the Middle Ages include those of Rüdiger Glaser (for Central Europe) and Heinz Wanner.[11]

Owing to the number and difficulty of the historical sources, most research has focused on the regional level. One notable example is the work of Laurent Litzenburger on medieval climate in France, particularly the climate of Lorraine and its impacts on the society and economy of Metz.[12] Jacques Berlioz has examined storms and droughts in medieval France.[13] Adriaan de Kraker's studies of the Netherlands have also included climate during the Middle Ages.[14] For the Low Countries, Jan Buisman has compiled an enormous number of sources, which have in turn formed the basis of long-term indices of summer and winter temperatures.[15] Elisabeth Gottschalk published extended compilations of floods and storm surges in the Low Countries, including the Middle Ages, and Chantal Camenisch has generated temperature and precipitation indices for the fifteenth-century Low Countries at a seasonal resolution (see Chap. 11).[16]

Christian Rohr's research, mostly on floods and avalanches, has focused on the Alpine region.[17] Oliver Wetter and Christian Pfister have employed grain phenology (see Chap. 5) in temperature reconstructions covering Switzerland and southern Germany during the later Middle Ages.[18] In 2010, Georg Jäger presented a climate history of Tirol (Austria) that included the high and late Middle Ages.[19] The research of Thomas Wozniak and Paul Edward Dutton has focused on extreme weather events in the early Middle Ages on continental Europe.[20] An interdisciplinary 2007 study by Michael McCormick, Paul Edward Dutton, and Paul A. Mayewski examined climate, volcanic activity, and winter severity in the Carolingian age.[21]

Longstanding scholarly interest in the historical weather and climate of Britain has also embraced the medieval period.[22] Charles Britton's 1937 *Meteorological Chronology to 1450* drew on weather references in chronicles and annals. Britton's work demonstrates a historian's expertise in collecting climate-sensitive information, which sets it apart from most other early compilations.[23] Britton's research provided an important foundation for Hubert Lamb's summer wetness and winter severity indices for medieval Britain, published in 1977.[24] During the 1960s, Jan Titow compiled weather information from the manorial accounts of the Bishopric of Winchester, a type of record not previously used by historical climatologists.[25] In 1978, a study by Wendy Bell and Astrid Ogilvie outlined guidelines for dealing with older weather compilations and medieval narrative sources.[26] On that basis, Ogilvie and Farmer improved the Lamb indices and extended them using new weather information.[27] Kathleen Pribyl has drawn on manorial accounts for grain phenological data, which form the basis for an April to July temperature reconstruction between the mid-thirteenth century and *c.* 1430, and studied the impact of climate on agriculture, subsistence crisis, and epidemic disease in late medieval England.[28] Other historians have continued to uncover and analyze climate-sensitive information in local medieval British records.[29]

Astrid Ogilvie has also been a leading figure in the historical climatology of Northern Europe, particularly Iceland.[30] A 2014 study by Dag Retsö collected documentary evidence for floods and extreme rainfall in Sweden from 1400 onwards.[31] Heli Huhtamaa has worked on historical climate variability and its impacts in Scandinavia, particularly Finland, including the late Middle Ages.[32]

Rudolf Brázdil and Petr Dobrovolný have led a school of research on the historical weather and climate of the Czech Lands (see Chap. 23). Although most of their studies focus on the past five centuries, some have covered the Middle Ages as well.[33] A team led by Dobrovolný recently provided a long-term reconstruction of Czech climate since 761 CE based on tree rings and other proxies.[34] For Hungary and the Carpathian Basin, Andrea Kiss has published several studies on floods and droughts that focus on, or at least include, the Middle Ages.[35] This research has profited from the relatively rich documentary, archaeological, and proxy evidence for the medieval kingdom of Hungary.

Few researchers have dealt with the medieval climate of Southern Europe. Dario Camuffo has published a long-term record of the freezing of the Venetian Lagoon; but his research (with collaborator Silvia Enzi) has focused on the early modern period.[36] Marco Pavese and Giovanni Gregori collected documentary evidence for weather and climate in the Upper Po Valley from the twelfth century onwards.[37] More recently, Martin Bauch has examined late medieval climate and its impact on society in Bologna, while Gerrit Jasper Schenk has carried out comparative research on hydrometeorological extremes in late medieval Tuscany.[38]

Climate studies for the eastern Mediterranean and the Byzantine Empire based on documentary evidence constitute a quickly expanding field of research. Ioannis Telelis provided the first rich and systematic collection of Byzantine sources relevant for climate history, and he has outlined a methodological basis for combining the archives of nature and society.[39] A 2012 monograph by archaeologist Ronnie Ellenblum argued for widespread climate-driven collapse in the eastern Mediterranean during the tenth and eleventh centuries, although its arguments sometimes verge on climate determinism.[40] A 2015 study by Johannes Preiser-Kapeller has discussed the same topic more critically.[41] Further recent research on the historical climatology of Anatolia is discussed in Chap. 18.[42]

22.3 Evidence

Two major types of sources provide most data for the historical climatology of medieval Europe. Narrative sources, such as annals, chronicles, memoirs, and journals, contain descriptions of weather events and (usually sporadic) information on climate proxies. Administrative sources—such as municipal account books and manorial accounts—provide standardized records of expenses and revenue. These can contain information on climate proxies, as well as direct weather descriptions.[43]

22.3.1 Narrative Sources

Different types of narrative sources were produced in continental Europe during the Middle Ages. The tradition of keeping chronicles dates back to antiquity. During the early and high Middle Ages they were usually compiled in a monastic or ecclesiastic context. Starting in the late Middle Ages, a growing number of chronicles were written by laypeople; from the thirteenth century onwards, these chronicles were frequently written in vernacular languages (rather than Latin). Medieval chronicles often combined compilations of older texts with new chapters which then catalogued events during the lifetime of the chronicler. Annals, which originally served as calendars to calculate the date of Easter, also grew to contain compilations of older events and year-by-year catalogs of recent events. Memoirs and journals are genres that first appeared during the late Middle Ages. The former were often composed many years after the events described, whereas the latter were written much closer to the contemporary events. However, there were no hard and fast distinctions between these genres during the Middle Ages.

The weather descriptions found in such sources vary. Some are quite extensive, while others provide just a brief mention of prevailing conditions (e.g., "a cold winter"). Some authors record only occasional extreme weather events. Others give regular summaries of temperature and precipitation during certain seasons.[44]

In England, as in other parts of Europe such as the German-speaking areas, Italy, France, and the Low Countries, narrative sources such as chronicles and annals tended to record information about extreme weather events. While narrative sources, such the *Anglo-Saxon Chronicle*, exist for the period before 1200, their information is too poor to allow the construction of a continuous series of temperature and precipitation extremes.[45] Medieval English historical writing reached its zenith in the thirteenth century, when many monastic chronicles and annals were composed, supplying dense climate information for modern researchers. Around 1300, however, the number of narrative sources begins to diminish, despite the appearance of more municipal (as opposed to monastic) chronicles. English historical writing reached a nadir around the mid-fifteenth century.[46] Medieval historical narratives for Scotland are sparser. Irish annals have to be considered with great care, since they are non-contemporary texts mostly written in the post-medieval period, and this large temporal distance generates high potential for dating errors.

Iceland is renowned for its variety and quality of medieval literary sources, including the narratives known collectively as "sagas."[47] Many of these cannot be considered reliable for climate reconstruction. Nevertheless, the *Sturlunga* and *Bishops' Sagas*, concerning twelfth- and thirteenth-century secular and religious leaders, were for the most part written soon after the events described and by authors familiar with these events. Other sources for the medieval period include early Icelandic annals, which contain contemporary information for the fourteenth century, as well as early works on travel and geography.[48]

22.3.2 Administrative Sources

The temporal and spatial distribution of administrative records closely mirrors that of their narrative counterpart. In Europe north of the Alps few of these sources survive for the period before 1200. During the thirteenth century their number greatly increases. In England, manorial accounts are of particular interest to historical climatologists. They describe agricultural activities of demesne land on individual manors, generally on an annual basis. Weather-related information and climate proxy data figure frequently in them. Most manorial accounts fall into the period from *c.* 1270 to the late fourteenth century. However, the longest series is formed by the accounts of the Bishopric of Winchester, which run from 1209 until 1450.[49] A number of British municipal accounts containing climate-sensitive information start in the late fourteenth or fifteenth century, but so far historical climatologists have hardly employed this vast corpus of records.

On the Continent, municipal records can be used for flood reconstruction at monthly or even weekly resolution where there are specific accounts dedicated to the maintenance of bridges. Christian Rohr has examined the *Bruckamtsrechnungen* (bridgemaster's accounts) of the city of Wels (Austria), starting from the mid-fourteenth century.[50] Similar accounts have survived from Bratislava (Slovakia), but they still are under examination. Accounts kept by medieval landowners may also enable the reconstruction of grain and grape harvest dates, providing proxies for spring and early summer temperatures (see Chap. 6).[51]

22.4 Methods

Most methods of historical climatology developed for the early modern period can be applied to the medieval period as well. This includes methods of calibration and verification of time series (see Chap. 10) and the creation of temperature and precipitation indices from proxy and narrative information (see Chap. 11). Nonetheless, the Middle Ages pose particular challenges, requiring some further methodological considerations.

22.4.1 Dating

Dating errors have a strong influence on the quality of every reconstruction (see Chap. 4). This is why it is absolutely necessary to deal with the typical problems of medieval calendar styles before reconstructing the climate of this era from historical documents. Most high and late medieval sources in continental Europe date events Anno Domini (that is, from the presumed year of the birth of Jesus Christ—the basis of the CE dating used in most of the world today); occasionally medieval sources used regnal years instead. The Julian calendar, employed throughout this era, consisted of a 365-day solar year, with an extra day every fourth year. However, the solar year actually only lasts 365 days, five hours, forty-eight minutes, and forty-six seconds, thus leaving a difference of eleven minutes and fourteen seconds per year. This means that Julian dates gradually deviated from the actual solar year. This deviation reached six days by the tenth century, nine days during the fifteenth century, and ten days by the time the Gregorian calendar was introduced in 1582.[52]

Furthermore, medieval sources could start the new year on any of the following dates: January 1 (Circumcision), March 1, March 25 (Annunciation), Easter, September 1, and December 25 (Christmas).[53] In England, documents concerned with economic and agricultural activities frequently started the new accounting year at Michaelmas (September 29).[54] Within the year, events were often dated by ecclesiastical feasts, such as those to celebrate a saint or to commemorate a certain event in the life of Jesus. Some fell on the same day every year (e.g., Michaelmas), while "movable feasts" (such as Easter) changed each year. The importance of particular feasts varied from region to region. All medieval feast days referred, of course, to the Julian calendar dates, which means that they need to be converted into modern calendar dates before being included in a reconstruction, in particular when dealing with phenological information.

22.4.2 Indices

Climate indices constitute an acknowledged method of medieval climate reconstruction.[55] The main advantage of this method is that many different types of information can be included in the reconstruction and summarized into one statistic for analysis and comparison (see Chap. 11). For some regions in late medieval Europe it is possible to produce indices at a seasonal resolution; however the density of source material varies from region to region and from century to century.[56] Such a seasonal reconstruction comprises four seasonal indices for temperature and four indices for precipitation—each index with its own criteria regarding the scale of values.[57]

22.4.3 Phenological Series

Some administrative sources contain proxy data. To serve in a climate reconstruction, such administrative records must be available in a more or less continuous centuries-long series.[58] Temperature reconstructions reaching back into the Middle Ages have been achieved using vine harvest dates in Burgundy, the freezing of the canals and other information in the Low Countries, and grain harvest dates in Switzerland and England.[59] Manorial accounts from East Anglia (England) between the mid-thirteenth century and *c*. 1430 record the grain harvest date, which functions as a proxy for temperature during the growing season for grain (i.e., April to July), resulting in the earliest documentary proxy-based climate reconstruction for Europe.[60] To reconstruct a climate variable from a proxy, usually there must be an overlap between the proxy data and instrumental series for that variable; although pseudo-proxies can also be employed for that purpose (see Chap. 10).[61]

22.5 Results

The Middle Ages can be divided into three climatic phases: (1) the period *c.* 500–1000, before the Medieval Warm Period (MWP); (2) the MWP, lasting *c.*1000–1300; and (3) the transition period between the MWP and the LIA, *c.* 1300–1500. Note, however, that the temporal boundaries of the MWP and LIA should not be regarded as fixed, and they are likely to vary across the globe.

22.5.1 Before the Medieval Warm Period, or 500–1000

Comparatively few written records exist from the period before *c.* 1000. The surviving material makes it possible to analyze times of extreme weather and their socioeconomic impacts, but not to construct long time series of temperature or precipitation indices. Most climatic information about this period comes from proxies drawn from the archives of nature, often at low temporal or spatial resolution. The period *c.* 500–1000 is marked by lower temperatures than those of the preceding "Roman Climate Optimum," and by wetness, climatic instability, and more continental conditions (i.e., colder winters and warmer summers).[62] Sources from the sixth and seventh centuries and from the Carolingian period describe a number of severe winters and cold, wet summers—often coinciding with volcanic eruptions—as well as their resulting socioeconomic impacts.[63]

22.5.2 The Medieval Warm Period, or 1000–1300

The exact dating of the MWP remains debated, and depends on the region studied and the measurement used. In some long-term climate reconstructions, the MWP starts as early as 800 and ends by 1250.[64] In many areas of Europe, the number of surviving documentary sources increases during the MWP, enabling the construction of indices. The dominant pattern of atmospheric circulation in the North Atlantic during these centuries favored a flow of dry, warm air into Europe, which reduced the frequency of freezing winters and cold, wet summers that could ruin harvests.[65] The warm and settled weather conditions contributed to a vast expansion of agriculture and settlements that went hand in hand with an increase in population throughout Europe. It was also during this period that the Vikings started to settle in Iceland and Greenland.[66] Some early research suggested that the period brought an especially mild and favorable climate to Iceland during the initial settlement period. The reality was undoubtedly more complex, with a high level of climatic variability.[67] In the Alps the tree line climbed above 2000 meters, and in England and the southern parts of Scotland, Norway, and the Baltic it was possible to produce wine.[68]

22.5.3 *After the Medieval Warm Period, or 1300–1500*

Around 1300 the climatically favorable MWP came to an end and a period of transition began. This transition was characterized by increased short-term climatic variability. Decades of relatively high April–July temperatures alternated with decades of cool conditions. These were superimposed on a long-term trend of decreasing spring and summer temperatures.[69] In England, spring and early summer temperatures decreased compared with those of the thirteenth century. Weather conditions during the second decade of the fourteenth century were exceptionally awful in many parts of Europe, and this climatic anomaly was a major factor in the Great Famine of the years 1315–22 (see Chap. 33).[70]

The Spörer Minimum—a period of reduced solar activity beginning in about 1420—again brought cooler temperatures and unstable weather conditions. During the 1430s there occurred a remarkable temperature anomaly marked by prolonged and severe winters, which generated food shortages and famine.[71] The 1480s and 1490s also brought an unusual cluster of cold, wet summers. Nevertheless, temperatures during the Spörer Minimum were not uniformly low: there were a number of years with very hot and dry weather conditions, such as 1473.[72]

22.6 Conclusion

The Middle Ages constitute a long and diverse period of European history. Climatically, it makes sense to divide the era into three parts: before, during, and after the MWP. Whereas research is already advanced for some areas—including the British Isles, the Low Countries, Iceland, Hungary, and the Byzantine Empire—historical climatology is still in its infancy for other areas. Narrative and administrative sources from southern Italy, Spain, and medieval Russia may offer promise for further research, but such investigations will almost certainly prove difficult and will be time-consuming work.

Given the limits of the evidence, most studies of medieval European climate have focused on extreme weather, including river floods, storm surges, extraordinarily strong winds, and droughts, or on extremes of temperature and precipitation during summers and winters. This tendency to report extremes could prove useful, however, in further studies of volcanic impacts on medieval climate and society. Series of continuous spring and fall temperatures remain difficult or impossible to reconstruct before the late Middle Ages, and then only in a few regions with a high density of narrative and/or administrative sources, such as the Low Countries and East Anglia.

In the past few years, several studies have tried to explain medieval human history by long-term climatic developments identified in the archives of nature.[73] However, these attempts have often lacked adequate specificity and historical context, and have therefore fallen into climate deterministic, monocausal approaches to political, social, and economic crises (see Chap. 29). Climate changes and extreme weather—particularly the impacts of volcanic eruptions, such as during the 530s–540s—certainly contribute to human crises; but they are definitely not their only causes (see Chap. 32). Further high-resolution climate reconstruction drawing on the sources and methods described in this chapter can help shed light on the connections between climate, weather, human impacts, and historical changes in medieval Europe.

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Notes

1. Browning, 1992; Gregory, 2010; Mango, 2002.
2. Bradbury, 2007; Costambeys et al., 2011; Wilson, 2016.
3. Keen, 2005.
4. Kleinhenz, 2004.
5. Kiss, 2011.
6. Lamb, 1965.
7. Le Roy Ladurie, 1967.
8. E.g., Le Roy Ladurie and Baulant, 1980; Le Roy Ladurie, 2004; Le Roy Ladurie et al., 2006; Lamb, 1977, 1982.
9. Alexandre, 1977, 1987.
10. Schwarz-Zanetti, 1998; Pfister et al., 1996, 1998a, 1998b.
11. Glaser, 2013; Wanner, 2016.
12. Litzenburger, 2015.
13. Berlioz, 1996, 1998; Berlioz and Quenet, 2000.
14. De Kraker, 2005, 2006, 2013.
15. Buisman and Van Engelen, 1995–1998; Van Engelen, 2006; Van Engelen et al., 2001; Shabalova and Van Engelen, 2003.
16. Gottschalk, 1971–1977; Camenisch, 2015a, 2015b.
17. Rohr, 2006, 2007, 2013.
18. Wetter and Pfister, 2011.
19. Jäger, 2010.
20. Wozniak, 2017; Dutton, 1995, 2008.
21. McCormick et al., 2007.
22. Pribyl, 2014, 2017.
23. Britton, 1937.
24. Lamb, 1977.
25. Titow, 1960, 1970.
26. Bell and Ogilvie, 1978.
27. Ogilvie and Farmer, 1997.
28. Pribyl et al., 2012; Pribyl, 2017.
29. E.g., Brandon, 1971; Stern, 2000; Addison, 2006; Schuh, 2016.

30. E.g., Ogilvie, 1984, 1991; Ogilvie et al., 2000.
31. Retsö, 2014.
32. E.g., Huhtamaa, 2015, 2017.
33. E.g., Brázdil and Kotyza, 1995.
34. Dobrovolný et al., 2015.
35. Kiss, 2009, 2011; Kiss and Laszlovszky, 2013; Kiss and Mikulić, 2015.
36. E.g., Camuffo, 1987; Camuffo and Enzi, 1995.
37. Pavese and Gregori, 1985.
38. Bauch, 2016a, 2016b; Schenk, 2012.
39. Telelis, 2000, 2004.
40. Ellenblum, 2012.
41. Preiser-Kapeller, 2015.
42. E.g., Haldon et al., 2014; White, 2011.
43. Pribyl et al., 2012; Camenisch, 2015a.
44. Camenisch, 2015a.
45. Pribyl, 2014.
46. Grandsen, 1982.
47. Hartman et al., 2016.
48. Storm, 1977.
49. Titow, 1960, 1970; Schuh, 2016.
50. Rohr, 2006, 2007, 2013.
51. Wetter and Pfister, 2011; Daux et al., 2012; Labbé and Gaveau, 2013.
52. Rohr, 2015.
53. Grotefend, 2007.
54. Cheney and Jones, 2000; Titow, 1970.
55. E.g., Lamb, 1977; Alexandre, 1987; Schwarz-Zanetti, 1998; Glaser, 2013; Shabalova and Van Engelen, 2003; Litzenburger, 2015; Camenisch, 2015a, 2015b; Pfister, 1999.
56. Schwarz-Zanetti, 1998; Litzenburger, 2015; Camenisch, 2015b.
57. Camenisch, 2015b.
58. Pfister et al., 2009.
59. Van Engelen et al., 2001; Wetter and Pfister, 2011; Daux et al., 2012; Labbé and Gaveau, 2013.
60. Pribyl et al., 2012; Pribyl, 2017.
61. Brázdil et al., 2010.
62. Hoffmann, 2014.
63. Büntgen et al., 2016; McCormick et al., 2007.
64. E.g., Wanner, 2016.
65. Hoffmann, 2014.
66. Fagan, 2000; Behringer, 2010.
67. Ogilvie and Jónsson, 2001.
68. Hoffmann, 2014.
69. Pribyl et al., 2012.
70. Jordan, 1996; Aberth, 2013; Pribyl, 2017.
71. Jörg, 2008; Camenisch, 2015a; Camenisch et al., 2016.
72. Camenisch, 2015b.
73. E.g., Büntgen et al., 2011, 2016.

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CHAPTER 23

Early Modern Europe

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23.1 Introduction

The most intensive research in historical climatology has concentrated on Europe in the early modern period (*c.* 1500–1800), and has established many of the methods and procedures that have become standard in this discipline. Research for this area and time period benefits from abundant material that can be found in archives and libraries. This material includes both unpublished manuscripts and early printed materials, as well as the greatest density of early instrumental measurements to use for calibration (see Chaps. 4 and 7).

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Moreover, European geography departments and centers of research have been at the forefront of investigations in both paleoclimatology and historical climatology. In this regard, an important development was the insistence by climate historians that historical sources needed to be carefully evaluated for reliability in order to ensure their suitability for climate reconstruction (see Chap. 1).[1]

Nevertheless, the historical climatology of early modern Europe also presents challenges, particularly when compared with China, the other leading region in the field. Europe's many languages and its many and shifting political boundaries mean that the coverage of evidence and research is often inconsistent and incomplete. Some countries (e.g., the Czech Lands, Germany, Switzerland, the Netherlands, and Iceland) are much better studied than others. Europe's geographic and climatic diversity also means that results for one part of the continent are not necessarily relevant for another. Thus ongoing research continues to expand the scope and detail of historical climatology for early modern Europe. This chapter provides an overview of the topic, including the available evidence, the state of research, and summaries of major trends and anomalies in the climate of the period.

23.2 Geography

Europe, the westernmost extension of Eurasia, has been called a "peninsula of peninsulas." At its heart are the European plain and the Alpine mountain chains. The European plain is a fertile and largely unbroken expanse of lowlands, stretching west from the Urals through Russia, the Ukraine, Belorussia, the Baltic countries, and Poland, across northern Germany, the Low Countries, and into northern France. The Alpine mountain chains are highlands ranging from the Pyrenees through southern France, Switzerland, Austria, northern Italy, southern Germany, and the Carpathians to the Black Sea. Between lies a hilly zone of plateaus and ridges. Reaching outward into the surrounding seas are several peninsulas. The largest, to the north, is Scandinavia, a worn-down plateau of highlands with varying soil types. To the west is Iberia, with a high, semi-arid plateau ringed by mountains and fertile river valleys. The southern perimeter, extending into the Italian and Greek peninsulas, is formed by the coastlands of the Mediterranean, consisting of a succession of plains and alluvial lowlands of which the largest are the Padan and the Pannonian plains. To the north-west lie the British Isles and Iceland, and to the south the Mediterranean islands.

The Alpine system forms the major climatic divide. The region to the north is dominated by westerly winds from the Atlantic Ocean, bringing rains at all seasons of the year. Northern Europe has a climate of cold winters and mild summers with short growing seasons.[2] South of the Alps, in Mediterranean Europe, high atmospheric pressure creates hot, dry weather in the summer months, but dissolves to bring cool, moist winters. In Western Europe, where the oceanic influence is strongest, maritime westerlies are the "leading role players" promoting a generally rainy mild climate, except when "zonal" (west–east) flows change to "meridional" (north–south) or "blocked" flows.[3] Moving eastwards, winters become cooler and drier and summers warmer, while annual rainfall decreases.

The climate of the island of Iceland is determined by its location at the intersection of cold polar air and warmer Atlantic air, and of the relatively warm Irminger and North Atlantic currents and the colder East Iceland Current. This situation leaves Iceland sensitive to minor fluctuations in the strength of these different air masses and ocean currents. The Arctic sea ice brought on the East Greenland Current is closely correlated with temperatures on land.[4]

23.3 History and Periodization

The period 1500–1800 in Europe is conventionally called the "early modern" period in the Anglophone, Germanic, and Slavic scholarly worlds. In the Romance languages, it is the "modern" (in contrast to "contemporary" history, which begins with the French Revolution and industrialization). Historians may criticize the term "early modern" or "modern" for implying some "inevitability of linear progress towards distinctly Western characteristics." However, as explained by Hamish Scott, these three centuries do share a number of salient characteristics, such as renewed demographic and economic growth following the Black Death, growing central governmental power, the cleavage of Christianity in the West owing to the Reformation, European overseas expansion, and the Scientific Revolution.[5] These centuries also witnessed new ways of observing, understanding, and recording weather, including the introduction of almanacs in the sixteenth century (see Chap. 6), instrumental observations in the seventeenth, and early meteorological networks in the eighteenth century (see Chap. 7).

Throughout this period Europe was politically fragmented into warring states and empires. Researchers need to be aware of these political shifts in order to make sense of shifting sources and boundaries of evidence. In the sixteenth century, Spain emerged as the dominant Western European power, while France—the most populous European country—suffered recurring religious conflict and civil war in the latter half of the century. England was already a unified state although Scotland was still independent; Norway and Iceland were in a union with Denmark. Italy was divided into more than a dozen principalities, with Naples and Sicily ruled by Spain for most of this period. The multiethnic Holy Roman Empire, the core of future Germany, was fragmented into a myriad of small polities (e.g., the Swiss cantons) and mid-sized principalities and kingdoms, of which Bohemia (the western part of today's Czech Republic) was among the largest. The Polish kingdom, extending far into present-day Russia, was by far the largest state in Europe, while the Russian Empire was just emerging as a major power, its population and territory expanding eastward into Siberia. The Balkans and Hungary had been conquered by the Ottoman Empire, which ruled the Eastern Mediterranean from its capital in Istanbul. The seventeenth century in particular was a period of intense conflict and political crisis, including the Thirty Years War, which devastated present-day Germany. Spain and the Ottoman Empire also suffered from political turmoil and economic stasis; yet the newly independent Netherlands thrived economically. Sweden briefly emerged as a major power in the Baltic region, and Hungary became part of the Austrian Habsburg domains. During the eighteenth century France and the United Kingdom (after the political union of Scotland and England in 1707) emerged as Europe's major powers. Poland was partitioned among Russia, Austria, and the rising kingdom of Prussia, while the Holy Roman Empire recovered economically and demographically but remained divided politically. This period ends with the French Revolution and Napoleonic wars, which pitted France against a variety of opposing coalitions.

The period 1500–1800 also overlaps with the so-called Little Ice Age (LIA). This term carries different meanings in different fields. Glaciologist François Matthes originally coined it in 1939 to refer to glacial readvances throughout the late Holocene.[6] Subsequently, it came specifically to refer to the maximum extent of glaciers in Alaska, Central Europe, and southern Tibet *c.* 1300–1850.[7] Glacier fluctuations are primarily influenced by air temperature, while precipitation is the second most important climatic factor.[8] A 2005 study concluded from a worldwide sample of 169 glacier-length records that the LIA expansion of glaciers was at its maximum in about 1800.[9]

In recent decades, paleoclimatologists (such as the authors of the last two Intergovernmental Panel on Climate Change reports) have started using the LIA to describe cooler global temperatures that began sometime after the giant explosion of the Samalas volcano in 1257 and that lasted until the onset of global warming during the nineteenth century (Chap. 25).[10] Large-scale proxy reconstructions have found that annual temperatures on each continent were on average cooler *c.* 1400–1850 than in any other long period of at least the past two millennia. Nevertheless, there is considerable spatial and temporal variation within this larger trend.[11] The cooling began earlier in the Northern Hemisphere, where it is especially evident in summer temperatures at high latitudes. The late sixteenth to late seventeenth centuries appears to be the only significant globally synchronous period of cooling in both the Southern and Northern Hemispheres (with the notable exception of Iceland).[12] The causes remain debated, but the LIA is usually attributed to a combination of orbital, solar, and volcanic forcings (see Chap. 15). Some recent research proposes that large volcanic eruptions sustained an ice-albedo feedback loop—that is, sudden cooling generated more ice cover in the Arctic, which reflected back more sunlight, which in turn further cooled temperatures at high latitudes.[13]

In the climate history of Europe (as in China), the LIA conventionally begins in either the early fourteenth or mid-sixteenth century and ends in the late nineteenth century. This periodization has a basis in both climatic and human circumstances. Alpine glaciers underwent three far-reaching advances, during the late 1200s–*c.* 1380, the 1580s–*c.* 1660, and 1810s–*c.* 1860.[14] These events are associated with minima in solar activity—the Wolf (1280–1350), Maunder (1654–1715), and Dalton (1790–1820) minima—and with the cooling effect of multiple large tropical eruptions.[15] With reference to Central and Western Europe, Heinz Wanner and colleagues have labeled these three glacial advances and their associated climate "Little Ice Age-Type Events" (LIATES) and have identified a set of overarching weather patterns underlying these events.[16] Seasonal patterns of LIATES include moist snowy winters, cold springs, cool and rainy (mid-)summers, and fewer warm anticyclonic situations during autumn.[17] The most extreme years were so-called "years without summers" immediately following large tropical eruptions (see Chap. 35). As described in the present chapter, the LIA in Europe was not consistently cold. Nevertheless, these LIATES did bring exceptionally low summer and spring temperatures to much of Europe. More importantly, the seasonal patterns characteristic of LIATES proved especially unfavorable for crops and livestock.

These LIATES also came at times of high vulnerability for populations in much of the continent. Europe's pre-industrial agriculture and husbandry still depended on seasonal weather, and Europe's mostly rural population depended for their lives and livelihoods on the success of each year's harvests. During the early fourteenth, late sixteenth, and early nineteenth centuries, demographic growth and declining incomes left the poor exposed to famine and epidemic diseases. During the 1310s, 1430s, 1590s, 1690s, 1740s, 1770s, and 1810s, climatic downturns triggered major subsistence crises and high mortality in many parts of Europe (see Chaps. 27 and 32). Therefore, among (climate) historians the LIA has come to be identified as much with human experiences as with climatic variability and change. Thus the use and the usefulness of the term LIA, as with any other historical periodization, remains open to discussion and depends on context.[18]

23.4 Evidence

The quantity and quality of documentary evidence for early modern Europe are disparate. Moving from east to west, the available evidence for the large territory of Russia is non-continuous and mostly uncritical. Some three dozen volumes of chronicles provide the greater part of available information prior to the mid-seventeenth century. In 1657 Tsar Aleksey Mikhaylovich established a special office to record the most important daily events at the court in Moscow, including weather, and such data were recorded until 1674. Tsar Peter the Great logged daily weather observations during his campaigns of 1695–1715; and temperatures in St. Petersburg were recorded continuously from 1743.[19] For Poland, there are a variety of narrative and personal sources for climate reconstruction, and the historical climatology of the country has recently received more attention.[20] Port records, providing proxies of sea-ice duration, provide some documentary evidence of winter severity in Riga (Lithuania), Tallinn (Estonia), and Stockholm throughout this period.[21] Geographers in Ireland, including the Irish Climate Analysis and Research Units (ICARUS), have recently promoted historical climate analyses in that country.[22]

For south-eastern Europe, only fragmentary data and uncritical compilations of weather descriptions have been made available so far.[23] However, this situation probably reflects not so much an absence of evidence as a shortage of research, particularly research in the abundant source material in Ottoman Turkish archives.[24] Hungary, however, has received considerably more focus, including climate histories based on narrative and phenological sources.[25]

Given its past sensitivity to climate-driven crop failures, Finland has received some attention from historical climatologists, including reconstructions of growing-season temperatures based on descriptive and phenological evidence.[26] Research on Estonia was promoted by Anders Tarand over the last 25 years.[27] Norway and Sweden appear to be rather short of data for the period prior to 1700, despite the pioneering climate history article by the Swedish economic historian Gustav Utterström in 1955.[28] Iceland is well known for its wealth of medieval documents, many of which contain weather-related information (see Chap. 22).[29] There is a scarcity of Icelandic data for the period *c.* 1430–1550.[30] However, starting *c.* 1600, there are many different types of documentary evidence, which make it possible to generate seasonal sea-ice and temperature indices. This evidence includes institutional sources such as government reports and personal sources such as the later Icelandic annals and weather diaries, as well as works by local Icelanders and foreign travelers.[31] The analysis of all these varying documentary sources has been undertaken by Astrid Ogilvie through various projects over a number of years. The analysis of early meteorological observations for Iceland has been pioneered by Trausti Jónsson.[32]

Further significant contributions to the field of historical climatology have focused on Central Europe. Thus a research team led by Rüdiger Glaser at the University of Freiburg has systematically collected and published data for Germany and beyond over the last twenty-five years.[33] Glaser's major thematic focus has been the history of floods in Europe.[34] Together with his staff, he has set up a large historical climatology database named HISKLID, which later became part of the "climate and environmental history collaborative research environment" named Tambora (https://www.tambora.org/). In proportion to its surface and population, Switzerland benefits from a rich legacy of high-quality weather and phenological observations, most of which has been evaluated and published over the last forty years by a research team led by Christian Pfister at Bern University.[35] All of this evidence—including almost continuous daily weather observations in different locations from 1684 to the onset of the Swiss Weather Service in 1864—has been published in the Switzerland Module of the new Euro-Climhist database (http://www.euroclimhist.unibe.ch/en/).

Similarly, the Czech Lands possess a rich documentary record that includes a broad variety of sources: personal papers, (weather) diaries, plant- and ice-phenological observations, pamphlets and newspapers, early scientific journals, and visual art as well as state and church records, municipal receipts and expenses, and epigraphic sources (see Chaps. 5 and 6). This abundant information was systematically collected, analyzed, and published during the past twenty-five years by a team led by Rudolf Brázdil at Masaryk University (Brno, Czech Republic) working together with colleagues trained in Czech history. The Brno research team published no fewer than eleven books in English as well as countless articles in reviewed journals.[36] They have also systematically collected and analyzed narrative documentary data during the instrumental period, thus creating the conditions to apply the calibration-verification approach described in Chap. 10.

The Netherlands, too, has a rich documentary record, particularly a high density of personal sources and printed materials beginning in the late sixteenth century. Much of this evidence has been reproduced and analyzed in a large Dutch publication.[37] Based on these sources, researchers have generated temperature indices for the period 764–2003 (see Chap. 11).

Italy also possesses a rich historical record, but research so far has been more limited.[38] The northern part of the country, particularly Venetian territory, is perhaps the best documented and most closely studied. Thus, for example, Dario Camuffo has generated long series of freezing winters and sea-level changes for the Venetian Lagoon, as well as temperature indices for northeastern Italy covering 1500–1759 (albeit with major gaps).[39] Venetian records can also contribute to the historical climatology of eastern Mediterranean islands including Crete and Cyprus, although most documentation for their early modern climate history remains in local and Ottoman archives, and has yet to be adequately explored.[40]

French scholars, including the historian Emmanuel Le Roy Ladurie, paved the way for historical climatology through their pioneering work during the mid-twentieth century. During the past two decades, Le Roy Ladurie and colleagues have returned to French climate history, with French-language publications detailing narrative- and proxy-based temperature and precipitation histories as well as climate and weather impacts from decade to decade through early modern and modern French history.[41] French historical climatology has drawn in particular on plant-phenological observations such as grape harvest dates (see Chap. 5).[42] In 2014, Georges Pichard and colleagues presented an elaborate study of climate and floods in lower Provence since 1300.[43]

England is particularly rich in early modern personal and printed materials for climate and weather, such as almanacs, pamphlets, and diaries. The British Isles were also home to pioneering research in historical climatology, including the work of Hubert Lamb, who in 1971 established the Climatic Research Unit (CRU) (see Chap. 1).[44] The historical climate work of the CRU has continued through the research of Astrid Ogilvie, Phil Jones, and John Kington, who compiled available weather evidence for Britain starting in the Middle Ages.[45] Another British pioneer, Gordon Manley, published a temperature reconstruction for central England based on early instrumental measurements. This reconstruction, extending back to 1659, is the longest instrumental record in existence.[46]

Both Spain and Portugal have received significant attention from historical climatologists.[47] For the early modern period, there are often fewer printed materials than elsewhere in Western Europe, but more abundant state and church records, providing useful climate proxies such as rogation ceremonies (see Chap. 5).

The first instrumental weather network in Europe was the Medici network based in Florence. It operated from 1654 until religious authorities shut it down in 1670.[48] Over time, instruments and measurement practices improved; nevertheless their use in climate reconstruction still requires historical and statistical analysis (see Chaps. 7 and 9). Philip Jones of the CRU, UK, has undertaken pioneering work on the reconstruction of early European instrumental temperature and precipitation records over a period of many years.[49] Some of the earliest continuous series of monthly temperature measurements come from the following: Paris from 1658; central England from 1659; Berlin from 1701; DeBilt (Netherlands) from 1706; Bologna (Italy) from 1715; Uppsala (Sweden) from 1722; and Padova (northern Italy) from 1725.[50] A team at the Central Institution for Meteorology and Geodynamics (ZAMG) in Vienna has created a long composite temperature series (from 1774) and precipitation series (from 1800) for the Greater Alpine Region.[51] Regular observations in Iceland and Greenland started in the late eighteenth century,[52] but are not continuous.

Compared with temperature series, early instrumental precipitation series are fewer and cover smaller areas, because precipitation patterns vary more locally. The longest precipitation records without any gaps are those for Ireland (1711–2016) and the London suburb of Kew (1697–1970).[53] The Paris series (from 1688) is a few years longer but includes several gaps; and the Padua (northern Italy) series runs almost without gaps since 1725.[54] Shorter series are available from Tallinn (Estonia) from 1751; Geneva from 1760; and Bern from 1760.[55] Fernando S. Rodrigo and Mariano Barriendos generated rainfall indices in Spain from 1500 onwards, based on evidence in municipal acts from six cities representing the major climatic regions of the country.[56] Further precipitation indices have been generated for the Czech Lands from 1500 (seasonal resolution); southern Portugal from 1600 (annual resolution, combining documentary and tree-ring evidence); and Europe as a whole from 1500 to 1900 (combining instrumental, documentary, and proxy evidence).[57]

In conclusion, the spatial and geographic coverage of historical climatology for early modern Europe remains uneven. While relevant historical sources exist for most of this period, and for nearly all of Europe, they are much more abundant for some times and places than others. Moreover, certain parts of the continent—particularly Central and Western Europe, as well as Iceland—have been more closely studied than others, especially for the period before 1700. Starting in the eighteenth century, a growing number of early instrumental series become available, predominately temperature series, and predominately in Central and Western Europe. Climate reconstructions for Eastern and southeastern Europe—about half the continent—still rely primarily on proxies from the archives of nature. Nevertheless, important research has begun in these regions. Moreover, (climate) historians have made occasional use of documentary evidence concerning weather and climate in Eastern and south-eastern Europe to provide essential detail and specificity for the analysis of climate's human and historical impacts.[58]

23.5 Climatic Variations and Extremes

This section provides an overview of climate variations and extremes at seasonal resolution, first for Europe as a whole and then for those regions with the most abundant data: Northern Europe and then Central and Western Europe. The section concludes with a brief overview of the major events and anomalies described by historical climatology in the Mediterranean region and Eastern Europe.

23.5.1 European Temperature

Combining the evidence from the archives of societies with proxies from the archives of nature, climatologist Jürg Luterbacher and colleagues have used the method of spatial-field reconstruction (see Chap. 12) to create increasingly sophisticated high-resolution reconstructions of monthly and seasonal temperatures across Europe.[59] This research has also made it possible to analyze relations between temperature anomalies and atmospheric circulation patterns over Europe, to identify modern (instrumental period) analogues for some pre-instrumental climate anomalies, and in some cases to place early modern temperature variations in long-term context.[60]

Most notably, these temperature reconstructions demonstrate a greater magnitude and frequency of severe winters and springs during this period than in the centuries since. These winters were characterized by a longer freezing of the Baltic and of large rivers and lakes in Western Europe. Such severe winters were rare prior to 1518 and altogether missing during the 1520s–50s. Some winters in this period were warm (1521, 1538) or even extremely warm (1530, 1540) by twentieth-century standards.[61] From 1560 to 1610, winter temperatures were generally lower, with notable troughs in the 1560s–70s and 1599–1608. Nevertheless, several winters in this period rank as warm (1597, 1609) or even very warm (1607). This indicates a high variability of winter circulation with cold winters dominated by northerly or north-easterly atmospheric circulation and mild ones influenced by circulation from the west and south-west.[62] From 1609 until the 1680s severe winters were somewhat less frequent and less extreme. A third trough in winter temperatures in 1684–1709 is associated with the late Maunder Minimum of low solar activity. This period includes some of the coldest European winters of the past five centuries, including 1684, 1695, 1697, and 1709. The period 1717–39 saw a return to less severe winter conditions, and the 1730s in particular stand out for the absence of even moderately cold winters. Winters of the early 1740s were very cold in much of

Europe. Subsequently, winter temperatures generally decreased, reaching another trough in the early nineteenth century (see Chap. 25).

European spring temperatures show a gradual decline starting in the 1560s. During 1686–1703 they drop to their lowest level of this era—another anomaly associated with the late Maunder Minimum. Thereafter, spring temperatures rose for much of the eighteenth century, before undergoing another trough in the 1830s–40s.

European summer temperatures demonstrate some similar patterns to those in winter. An exceptionally cold period occurred during the late sixteenth and early seventeenth centuries.[63] Cold summers were also prominent during the late seventeenth century (the Maunder Minimum) over north-eastern Europe and during the first half of the nineteenth century over Central and Southern Europe. The coldest summers—so-called "years without summers"—followed large regional and tropical volcanic eruptions, such as the eruptions of Nevado del Ruiz (Colombia) in 1595, Huaynaputina (Peru) in 1600, and later Tambora (Indonesia) in 1815 (see Chap. 35). Luterbacher and colleagues have stressed, however, that subcontinental regions may undergo multidecadal and longer periods of sustained temperature deviations from the continental mean, indicating that the internal variability of the climate system is particularly prominent at regional scales.[64] Finally, Europe's autumn temperatures in 1500–1800 remained somewhat below the twentieth-century values without showing notable variation. Autumns during the late eighteenth century seem to have been the warmest of the period *c.* 1500–2000.[65]

Trends in European temperature over spans of years and decades have been strongly influenced by the North Atlantic Oscillation (NAO). This describes the difference between sea-level pressure at two points in the North Atlantic: the Azores and Iceland. The balance of pressure at these points influences the strength of westerly circulation across Europe, particularly during winter in Western Europe. In its positive mode (NAO+), the subtropical anticyclone around the Azores ("Azores high") and cyclonic conditions around Iceland ("Iceland low") are both well developed. In its negative mode (NAO−), sea-level pressure remains lower than usual around the Azores and higher than normal around Iceland. NAO+ periods tend to bring more mild and humid maritime climate to Western and Northern Europe and more persistent droughts to the western Mediterranean. NAO− periods create more meridional (north–south) flow over Western Europe, bringing colder and drier winters on average. In severe winters, the usual pressure distribution over the North Atlantic might even be reversed, with a stable anticyclone in the north. This situation drives cold, dry polar, or Siberian air into Central and Western Europe, but brings high amounts of winter precipitation into the Mediterranean and Black Sea regions. These strong NAO− anomalies may explain some periods of exceptionally cold winters in Central and Northern Europe described below.[66]

Since modern instrumental records for the NAO only began around a hundred years ago, and proxies from the archives of nature often lack the necessary resolution, historical climatologists have worked with documentary and early instrumental sources to extend NAO reconstructions back into the early modern period. These sources include daily and monthly observations of wind direction in parts of Central Europe, and regular barometer readings in London and Paris starting in the eighteenth century.[67] These reconstructions show limited agreement thus far. In general, they indicate that negative modes of the NAO predominated during most of the late sixteenth, seventeenth, and nineteenth centuries, compared with more positive modes during the early sixteenth, eighteenth, and twentieth centuries (the instrumental record), but with annual and decadal variability throughout this period. Recently, the compilation and analysis of thousands of ship logbooks from voyages in the North Atlantic (see Chap. 6) have offered a new way to calculate the frequency of different wind directions, and indirectly, the state of the NAO. The westerly circulation index by Barriopedro and colleagues provides the longest North Atlantic circulation index currently available assembled exclusively from direct weather observations. The index shows that the frequency of westerlies in the English Channel has not undergone major long-term changes during the past three centuries, and that Atlantic circulation during the late twentieth to early twenty-first centuries was not unprecedented in the long-term context.[68]

23.5.2 Northern Europe

The most notable climatic feature of this period in Scandinavia was the exceptionally cold summers of the late sixteenth to early seventeenth century. Since parts of Northern Europe lie at the margin of grain cultivation, early or late frosts could ruin entire harvests. This danger has been especially well documented in Finland, where killing frosts (*kesähalla*) could occur at planting time (May–early June) or just before harvest (late August–early September).[69] Following a relatively favorable period in the mid-sixteenth century, harvest failures in Finland began to occur almost every third year by the mid-1580s.[70] The summer of 1601, one of the coldest of the past two millennia in the Northern Hemisphere, was particularly disastrous in much of this region.[71]

Summer frosts and harvest failures recurred periodically throughout the 1600s. The worst years of the century came during the 1690s. In Denmark it was a time of stronger winds and higher frequencies of northerly and northwesterly winds during summer.[72] The 1695 harvest in Finland was ruined by a September frost; rainy weather that autumn impeded the sowing of grains for the following year. A late spring and rainy summer in 1696 delayed the ripening of crops, and then severe frost in August destroyed what crops remained. Although the weather of 1697 was more favorable, there was no seed grain left to plant. A severe famine persisted for three years, accompanied by outbreaks of disease, leading to the death of an estimated 25–33% of Finland's population.[73] During the eighteenth century, the climate generally became more favorable for crops. However, the exceptional cold of the 1740s accompanied by the death of livestock again created hardship and high mortality, particularly in Norway.[74]

Because of its location in the North Atlantic, Iceland is particularly interesting climatically. It also offers a wealth of documentary data for climate reconstruction covering most of the early modern period. These data include the incidence of sea ice off the coasts, which provides a further indication of temperature variations.[75] Although there are very few contemporary sources between 1430 and 1560, circumstantial evidence suggests the climatic regime was not unduly harsh during the period *c.* 1412–70. At that time the English dominated trade with Iceland, and Iceland's major import was cloth—not grain or other food items—implying that the economy was not then in crisis. A reliable account suggests that the 1560s were very cold with much sea ice while the 1570s were mild. It is likely that the 1590s were cold with severe sea-ice conditions. From *c.* 1640 to 1680, there appears to have been little sea ice off Iceland's coasts, but both the early and latter decades of the seventeenth century were years with much ice present. Thereafter, the years with most ice present were the 1780s, early 1800s, and the 1830s, with further periods of sea ice coming later in the nineteenth century. From 1900 onwards sea-ice incidence fell off dramatically.[76]

The temperature pattern in Iceland correlates well with these sea-ice variations. A cooling trend may be seen around the beginning and end of the seventeenth century, separated by a mild period *c.* 1640–80.[77] The early decades of the 1700s were relatively mild, in comparison with the very cold 1690s, 1730s, 1740s, and 1750s. The 1760s and 1770s show a return to a milder regime by comparison. The 1780s are likely to have been the coldest decade of the century, but this was compounded by local volcanic activity—specifically the Lakagígar eruption (see Chap. 34).[78] While economic and political conditions undoubtedly played a significant role, there is no doubt that Iceland's variable and frequently harsh climate was implicated in the numerous famines that occurred throughout the country's history, notably in the 1690s, 1740s, 1750s, and 1780s. The last great subsistence famine in Iceland occurred in the 1880s, a period of unusual cold with heavy sea ice.[79]

23.5.3 Western and Central Europe

As described above, the regions of Western and particularly Central Europe have among the best climate records from the archives of society and have been the most intensely studied. The following paragraphs explain trends and anomalies based on the following records: monthly temperature indices for Central Europe since 1500; the instrumental Central European Temperature Series (CEUT) (see Chap. 11); early instrumental series since the late 1650s from Paris and central England (CET); seasonal precipitation reconstructions for the Czech Lands; and monthly precipitation indices for Switzerland and the Czech Lands.

In most cases, Western and Central Europe underwent similar climatic trends, but winters in Central Europe seem to have been considerably colder than those in Paris and central England. On average, winters in Central Europe over the entire period 1500–1800 were 1.1 °C and autumns 0.6 °C colder than the 1961–90 reference period (see Table 23.1). These deviations are the most prominent feature of the LIA compared with the climate of the twentieth century.

Table 23.1 Early modern temperature anomalies in Central Europe, Paris, and central England from twentieth-century means (°C)

Period	*Season*	*Central Europe*	*Paris*	*Central England*	*Period*	*Season*	*Central Europe*	*Paris*	*Central England*
1500–1799	Winter	−1.1			1500–1799	Spring	−0.3		
1500–18		−1.2			1501–67		−0.1		
1519–60		−0.5			1568–1600		−0.6		
1561–1600		−1.8			1601–86		−0.1		
1591–1600		−2			1687–1700		−1.4	−0.7	−1.5
1601–90		−1			1701–1800		−0.3	−0.4	−0.4
1691–1700		−2.6	−1.8	−1.7	1701–39		0.1	0.1	−0.2
1701–1800		−0.9	−0.6	−0.7	1740–85		−0.7	−0.7	−0.5
1500–1799	Summer	−0.2			1500–1799	Autumn	−0.6		
1500–68		0			1501–1600		−0.4		
1569–1600		−0.8			1501–60		−0.2		
1585–98		−1.2			1561–1600		−0.5		
1601–87		−0.1			1601–87		−0.5		
1688–1700		−0.8	−0.6	−0.8	1688–1700		−1.1	−1.4	−1.4
1701–1800		0	0	0.1	1701–1800		−0.7	−0.2	−0.4
1500–1799	Year								
1500–60		−0.2							
1561–1600		−0.9							
1591–1600		−1.2							
1601–1700		−0.6							
1601–86		−0.5							
1687–1700		−1.4	−0.9	−1.3					
1701–1800		−0.5	−0.3	−0.3					

Source Central Europe: Dobrovolný et al. (2015)—anomalies refer to the 1961–90 mean; Paris: Rousseau (2015)—anomalies refer to the 1901–2000 mean; central England: Manley (1974)—anomalies refer to the 1901–2000 mean

At the beginning of this period, winter temperatures showed considerable variability. The first two decades of the sixteenth century include several cold (1502–4, 1508, 1509, 1511) and even severe winters (1512–14, 1517), but also some very warm ones (1505–7, 1516). The four decades 1520–60 brought a notable Europe-wide return to warmer conditions. Severe winters were absent while temperatures in spring, summer, and autumn were at similar levels to those of the twentieth century, apart from two short sequences of cool summers (1526–9, 1542–4). The year 1540 was probably the hottest and driest year during the entire period 1500–2000. Annual precipitation, as estimated for Switzerland and Poland, was about a third of the mean, whereas maximum temperatures in July probably exceeded 40 °C. Precipitation both in Switzerland and the Czech Lands began the century somewhat below average,[80] while values for 1520–60 were probably about average throughout Central Europe.[81] The relatively favorable climatic conditions for agriculture helped to sustain a trend of rising population in Central and Western Europe during the early to mid-1500s.[82]

After 1560, climatic conditions gradually deteriorated, first and foremost in winter. The severe winter of 1561—the first in almost fifty years, as the Zürich weather diarist Wolfgang Haller noticed—was the forerunner of an almost uninterrupted series of cold and severe (1565, 1569, 1573, 1587, 1589, 1595, 1600, and 1601) winters with just a few "average" winters in between (1584, 1585, and 1592). Mean winter temperatures during 1561–1600 fell 1.2 °C, and those from 1591 to 1600 fell 1.5° below the 1520–60 average. For instance, during early November 1572 to mid-March 1573, European weather was dominated by a blocking anticyclone centered over Scandinavia, bringing the coldest winter of this period in Central and Western Europe. Rivers froze and the ice on Lake Constance did not break up until early April.[83] Polar air masses reached into parts of the Mediterranean region such as Catalonia. The mixing of moist air masses from the Mediterranean depression with the cold air layer north of the Alps led to heavy accumulations of snow.[84]

Starting in 1568 spring temperatures also fell by 0.5 °C compared to the previous period 1501–67, with extremely late seasons in 1587, 1596, and 1600. However, this trend was interrupted by three very warm (1571, 1583, 1599) and nine "warm" or "average" springs (1567, 1574, 1576, 1579, 1581, 1584, 1585, 1591, and 1596). In general warm springs were rather rare in the sixteenth century.[85] Springs in the second part of the sixteenth century tended to be dry in Switzerland and of average precipitation in the Czech Lands.

Falling summer temperatures began with three cool and rainy summers in a row (1569–71). Together with cold springs and autumns, these triggered a severe crisis in large parts of Europe (see Chap. 27). These were followed by a decade of variable summer temperatures.[86] Then in 1585–1601, Central Europe suffered a series of seventeen cold or severe (1585, 1588, 1594, and 1596) summers in a row (apart from the hot summer of 1590), most of which were also snowy in Alpine pastures. The mid-1580s and 1590s were notorious for cold wet summers, crop failures, and even famine in parts of England.[87] Summer precipitation was high from 1570 to the end of the sixteenth century both in the Czech Lands and in Switzerland.[88] The Lucerne scientist Renward Cysat duly counted seventy-seven days of rain in the summer of 1588 and then seventy-five days of summer rain in 1596 (out of ninety-two total days of summer).[89] The stormy weather of 1588 remains famous for its role in the defeat and destruction of the Spanish Armada during its attempted invasion of England. Admiral Medina Sidonia wrote on July 27: "The sea was so heavy that all the sailors agreed that they had never seen its equal in July. Not only did the waves mount to the skies, but some seas broke clear over the ships."[90] Climatologist Hubert Lamb argued that a southward displacement and enhancement of the jet stream must have created these unusual conditions. On average, summers from 1569 to 1600 were 0.8 °C colder—and those from 1585 to 1598 1.2 °C colder—than the 1961–90 mean. Alpine glaciers responded to the long series of snowy summers with far-reaching advances: in just two decades the Lower Grindelwald Glacier pushed forward by about a kilometer, crushing forests and farms under its ice.[91]

Autumn temperatures during 1561–1600 decreased by 0.7 °C compared with those of 1520–60 (not shown). This trend includes a long sequence of cool (1575–83) autumns and isolated severe seasons (1579, 1597, and 1601). Autumn precipitation was average in Switzerland and the Czech Lands. Overall, the exceptional cooling of the late sixteenth century had significant effects on the agriculture, and consequently the economy and population, of Central and Western Europe. Partly as a consequence of frequent harvest failures, demographic growth slowed considerably in Germany, and in England during the 1590s real wages fell to their lowest levels since the Great Famine of the 1310s (see Chap. 33).[92]

From 1600 to 1680, winters were only 1 °C colder than the 1961–90 mean. However, this average masks a period of extreme variability between 1603 and 1618, when cold and severe seasons (1603, 1608, 1612, 1614, 1616, and 1618) alternated with warm and very warm ones (1604, 1607, 1609, 1613, and 1617). In Iceland, the years *c.* 1640–80 were relatively mild with little sea ice off the coasts—a stark contrast to the situation elsewhere in Europe, which highlights the importance of not extrapolating from one region to another without careful examination of the records.[93] The 1690s turned into the coldest decade of the period, with winter temperatures 2.6 °C below the reference period. In 1695 most Central European rivers and lakes froze for long periods, and people could cross over Lake Constance for the first time since 1573.[94] Winters in Switzerland were dry throughout the century, while precipitation in the Czech Lands remained above average, except during the 1680s and 1690s.[95]

Spring temperatures fluctuated between cool (1625–8, 1640–3) and warm (1636–8, 1673–7) during most of the century, with only two severe seasons (1614 and 1627). However, from 1687 to 1701 springs turned consistently cold for fifteen years, with seasonal temperatures 1.3 °C below the seventeenth-century mean. Spring precipitation in Switzerland and in the Czech Lands was below average.[96]

Summer temperatures, like those in spring, reached almost twentieth-century levels during most of the seventeenth century, before falling 0.8 °C below the 1961–90 mean during the cold years of 1688–1700. Nevertheless, these high average values mask considerable variability between cold and wet (1608, 1618, 1621, 1627, 1628, 1663, and 1675), warm and dry (1684), and even torrid (1616, 1666, and 1669) seasons. The year 1628 was clearly a "year without a summer" to judge by the substantial delay in the development of vegetation and the high frequency of snowfalls in the Alps; and 1675 was probably almost as cold.[97] Summer precipitation in Switzerland and in the Czech Lands remained above average throughout the century.[98]

Autumn temperatures were 0.5 °C below the 1961–90 mean up to 1686, and then fell to 1.5 °C below the mean in 1688–1700 in Central Europe and central England. This season was dry in Switzerland and in the Czech Lands, except in the final decades of the century, which were wet in both countries. Overall, the seventeenth century had the lowest average annual temperatures of the period, at 0.6 °C below the mean, due largely to the exceptionally cold years during the first and last decades of the century. The simultaneous cooling of springs and autumns during the 1680s and 1690s, particularly in May and September, drastically curtailed the grazing period in the Alps, which led repeatedly to shortages of fodder.[99]

During the eighteenth century, winter temperatures in Central Europe were on average 0.9 °C colder than the reference period, and almost as cold in central England and Paris. To a large extent, this value is due to the frequency of severe (1709, 1729, 1740, 1766, 1784, and 1789) and cold (1726, 1731, 1755, 1763, 1768, 1796, and 1799) winters, which was the highest since 1500. The winter of 1709 was perhaps the most outstanding of this period, both for its extreme cold and its human impacts. Temperatures plunged across Western Europe from January to March as Arctic air descended over the continent. During the night of January 5–6, 1709, one of the pioneers of instrumental meteorology, Louis Morin (see Chap. 6), noted a change in the wind direction in Paris from south-west to north-east followed by a sudden drop in temperatures of ~15 °C. The intense weather passed from north to south over France, bringing temperatures as low as −20 °C, freezing lakes and rivers and killing vines and cold-sensitive crops. South-westerly winds and rains were followed by another freeze, leaving fields buried under ice. In the ensuing famine, grain transports were looted, and the hungry rioted in Paris and the provinces.[100] The winter of 1740, also among the coldest of the LIA, brought crop failures and the death of livestock across much of Central and Western Europe. It was an important driver of the 1740–1 famine in Ireland, in which more than one in ten of the Irish population died (see Chap. 31).[101] The 1740s were also cold years in Iceland, with frequent sea ice off the coasts.[102]

Eighteenth-century spring temperatures in Central Europe were 0.3 °C and in Paris and central England 0.4 °C below the reference period. Cold (1701, 1714, 1729, and 1770) and severe (1740, 1785) seasons were common, particularly in the first half of the century, which included a continuous series of eleven cool or cold springs from 1739 to 1749. The long freezing winter of 1740 made for a "year without a spring." March 1785 was also as cold as a severe winter month, with a monthly mean temperature of −3.6 °C measured in Basel. By contrast, warm springs (1723, 1728, 1734, and 1794) occurred only rarely. Both winters and springs were dry through the century in the Czech Lands and in Switzerland.[103]

The eighteenth century is distinguished by a near absence of both cold (1725) and warm (1719, 1728) extremes in summer temperatures. Summers were predominately wet in Switzerland while there were distinct dry periods early and late in the century in the Czech Lands.[104]

Reconstructed autumn temperatures during the eighteenth century were 0.7 °C below the reference period in Central Europe and in central England. The century was marked by four periods of continuous cool or cold autumns in 1761–6, 1774–8, 1780–6, and 1788–92. Three seasons (1739, 1782, and 1786) were severe, while not a single warm autumn is known for the century. Autumns in Switzerland during the first half of the century were extremely dry, but became very wet after 1760, a trend also found in the Czech Lands.[105]

23.5.4 The Mediterranean and Eastern Europe

Climate reconstructions for Mediterranean and Eastern Europe rely mainly on proxies from the archives of nature, particularly for the period before 1700. Nevertheless, research in historical climatology, as described above, has shed light on some major climatic events and trends in these regions. For Mediterranean Europe, where crops are most sensitive to spring droughts and freezes, most evidence concerns spring precipitation, flooding, and anomalous cold. In Eastern Europe, with its more continental climate, the evidence principally describes extremes of heat and cold.

The climate in (northern) Italy during the early modern period is well documented due to the longstanding efforts of the research group led by Dario Camuffo. Temperature indices (with some gaps) were established for the sixteenth and seventeenth centuries. Continuous temperature and precipitation were elaborated from the early eighteenth century. Cold extremes in winter and spring were more frequent during the sixteenth, seventeenth, and late eighteenth centuries than in the twentieth century.[106]

In Spain, the early sixteenth century began with dry anomalies and a longer-term minimum of precipitation in about 1540. By contrast, the eastern Mediterranean appears to have enjoyed favorable conditions for agriculture, with no major droughts (although absence of evidence is not necessarily evidence of absence). However, during the late sixteenth to early seventeenth century, the Mediterranean experienced a period of unusual variability, characterized by numerous freezing winters and a "see-saw" contrast in precipitation.[107] In Spain there were extremes of both cold and rainfall. In the southern part of the country, the 1590s were probably the second rainiest decade of the period 1500–2000.[108] The Guadalquivir and other Mediterranean rivers underwent more and greater flooding than in any other period since the Middle Ages.[109] At the same time, tree rings in central Spain indicate that the late 1590s–1610s brought the most summer drought of any period from the early sixteenth century until the impacts of global warming in the late twentieth century, an anomaly partially confirmed by records of rogation ceremonies.[110] The tree rings of 1600–2 in the Guadarrama Mountains are the thinnest on record, pointing to exceptionally cold dry weather following the Huaynaputina eruption—another phenomenon reflected in contemporary narrative descriptions.[111] In the southern Balkans and central and western Anatolia, by contrast, Ottoman documents record three regional droughts and food shortages during the 1560s–80s, followed by possibly the worst drought in Ottoman history during the 1590s.[112] In northern and central Italy both droughts and floods were frequent from 1600 to 1620.[113]

Throughout the period 1500–1700, cold episodes during winter and spring were more common than in the twentieth century. However, they were especially frequent and severe during the 1570s–1610s, a feature demonstrated in studies of southern France and of north and central Italy.[114] Various contemporary narratives also point to extreme winters in south-eastern Europe and the Greek islands, especially during the 1590s. On the island of Crete, for example, snow and rain fell almost continuously for three months in 1595.[115] Both Ottoman and Habsburg sources describe frequent severe weather during the campaigns of the "Long War" of 1593–1606. In early 1621 the Istanbul Bosphorus, the narrow passage between Europe and Asia, froze all the way across.[116] Frequent severe winters returned to the region during the 1680s–90s, as indicated in both Ottoman Turkish and Greek sources.[117]

The LIA was a period of glacier expansion in the Mediterranean area. In the Pyrenees (Spain) the largest advance period was during the late sixteenth and early seventeenth centuries, that is, at the same time as in the Alps. Similarly, substantial LIA advances of glaciers in the Appenine mountains (central Italy) and Slovenia are documented.[118]

Given the limits of the Eastern European documentary evidence it is often difficult to establish definite climatic trends. Narrative evidence from European Russia indicates variable conditions during the sixteenth century, with an unusually high frequency of warm summers early in the century, and the onset of more severe winters during the 1580s. The years 1601–3, in the wake of the Huaynaputina eruption, brought extraordinary winter cold, accompanied by famine and violence.[119] The remaining part of the seventeenth century enjoyed generally favorable conditions, but with more frequent drought starting in the

1640s. The first half of the eighteenth century again saw variable conditions and some particularly severe winters, including 1708–9 and 1740. The 1770s and 1790s brought multiyear droughts and famine.[120]

In Poland, too, the first half of the sixteenth century had variable temperatures and precipitation, with an unusually high frequency of mild winters. Also similar to Russia, severe winters became much more common late in the century, with six severe winters during the 1590s alone. The 1620s–30s brought warmer summers and mild winters, but the 1640s–50s contained more years of unusual cold. The eighteenth century included a number of exceptionally cold winters, particularly during the 1730s, 1770s, and 1780s, when early instrumental records reveal average temperatures 0.8 °C below those of the late twentieth century. The 1740s were unusually wet.[121]

23.6 Conclusion

French scholar Fernand Braudel (1902–85), in his celebrated work on the sixteenth-century Mediterranean, was among the first modern historians to consider climate change. However, he subsumed climate and other environmental forces in what he called the "*longue durée*": that is, the slow-moving substructure of history, rather than the short-term level of events and individual lives on the surface of history.[122] Braudel's most famous student, Emmanuel Le Roy Ladurie, would become one of the pioneering figures in the historical climatology of early modern Europe. However, in his early work he was reluctant to address short-term climate fluctuations or emphasize their role in history.[123] Only when he returned to climate history in the 2000s did Le Roy Ladurie make the case that climatic events on the scale of years or seasons had a significant historical impact.

What had changed in between? On the one hand, concern over global warming raised new interest in climate change, after decades when most historians dismissed any mention of it as crude determinism.[124] On the other hand, advances in paleoclimatology and historical climatology revealed how much and in what ways Europe's climate had varied, and how those variations affected early modern populations.

As emphasized in this chapter, the historical climatology of early modern Europe has taken climate reconstructions beyond gradual changes in temperature or even annual temperature time series. Its aim has been to reconstruct not only decades-long trends but also the seasonal, monthly, or even daily weather patterns that most affect human life. In some parts of Europe, researchers have largely achieved that aim through the careful compilation and analysis of early instrumental records (where available) or through the construction of temperature and precipitation indices from narrative and proxy records in the archives of societies. In other parts of Europe, historical climatology remains a work in progress.

This work has begun to yield important insights for our understanding of climate and of human history. These reconstructions facilitate comparisons with the recent past, revealing how larger climatic trends appeared in certain regional and seasonal patterns and extremes. For instance, it is noteworthy that differences at the century level are rather small for summer and spring in contrast to autumn and winter (see Table 23.1). This detailed record facilitates the ability to distinguish between phases of multidecadal climatic change and shorter variations in seasonal climate. In this way, it emphasizes the human perception and experience of climate. Moreover, the historical climatology of early modern Europe helps relate periods of climate to historical periods and developments—for example, Western and Central Europe's demographic growth during the relatively high and stable temperatures of the 1520s–50s, compared with the declining growth rates during the frequent freezing winters and cold and rainy summers of the 1560s to the early seventeenth century. With the benefit of seasonal and monthly temperature and precipitation data, it becomes possible to establish links between climatic trends, regional and local weather, harvest failures and subsistence crises, and larger economic and demographic patterns in parts of Europe. In this manner, the work of historical climatology in early modern Europe has helped guide the way out of simple climate determinism (or its opposite, a "climate indeterminism") into useful climate history.[125]

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Notes

1. Bell and Ogilvie, 1978; Ingram et al., 1981; Pounds 2009, 5–6.
2. Ogilvie and Jónsson, 2001a, 2001b.
3. Kington, 2010, 53.
4. Bergthórsson, 1969; Ogilvie and Jónsson, 2001a, 2001b; Ogilvie, 2010.
5. Scott, 2015.
6. Matthes et al., 1939. For a discussion of the meaning and development of the term, see Ogilvie and Jónsson, 2001a, 2001b.
7. Solomina et al., 2008, 1–9. A detailed comprehensive review of Holocene glaciation is provided by Grove, 2004.
8. Oerlemans, 2001.
9. Oerlemans, 2005.
10. Lavigne et al., 2013.
11. Ogilvie and Jónsson, 2001a.
12. Ogilvie, 2010.
13. Ahmed et al., 2013; Neukom et al., 2014; Wilson et al., 2016; Miller et al., 2012.
14. Holzhauser and Magny, 2005; Nussbaumer et al., 2007; Holzhauser, 2010.
15. Wanner et al., 2008, and references quoted therein.
16. Wanner et al., 2000.
17. Messerli et al., 1978.
18. Ogilvie and Jónsson, 2001a, 2001b; White, 2014.

19. Jones and Lister, 2002.
20. Przybylak et al., 2010.
21. Tarand and Nordli, 2001; Jevrejeva, 2001; Leijonhufvud et al., 2010.
22. https://www.maynoothuniversity.ie/icarus (last accessed April 28, 2017); Murphy et al., 2018.
23. *Romania:* Teodoreanu, 2011; Cernovodeanu and Binder, 1993. *Slovenia*: Zwitter, 2013, 2015. *Greece*: Xoplaki et al., 2001.
24. On climatic evidence for the early modern Ottoman Empire, see White, 2011.
25. Rácz, 1999; Kiss, 2009, focuses on longer-term phenological and hydrological documentary proxy evidence.
26. Vesajoki and Tornberg, 1994; Holopainen and Helama, 2009. See also Nordli et al., 2007.
27. Tarand and Kuiv, 1994; Tarand et al., 2013.
28. The systematic documentation of instrumental measurements began in Uppsala (Sweden) in 1739 and a few years later in Turku (Finland) and Stockholm (Myllyntaus, 2009, 79 and references quoted therein). Utterström, 1955, 3–47.
29. Ogilvie, 1991, 2005; Hartman et al., 2017.
30. See e.g., Ogilvie, 1991.
31. Ogilvie, 1995, 2010 (and references quoted therein); Miles et al., 2014.
32. See e.g., Jónsson and Garðarsson, 2001.
33. Glaser, 2008.
34. Glaser et al., 2010.
35. Pfister, 1975, 1984, 1999, 2015.
36. See Brázdil et al., 1995–2015. For articles, see e.g., Brázdil et al., 2012.
37. Buisman and van Engelen, 1996–2015.
38. For a synthesis, see Guidoboni et al., 2010.
39. Camuffo and Enzi, 1995; Camuffo, 1987; Camuffo et al., 2010, 2014. For an example from southern Italy, see Diodato, 2007.
40. Grove and Conterio, 1995. For examples of Ottoman sources see, e.g., Stavrides, 2012.
41. Among his publications, see Le Roy Ladurie, 1971. See also Le Roy Ladurie et al., 2011; Le Roy Ladurie, 2004.
42. For phenological studies, see e.g., Daux et al., 2012 (but the widely cited series by Chuine et al., 2004 is flawed for reasons discussed in Chap. 6); Pichard and Roucaute, 2014.
43. Pichard and Roucaute, 2014. Pichard's data are available online on the HistRhone database at: https://histrhone.cerege.fr/.
44. Lamb, 1977.
45. Kington, 2010, presents a rough overview of climate and weather in the British Isles during 1–1599 and much more detail during 1600–2000, including an extended list of sources.
46. Manley, 1974.
47. Machado et al., 2011; Barriendos, 2005, 2009; Alberola Romá, 2014. In Portugal the klimhist project from 2012 to 2015 (http://clima.ul.pt/kh-tasks) generated several case studies and the following surveys: Santos et al., 2015a, 2015b.
48. Camuffo and Bertolin, 2012.
49. Jones, 2001.

50. Pichard and Roucaute, 2014; Brönnimann, 2015; Bergström and Moberg, 2002; Camuffo, 2002; Camuffo et al., 2016.
51. Auer et al., 2007.
52. Vinther et al., 2006.
53. Wales-Smith, 1971; Wigley et al., 1984; Murphy et al. 2018.
54. Slonosky, 2002; Camuffo, 1984.
55. The series from Geneva and Bern (since 1760) in the Euro-Climhist database (Module Switzerland) http://www.euroclimhist.unibe.ch/en/is not homogenized; Tarand, 1993; Pfister, 1975; Gimmi et al., 2007.
56. Rodrigo and Barriendos, 2008.
57. Dobrovolný et al., 2015; Santos et al., 2015b; Pauling et al., 2006.
58. E.g., Degroot, 2015.
59. Luterbacher et al., 2007; Xoplaki et al., 2005.
60. Luterbacher et al., 2010, 2016.
61. On the anomalous weather of 1540, see Wetter et al., 2014.
62. See also Pfister, 1984.
63. Luterbacher et al., 2004.
64. Luterbacher et al., 2016.
65. Xoplaki et al., 2005; Luterbacher et al., 2004.
66. Luterbacher et al., 2010; Mellado-Cano et al., 2018.
67. E.g., Luterbacher et al., 2001; Slonosky and Jones, 2001; Cornes et al., 2013.
68. Barriopedro et al., 2014.
69. Myllyntaus, 2009.
70. Vesajoki and Tornberg, 1994.
71. Dybdahl, 2012.
72. Frich and Frydendahl, 1994.
73. Lappalainen, 2014.
74. Post, 1985.
75. Ogilvie and Jónsson, 2001a, 2001b; Ogilvie, 2010; Hartman et al., 2017.
76. Ogilvie, 1995, 2010.
77. Ogilvie and Jónsson, 2001a, 2001b.
78. Demarée and Ogilvie, 2001.
79. Ogilvie, 2010.
80. Pfister, 1999, 68–69; Dobrovolný et al., 2015.
81. Dobrovolný et al., 2015; Pfister and Brázdil, 1999, Fig. 2.
82. Pfister, 1996.
83. Pfister, 1999, 106–07; Buisman and van Engelen, 1996–2015; Brázdil et al., 2013, 123.
84. Pfister, 1999, 106–07.
85. Brázdil et al., 2013.
86. Pfister, 1999; Dobrovolný et al., 2015.
87. Appleby, 1978; Le Roy Ladurie, 2004.
88. Brázdil et al., 2013.
89. Pfister, 1984, 119.
90. Fernandez-Armesto, 1988, 237.
91. Lamb and Frydendahl, 1991, 40; Pfister 1984, 145.
92. Pfister, 1996; Campbell, 2010.
93. Ogilvie, 2010.
94. Glaser, 2008; Le Roy Ladurie, 2004; Buisman and van Engelen, 1996–2015; Pfister, 1984.

95. Pfister, 1999; Dobrovolný et al., 2015.
96. Pfister, 1999; Dobrovolný et al., 2015.
97. For the grape harvests Daux et al., 2012; for the alpine snowfalls Pfister, 1999.
98. Dobrovolný et al., 2015.
99. Pfister, 2005, 63–65.
100. Lachiver, 1991; Monahan, 1993; Garnier, 2010.
101. Post, 1985; Engler et al., 2013.
102. Ogilvie, 1995.
103. Pfister, 1999; Dobrovolný et al., 2015.
104. Pfister, 1999; Dobrovolný et al., 2015.
105. Pfister, 1999; Dobrovolný et al., 2015.
106. Camuffo et al., 2014.
107. Roberts et al., 2012.
108. Rodrigo et al., 1999. Broken down seasonally, it appears the winters and springs were exceptionally rainy, but summers dry—compare Rodrigo and Barriendos, 2008, and Creus-Novau et al., 2005. See also lake-level and lake sediment data for southern and eastern Spain in Roberts et al., 2012, and Oliva et al., 2014.
109. Barriendos and Martin-Vide, 1998; Glaser et al., 2010; Ruiz et al., 2014. Bullón, 2008, creates a temperature index based on written evidence and finds that temperatures of the 1590s were low, but not exceptionally so. This may be because the temperatures of the preceding decades were already unusually low, and so the cold was not especially noted.
110. Ruiz-Labourdette et al., 2014; Saz Sanchez et al., 2001; Domínguez-Castro et al., 2008.
111. Genova, 2012; Cabrera de Cordoba, 1857, 57, 166, 205–06; Font Tullot, 1988, 75–82.
112. White, 2011 and sources therein.
113. Camuffo et al., 2015.
114. Camuffo et al., 2015; White, 2011.
115. Grove and Conterio, 1995.
116. White, 2011.
117. Xoplaki et al., 2001.
118. Hughes, 2014.
119. Dunning, 2001.
120. Borisenkov, 1995.
121. Przybylak et al., 2010, 2014.
122. Braudel, 1995, 285.
123. He discusses his own and other scholars' early work in the field in Le Roy Ladurie, 2013.
124. Wigley et al., 1981; Hulme, 2011.
125. Hulme, 2011.

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CHAPTER 24

North American Climate History (1500–1800)

Sam White

24.1 Introduction

The historical climatology of North America (here defined as the territory of the present United States and Canada) from 1500 to 1800 remains a small but growing field of study. Most climate reconstructions for the region and period rely on proxies from the archives of nature (see Chap. 3). North American universities and researchers have not usually followed the same traditions of documentary-based climate reconstruction as in Europe and China, and pre-instrumental climate reconstruction has usually been a subject for archaeologists and climatologists rather than historians. There remain more works gathering interesting historical anecdotes and weather lore than rigorous documentary-based climate reconstructions and climate history.[1]

Nevertheless, there are substantial resources from the archives of societies to improve our picture of past climate and weather in North America, and its role in human history. This chapter provides an overview of that evidence as well as recent research into North American historical climatology. Given the still limited state of the field, this chapter will be brief. Readers interested in further studies, including the range of paleoclimate and archaeological evidence for past climate in North America, may consult one of a number of recent review articles listed in the bibliography.[2]

24.2 Geography, Climate, and Context

North America's size and topography create varied climates with sharp contrasts from region to region. Temperatures range from extremely low in northern Canada to extremely high in the deserts of Nevada and Arizona. The Pacific

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coast alone has a mild maritime climate. Cold coastal currents contribute to cool, rainy weather much of the year in the Pacific Northwest but a more Mediterranean climate of arid summers and occasional winter rain in coastal California. The Rocky Mountains, running the length of western North America, block Pacific moisture from reaching the continental interior, creating a rain shadow with more arid conditions and sharp seasonal contrasts in the western uplands and the central Great Plains and prairies. Subtropical high pressure creates desert conditions in most of the south-western USA, apart from a brief "monsoon" of midsummer thunderstorms. In the south-eastern USA warm moist air from the Gulf of Mexico creates more mild, if variable, winters and muggy summers. Central and eastern North America have a continental climate with strong seasonal contrasts in temperature and high weather variability. This comes from the west-to-east circulation of continental air masses and from the effect of jet streams, which can alternately pull down cold dry Arctic air or draw up warm moist air from the Gulf of Mexico into the interior of the continent. Quebec, for instance, is at roughly the same latitude as Paris, but its winters are far longer and colder—more comparable to those of Moscow.

The variability and extremes of North America's climate posed challenges to the first European explorers and settlers, who often struggled to colonize the continent during this period. European exploration of North America began shortly after Columbus crossed the Atlantic in 1492. However, the Spanish Empire failed for generations to gain a foothold there. By the first decade of the seventeenth century, after much trial and error, the Spanish established their first permanent settlements in the south-west (Santa Fe) and south-east (St. Augustine), the French in the St. Lawrence Valley (Quebec), and the English in the mid-Atlantic (Jamestown). Spanish colonies and missions spread slowly over the following centuries, reaching California only in the eighteenth century. The French presence spread through the St. Lawrence Valley, then the Great Lakes region, and finally down the Mississippi River valley to Louisiana; but the French settler population was small and dispersed. The English settler population soon grew far larger, and by the early eighteenth century it reached from Newfoundland down the Atlantic coast to Georgia. At the end of the Seven Years War (also known as the French and Indian War, 1754–63), France ceded Quebec to Britain and its trans-Mississippi claims to Spain. In 1783, following the American War of Independence, the thirteen British colonies from present-day Maine to Georgia became the United States. At the end of the century, during the course of the Napoleonic wars, France seized the Mississippi territory from Spain only to sell it to the USA in 1803. In the meantime, American settlement began to push through the Appalachian Mountains into the interior of the continent, particularly along the Ohio River valley. During these three centuries, North America's indigenous population (usually known as Indians or Native Americans in the USA and as First Nations in Canada—but historically representing many diverse nations, cultures, and languages) faced epidemic diseases from the

"Columbian Exchange" while adapting to European technologies, trade, missionization, and colonization. The place of indigenous peoples and perspectives in climate history is discussed in Chap. 31.

24.3 Sources

This historical background is key to understanding the strengths and weaknesses of source material for North American climate from the archives of societies (see Chap. 3). While early exploration left many observations about weather and climate, these remain scattered and inconsistent until permanent settlements began during the seventeenth century. Thereafter, the number, consistency, and geographical coverage of written sources gradually increases; however, it remains heavily weighted toward the Gulf of Mexico, the Atlantic coast (particularly New England), to a lesser degree Quebec and New Mexico, and then starting in the eighteenth century, Louisiana. As populations became more numerous and literate, particularly in the English colonies, personal descriptive sources such as letters, travel narratives, and pamphlets were supplemented by more abundant and objective sources including newspapers, weather diaries, and finally early instrumental records. Both the evidence for, and the research on, North American historical climatology has been predominately Anglophone. However, French and particularly Spanish colonial records offer considerable potential for climate reconstruction.[3]

Europe's interest in the New World ensured that sixteenth- and seventeenth-century visitors to North America left many published accounts in English, French, Spanish, and other languages. In fact, the very novelty of New World weather and seasons was a key factor in early modern attempts to understand climates and their causes.[4] Early narratives of travel, exploration, and settlement remain useful mainly as sources of occasional weather observations. Given that Europeans often found the climate of North America unfamiliar and extreme, these observations can be difficult to interpret objectively. Nevertheless, they often add confirmation or detail to proxy-based climate reconstructions, as well as providing descriptions of human perceptions and impacts. Moreover, some examples include specific plant- or ice-phenological information, providing more objective data for reconstruction (see Chap. 5), as shown in the following section. Many of these sources have now been published in modern critical editions.[5] Researchers should take care to work with sources in their original language and context—not translations—since many terms related to weather and climate are specific to certain languages and have changed their meanings over time.

With the first permanent colonies came at least three additional sources of information. In the Spanish Empire, colonial officials engaged in frequent correspondence with local officials and royal councils, much of which is preserved in Spanish archives.[6] While little of this information directly pertains to climate, it often records climatic impacts. For instance, letters from the governor of Spanish Florida describe drought, harvest failures, and a possibly related outbreak of disease among Florida's Indians during the 1650s.[7] Since most early English colonization was sponsored by private corporations, it often left less detailed official correspondence. However, the business of English colonies encouraged more production of promotional and narrative pamphlets, as well as travel and personal narratives. Some of these sources contain general descriptions of weather and climate, indicating changing perceptions, conditions, and occasionally impacts of extreme weather. They have proven useful, for instance, in detailing the combination of drought and storms that ruined harvests and contributed to conflict over land and food in the Pequot War (a conflict between Massachusetts colonists and Native Americans in 1636–8).[8] Finally, in both the French and Spanish cases, Catholic missionaries generated correspondence about their activities and living conditions, much of which has been published.[9] While not necessarily focused on climate, missionaries were often careful to record the culture and practices of Indians, including their weather rites and the possibilities for settling them in permanent agricultural villages.[10]

For the late seventeenth and eighteenth centuries, researchers have more abundant and varied records from the archives of societies for North America. Decades of settlement in America acquainted Europeans and European-Americans with the distinctive features of North American climates. Therefore, historical sources begin to reveal not only isolated weather events but more subtle shifts and variations. In New England, and to a lesser extent other parts of North America, some farmers began to keep personal journals and weather diaries. Historical climatologist William Baron has estimated there are at least 2500 diaries preserved in north-eastern North America from the late seventeenth–nineteenth centuries, including over 500 with daily weather descriptions and many more with monthly or seasonal descriptions.[11]

Newspapers and almanacs began to appear in the English colonies around the turn of the eighteenth century, and soon became very widespread. If used carefully—avoiding such problems as second-hand reporting and exaggerated accounts—their geographical specificity and daily frequency make newspapers a particularly valuable source for some types of reconstruction. Besides detailing the human perceptions and impacts of weather, they can provide objective information such as the duration of snow cover and/or ice-phenological data.[12] Almanacs in colonial North America, as in early modern Europe, not only reflected contemporary weather perceptions and weather lore, but also served as a place to write down weather observations, providing sources similar to weather diaries (see Chap. 5).

The first instrumental records in North America date back to the 1740s in both New England and Quebec.[13] Several more series followed in other parts of New England and Virginia throughout the century, including those of America's "founding fathers" Thomas Jefferson and James Madison.[14] Most such series were short-lived, but once properly aggregated and homogenized (see Chap. 9) they can extend local temperature, pressure, and (less often) precipitation records into the eighteenth century at monthly, daily, or even sub-daily resolution. Combining these historical sources, researchers have attempted reconstructions of key climate variables in parts of North America back into the eighteenth and even seventeenth centuries. These include, for instance, drought frequency and growing season duration in New England.[15] In contrast to European and Chinese historical climatology, North American researchers have not usually made use of temperature and precipitation indices from narrative and proxy data (see Chap. 11).

Agriculture in French Canada was sensitive to both early and late frosts, while the annual freeze and thaw of the St. Lawrence River determined the yearly rhythms of travel and transportation. These two phenomena can also serve as useful proxies for temperature trends in Quebec. The first person to keep regular instrumental records in Quebec, French doctor Charles Gaultier, also recorded the colony's first regular plant- and ice-phenological data, starting in the 1740s. Gaultier's records, along with those of subsequent observers, indicate that winters of the eighteenth century were generally milder than those of the early nineteenth century, probably the coldest period of the last millennium in Canada.

A major achievement for this period of North American historical climatology has been the reconstruction of two phenomena often poorly captured in the proxy record: storms and sea ice extent. Although sediment cores along the Atlantic and Caribbean coast can reveal the approximate frequency and magnitude of major storms, only the archives of societies have been able to reconstruct their numbers, strength, and human impacts at high resolution.[16] Historical climatologists including Michael Chenowith, Dennis Blanton, and Cary Mock have used various records, including Spanish official correspondence and American newspaper reports, to extend Atlantic storm reconstructions well beyond the instrumental period, revealing greater variability than is found for the past century alone.[17] Several historians have addressed the role of hurricanes in the colonial history of the Caribbean and Gulf of Mexico, and Eleonora Rohland has recently written on hurricanes in French colonial Louisiana as a case study in extreme weather impacts and adaptation.[18] The Hudson's Bay Company, which claimed a monopoly on the fur trade over nearly half of present-day Canada, also established early networks of scientific observations and correspondence, including information on climate and weather. Using the ship logbooks of its trading vessels, A. Catchpole calculated an annual sea ice severity index for Canadian waters from 1751 to 1870. Its station reports also provide a unique continuous record of written and early instrumental evidence for parts of western and northern Canada during the eighteenth century.[19]

24.4 Climatic Trends and Events

During the period 1500–1800 North America generally experienced lowered Little Ice Age (LIA) temperatures (see Chap. 23). Various proxy climate reconstructions, mostly taken from pollen and tree rings, indicate that the continent experienced broadly similar climatic trends as elsewhere in the Northern

Hemisphere, including Europe. Particular phases of cooling coincided with major volcanic eruptions and/or diminished solar activity, including the 1590s–1600s, 1680s–90s, and 1810s–30s. Yet temperature and precipitation reconstructions for LIA North America also reveal considerable variability over time and space.[20] Given the limits of available evidence, it is difficult to offer detailed case studies of North American climate variability for this period based solely on the archives of societies. Three episodes, however, stand out for their climatic and particularly their human historical significance.

24.5 Early Colonial Weather

Even with the luckiest of weather, early European invasions and colonizing efforts in North America would have faced serious challenges. Many came to the continent undersupplied, poorly prepared, and ignorant about its environment and indigenous peoples. Moreover, as historian Karen Kupperman first argued, Europeans faced "the puzzle of the American climate."[21] Based on classical meteorological and geographical ideas, they expected to find similar climates around the world at the same latitudes—an expectation that failed to account for eastern North America's continental climate, with stronger variability and seasonal contrasts. For instance, attempts to plant Mediterranean crops in Virginia and New England (at roughly the same latitudes as Sicily and mainland Italy) were destined for failure.

However, the first colonists were anything but lucky with the weather. Expeditions repeatedly arrived in North America only to face droughts, storms, and winters that were exceptionally cold even by the standards of the LIA. During the early 1540s, for instance, Spanish conquistadors encountered freezing winters and heavy snows in parts of California, the south-west, and south-east, where such weather is extremely rare or unheard of since modern instrumental records began in the late nineteenth century. The first colonists in Spanish Florida during the 1560s–80s also encountered alternating droughts and storms, which contributed to the decision to abandon the outpost of Santa Elena (Parris Island, South Carolina). A short-lived Spanish Jesuit mission to Virginia in 1570 found the land in the middle of a serious drought and freezing weather, "punished with six years of sterility and death."

The tropical eruptions of Nevado del Ruiz (1595) and Huaynaputina (1600) caused North American temperatures to plunge to some of their lowest levels of the LIA just when new Spanish, French, and English expeditions arrived in several parts of the continent. Juan de Oñate's invasion of New Mexico in 1598 faced severe drought; and then the winter of 1601 was so cold the Rio Grande froze for weeks on end. The exceptional climate contributed to hostilities with the indigenous Pueblos and the defection of more than half the first colonists. Attempted French colonies at Tadoussac, Quebec (1600–1) and St. Croix, Maine (1603–4) were nearly destroyed by scurvy when long winters left fresh food unavailable; and the first winter in Quebec (1608–9) killed nearly a third of the colonists. Jamestown, Virginia (established 1607) faced exceptional drought, which withered crops and may have hurt water quality, as well as an extraordinary winter in 1607–8, when the lower James River apparently froze halfway across, something that has almost never happened since.[22]

24.6 The Maunder Minimum

After the exceptional cold of the first colonial winters, the decades of the mid-seventeenth century were generally milder. This apparent change even led some French Canadian and New England settlers to speculate that their clearance and cultivation of the land were modifying the climate to make it more like Europe's.[23] However, during the late seventeenth century—sometimes known as the Maunder Minimum, for its low sunspot activity—north-eastern North America cooled again.

This climatic change raised new doubts about the suitability of North America's climate for European settlers. It has also been implicated in conflicts between colonists and Native Americans. For example, proxy, documentary, and archaeological evidence all demonstrate that New Mexico faced a severe drought during the 1670s, which forced many Pueblos to abandon their land. In 1680, a revolt of the Pueblo nations drove colonists and missionaries out of New Mexico for a dozen years.[24] In north-eastern North America, the Maunder Minimum brought a return of very cold, snowy winters. During the worst years in New England, the damage to crops and livestock revived fears of the famines that had plagued the first English colonies there during the 1620s. Among the highly religious Calvinist population, the severe climate raised anxieties of divine retribution.[25] In Maine and the Canadian Maritimes, as historian Tom Wickman has discussed, the long, heavy snow cover characteristic of the 1690s–1710s initially gave an edge to Indians during the first and second Anglo-Wabanaki Wars, until the English acquired traditional Native adaptations to the cold, such as snowshoes.[26]

24.7 Revolutionary Weather: The 1770s–90s

The 1770s–90s were a time of unusual climatic variability around the globe. As discussed in Chap. 34, this variability probably came from a combination of volcanic forcing (the Lakagígar eruption of 1783) and persistent El Niño and La Niña events that followed. Several historians have found connections between the climate and weather of this period and the onset, outcome, and aftermath of the American War of Independence (1775–83).

Sherry Johnson, for instance, has argued that unusually frequent and severe Atlantic storms impeded Spain's ability to keep Cuba and the Caribbean adequately supplied by sea during the 1760s and 1770s. Pressure from the islanders forced Spain to open its markets to trade with the British American colonies. This in turn helped those colonies reorient their economies away from Britain and its empire, boosting the economic case for independence.[27] The characteristic LIA weather of the late 1770s has come down in iconic American images of the War of

Independence, such as General George Washington crossing the ice-choked Delaware River in late 1776, or freezing with his troops in their winter camp at Valley Forge. Yet almost certainly the warm summers of the early 1780s played a more decisive role in the conflict, by helping to spread malaria among General Cornwallis's British army in the South.[28]

The 1780s also witnessed some unusually severe winters in the northern Great Plains, New England, and Quebec. In the upper Missouri River valley, extreme cold is thought to have decimated the bison population, leading to famine and an outbreak of smallpox among Plains Indians during 1780–2. In 1789, an outbreak of Hessian fly (a crop pest blamed on German mercenaries during the American War of Independence) along with exceptionally cold spring weather led to a severe dearth throughout the eastern American–Canadian borderlands—one of the last widespread climate-induced food shortages in North American history.[29]

24.8 Conclusion

Although North American scholars have often led the field of environmental history, very few have specialized in climate history and historical climatology, particularly during the colonial era. In part, this neglect reflects a lack of sources compared with Europe and China. Yet it also reflects the human history and historiography of North America during this period. American and Canadian populations were dynamic and mobile, moving across the continent, reshaping its landscape, and adapting to new markets and technologies. As geographer William Meyer put it in 2010, "the history of American weather to date is not principally the story of how the weather has changed, but of how Americans have changed."[30] The evidence and examples outlined in this chapter are intended to demonstrate how historical evidence, alone or in combination with proxy data, has already revised and can continue to revise views of early North American history that once paid little or no attention to weather and climate change.

Acknowledgments The author would like to thank Vicky Slonosky for her comments and for sharing material. Any errors are entirely my own.

Notes

1. E.g., Ludlum, 1963, 1966, 1984.
2. E.g., Baron, 1995, 1989; Mock, 2012; White et al., 2015; Foster, 2012.
3. Official archives in Santa Fe were destroyed in the Pueblo Revolt of the 1680s, creating a gap in those records.
4. White, 2015a, 2015b.
5. E.g., Quinn and Quinn, 1978 for English colonial sources, and the Cibola Project—https://escholarship.org/uc/rcrs_ias_ucb_cibola (last accessed April 14, 2016)—for the Spanish south-west.

6. The Archivo de Indias in Seville has made many of these series, such as the Cartas de Gobiernas from Spanish Florida, available online through http://pares.mcu.es/ (last accessed April 14, 2016).
7. Described in Hoffman, 2002, 126–28.
8. Grandjean, 2011.
9. See especially Thwaites, 1896.
10. See examples in, e.g., White, 2015a.
11. Baron, 1995.
12. Mock, 2012.
13. Slonosky, 2003.
14. Baron, 1988, 1989; Druckenbrod et al., 2003. For an early compilation and description of records, see Blodget, 1857.
15. Baron, 1995, 74–91.
16. E.g., Besonen et al., 2008; Burn and Palmer, 2015.
17. E.g., Chenoweth, 2006; Blanton et al., 2009.
18. E.g., Schwartz, 2015; Rohland, 2015.
19. Binnema, 2014; Catchpole, 1995; Ball, 1995.
20. Pages 2k Consortium, 2013.
21. Kupperman, 1982.
22. On early colonial weather, see e.g., Blanton, 2000, 2003a, 2003b, 2004, 2013; Paar, 2009; White, 2014; 2015a; 2017.
23. On the history of ideas relating to land use and climate change, see Golinski, 2008; Thompson, 1980; Vogel, 2011; Coates and Degroot, 2015.
24. Ivey, 1994; Parks et al., 2006.
25. Kupperman, 1984.
26. Wickman, 2015.
27. Johnson, 2005.
28. McNeill, 2010.
29. Campanella, 2007; Hodge, 2012; Taylor, 1999.
30. Meyer, 2000, 6.

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CHAPTER 25

Climate from 1800 to 1970 in North America and Europe

Stefan Brönnimann, Sam White, and Victoria Slonosky

25.1 Introduction

The climate history of North America and Europe from 1800 to 1970 has been relatively well studied. Climate reconstructions for the early nineteenth century largely depend on proxy data from natural archives, documentary evidence, and early instrumental series. The period marks a transition from the Little Ice Age to the current age of global warming. The climate underwent several fluctuations during these two centuries, with cold periods in the early and late nineteenth century and the cool mid-twentieth century interspersed with rapid warming, as in the early twentieth century. The establishment of American and European national weather services during the mid- to late nineteenth century marked a new era, with continuous standardized instrumental data. A global observation system gradually came into being, with particularly dense information for North America and Europe.[1] This chapter provides an overview of the available data and main climatic trends for the period, followed by descriptions of major climate historical events.

25.2 Data

By 1800 in Europe, early instrumental measurements were recorded by a variety of individuals and institutions, from religious figures and educated amateurs to doctors, explorers, colonial administrators, and commercial corporations.

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The motivations for keeping such detailed records ranged from curiosity about the natural environment, to investigating the effects of weather and climate on health, to determining whether climate change—including anthropogenic climate change—was occurring. Although some coordinated activities (i.e., meteorological networks) began in the late 1700s, most of them were not successful in the long term (see Chap. 7).

North American counterparts started somewhat later and took longer to spread across the continent. The earliest instrumental records in the United States and Canada date back to the 1740s (see Chap. 24). Some groups of observers and regional networks can provide more or less continuous instrumental data for parts of North America since the early decades of the nineteenth century.[2] For example, some military units kept regular observations going back to almost the start of that century.[3] In Canada, colonial officials, military officers, and clergymen kept long-term records, while explorers from the Hudson's Bay Company were among the first to keep widespread, if sporadic, weather observations. In the early nineteenth century, their trading posts were ordered to keep daily temperature and weather records, which are currently used for climatic reconstruction.[4] Royal Navy ship records in Hudson's Bay and the Arctic can also provide frequent temperature measurements and ice-phenological observations going back to the 1810s.[5]

The invention of the telegraph in 1837, the relevance of weather for rising global transportation and trade, and new government responsibilities in emerging nation states all promoted the establishment of national meteorological networks. In Europe, most national weather services were founded during the 1850s–80s. The Meteorological Service of Canada was established in 1871. In the United States, the Smithsonian Institution started operating a network in the 1840s; national weather reporting was assigned in 1870 to the Army Signal Service, and then in 1890 to a civilian Weather Bureau, the precursor of the US National Weather Service. The main activity was weather observing; weather forecasting was initially considered unscientific and often started at a later stage. Indeed, in the 1870s, meteorology was still a long way from developing a physical theory of the atmosphere (see Chap. 38). What was of considerable concern to both military and commercial shipping was storm warnings, and it was for this purpose that many of the state-supported weather networks arose in the mid-nineteenth century.[6]

Weather was of particular importance at sea. Officers on ships kept meteorological observations meticulously. During the mid-nineteenth century, agreements such as the 1853 Brussels Maritime Conference, and emerging conventions such as Beaufort's wind scale, promoted the worldwide standardization of maritime weather observations and their application to meteorology.[7] For land observations, the 1873 International Meteorological Congress and the subsequent foundation of the International Meteorological Organization had similar aims, although these turned out to be very difficult to achieve.[8] Meanwhile, the number of weather measurement sites increased very rapidly worldwide (see Fig. 25.1 for the example of air pressure).

The measurements made by individuals in the early nineteenth century were often communicated through scientific journals or newspapers, but coordi-

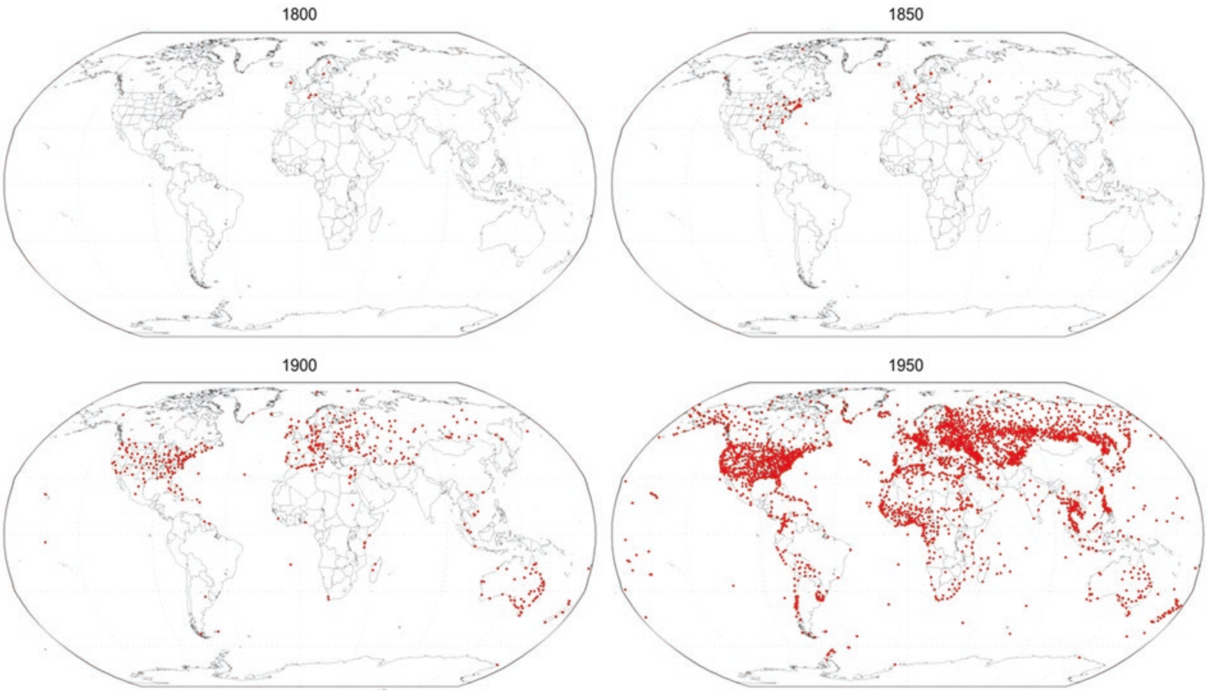

Fig. 25.1 Coverage of meteorological stations with daily pressure readings for the years 1800, 1850, 1900, and 1950 in the International Surface Pressure Databank (ISBD) Version 4. Reproduced with permission from https://www1.ncdc.noaa.gov/pub/data/ispd/add-station/v4.0/

nated collection and publication of observations often failed (see Chaps. 7 and 34).[9] UK Admiral Robert FitzRoy instigated one of the first systems of weather observation collection, analysis, and dissemination for the purposes of issuing storm warnings in the 1860s. Inspired by Alexander von Humboldt's *Cosmos* and his pioneering use of isothermal maps, a new interest arose in the collection and analysis of climatic data. Eventually, the national weather services published observations in yearbooks. Efforts at collecting global datasets relied largely on a few individuals. In North America, James Pollard Espy, Cleveland Abbe, and (for marine data) Matthew Maury compiled large collections. In Europe, Heinrich Wilhelm Dove (in the 1830s), then Julius Hann, Robert FitzRoy, Francis Galton, Wladimir Köppen, Eduard Brückner, and later Felix Exner put together large datasets for climatological purposes (see Chap. 38). In the 1920s, the Smithsonian Institution started its global compilation of weather data, the World Weather Records.[10] After the 1960s, pioneers of climate history such as Christian Pfister, Emmanuel Le Roy Ladurie, and Hubert H. Lamb also compiled historical instrumental and documentary records.

The two world wars affected operations and interrupted data exchange. Upper-air observations, which had been performed in only a few places during the early twentieth century, became standard in many countries after World War II, when international cooperation resumed. The World Meteorological Organization (WMO) was created by the World Meteorological Convention and adopted in 1947. The International Geophysical Year of 1957/8, a global research program, brought a further massive improvement and standardization of observation systems and data exchange; and many currently available global data products date back to 1957 (see Chap. 26).

25.3 Climate Trends

The period from 1800 to 1970 marks the transition from the Little Ice Age (LIA; see Chap. 23) to the recent period of global warming, both as a recovery from the LIA and from anthropogenic contributions. Following a cool phase during the 1810s–30s, temperatures increased globally. The trend was not steady over the period. Rather, temperatures underwent several phases of accelerated warming interrupted by periods of stability or even cooling, such as the 1880s–90s and mid-twentieth century. The main phases of warming and stability in Europe and North America were similar to those of the world as a whole.

Several of the changes in global temperature during the 1800–1970 period have been attributed to external forcing of the climate system. The cool period in the early nineteenth century was most likely caused by increased volcanic activity—four major tropical volcanic eruptions within less than three decades, including the 1815 Tambora eruption (see Chap. 35)—and arguably to a lesser extent by a minimum in solar activity known as the Dalton Minimum from 1790 to 1830.[11] The temperature increase during the early twentieth century can partly be explained by greenhouse gas forcing (hypothesized as early as 1938[12] and then studied in more detail since the mid-1950s[13]), but unusual internal variability of the climate system must have contributed.[14] The slowdown in warming during the 1950s–70s has been attributed to increased aerosols, particularly in the Northern Hemisphere. In addition to forced variability, internal variability influenced climate from year to year (as expressed in atmospheric circulation indices such as the North Atlantic Oscillation or the Pacific North American Pattern) and decade to decade (as expressed in indices of the Atlantic Multidecadal Oscillation—see Fig. 25.2).[15] The strong southwesterly winds of the period 1900–20 contributed to a warming of the European Arctic because they brought warm oceanic air to the western continental regions and polar region. Similar strong westerly circulation occurred in the period 1980–2000.

25.4 Climate Events

25.4.1 The Tambora Eruption and the "Year Without a Summer" of 1816

The 1815 eruption of Tambora caused the most pronounced climate anomaly of the period, and one of the largest of the past two millennia in Europe and North America. In the following year, global temperatures dropped by 0.4–0.8 °C (although a strong eruption six or seven years earlier arguably also contributed to low temperatures in the 1810s). The climate anomaly particularly affected New England and the St. Lawrence valley as well as Central Europe, where 1816 went down in history as a "Year Without a Summer." In Switzerland, summer (June–August) temperatures fell as much as 3 °C below the average of the two preceding decades (Fig. 25.3). The number of rainy days almost doubled, and cloud-free days became very rare. Apart from some direct radiative cooling owing to volcanic aerosols, this cold cloudy weather was probably due to a southward shift in the track of Atlantic depressions, perhaps a remote effect of the volcano-induced weakening of the African monsoon system.[16]

The "Year Without a Summer," which struck Europe in the wake of the Napoleonic wars, a period of high social and economical vulnerability, had substantial impacts on society. Harvests were late and meager. In some areas prices rose dramatically, leading to malnutrition and elevated mortality.[17] The "Year Without a Summer" is known as the "last great subsistence crisis of the Western world." In North America, cold waves and snowstorms as late as June caused many fatalities.[18] (For more on the "Year without a Summer" see Chap. 35.)

25.4.2 The 1830s Climate Cooling and Glacier Advances around 1850

As in the 1810s, a sequence of two eruptions (Babuyan Claro, Philippines, in 1831 and then Cosiguina, Nicaragua, in 1835) led to lower temperatures worldwide during the 1830s. Temperatures remained low in Europe, Asia, and North America until the early 1840s. In Switzerland, as a consequence of the low summer temperatures and increased winter rainfall, glaciers grew, reaching

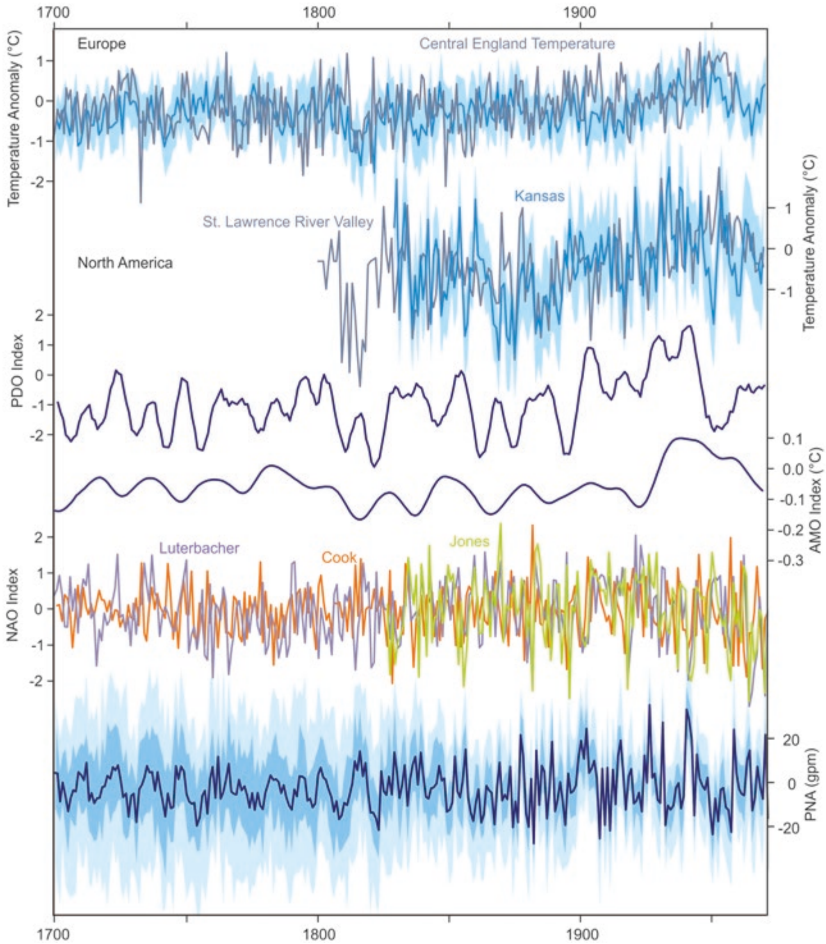

Fig. 25.2 Time series of annual mean temperature anomalies (with respect to 1700–1890) for Europe from PAGES 2k (2013) (blue, light blue shading indicates maximum and minimum). Instrumental records from central England (Manley, 1974), the St. Lawrence River valley (Slonosky, 2014, 2015), and Kansas (Burnette et al., 2010; light blue shading indicates the 95% confidence interval), respectively. The middle two lines indicate annual mean sea-surface temperature indices of the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO) from reconstructions by Mann et al. (2008). The bottom two lines indicate boreal winter (Dec.–Feb.) mean values of indices of the North Atlantic Oscillation (NAO, an instrumental series from Jones et al. (1997) as well as reconstructions by Luterbacher et al. (2001) and Cook et al. (2002)) and the Pacific North American pattern by Brönnimann (2015). The dark blue line shows the mean value of thirty reconstructions, dark and light shading indicating the 50% and 90% range, respectively. All values are anomalies with respect to 1901–60

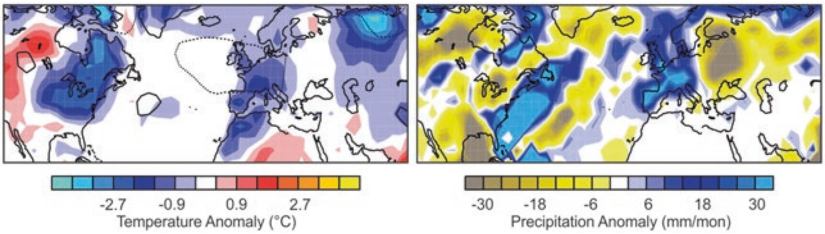

Fig. 25.3 Reconstructed fields of (left) temperature, sea-level pressure (solid and dashed contours denote 2 hPa and −2 hPa, respectively), and (right) precipitation during Jun.–Aug. 1816, relative to 1700–1890 (Reproduced from Stefan Brönnimann, *Climatic Changes Since 1700* (Berlin: Springer International Publishing, 2015). With permission from Springer)

another maximum in around 1850. After 1850, glaciers in Europe and North America began their steady decrease, which has continued to the present day, punctuated with short phases of stability or even slight advances. The year 1850 is often used to mark the end of the LIA. However, average global temperatures remained low until the 1890s, with the 1880s being a particularly cold decade in North America.

25.4.3 The Early Twentieth-Century Warming

During the period 1910–40, the North Atlantic, Europe, North America, and especially the Arctic underwent pronounced warming.[19] In Spitsbergen, a step change of 2–3 °C in annual mean temperature occurred in the late 1910s, then temperatures remained high until the early 1940s.[20] A peculiar atmospheric circulation anomaly, with a strong Siberian High extending over Scandinavia and low pressure over Greenland, transported warm air masses into the Arctic. Temperature records show warming on a global scale at this time. Both the tropical Pacific and the Atlantic have been suggested as drivers for this early twentieth-century warming.[21]

25.4.4 The "Dust Bowl" Droughts in North America in the 1930s

In the 1930s, concurrent with the Arctic warming, the Great Plains of the United States experienced a decade of drought and wind-blown erosion known as the "Dust Bowl." Studies based on model simulations have identified a specific pattern of sea-surface temperature anomalies (Fig. 25.4), consisting of a cold tropical and northern Pacific with a warm tropical and northern Atlantic, as a trigger for the drought.[22] These anomalies affected large-scale atmospheric circulation and the Great Plains Low-Level Jet, the mescoscale circulation feature responsible for the moisture influx from the Caribbean Sea into the central United States.

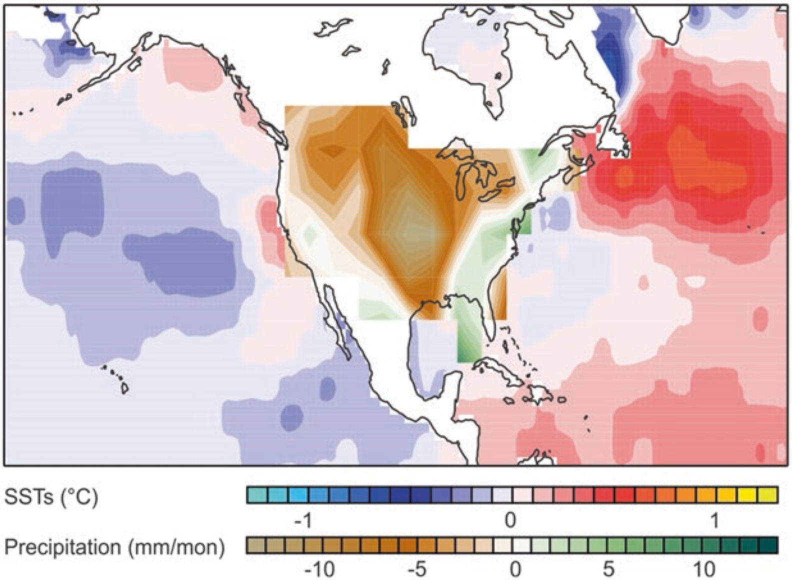

Fig. 25.4 Precipitation and sea-surface temperature anomalies in 1931–39 relative to 1920–50[25]

A large drought affected all of central North America (Fig. 25.4), reaching from north Texas to the northern Rocky Mountains and the Canadian Prairies. In the worst-affected areas, centered around the state of Oklahoma, intense dust storms blew away the top soil and turned farm land into desert. While the North American Great Plains had been subject to recurring droughts during past centuries, the expansion of agriculture during and after World War I may have amplified the drought, and it certainly left the population more vulnerable.[23] The droughts and erosion, which coincided with the Great Depression, had major social and economic effects, including accelerated migration out of the southern Great Plains. The Dust Bowl also triggered major US government initiatives in soil conservation.[24]

25.4.5 Climatic Anomalies in 1940–2

The climate of North America and Europe exhibited pronounced anomalies in 1940–2. Winters were extremely cold in northeastern Europe, but very warm in Alaska. Springs were wet in central Europe. Anomalies in Antarctica and Asia suggest that this must have been a global climate event. These phenomena can, at least to some extent, be attributed to a strong persistent El Niño event in the tropical Pacific.[26] (On the workings of El Niño events, see Chap. 2; on persistent El Niños, see Chap. 34.)

The exceptional European winters played a famous and historic role during World War II. Extreme cold in Russia slowed the advance of invading German troops—much as similarly cold winters had devastated Napoleon's Grande Armée in 1812 and Swedish King Charles XII's army in 1709 during previous attempts to invade Russia. At the same time, the exceptional weather contributed to the starvation and suffering of populations in occupied Eastern Europe.[27]

25.4.6 Retraction of the Northern Tropical Edge after 1945

During the post-war years, Central Europe suffered from several pronounced summer droughts, including 1945, 1947, 1949, 1950, and 1954. In many places, the heatwaves of 1947 set the (instrumental period) record until 2003. In the United States, droughts were frequent during the 1950s. The droughts on both sides of the Atlantic might have been related to the fact that the Atlantic Ocean was very warm (i.e., a high AMO index—see Fig. 25.2); consequently the tropical edge reached further to the north than normal, pushing the subtropical ridge of high pressure and low precipitation into higher latitudes. Agriculture and the transport and energy sectors were severely affected.

Over the following thirty years, the Southern Hemisphere warmed rapidly while the Northern Hemisphere (and particularly the North Atlantic) cooled. The entire northern tropical circulation moved southward. The Sahel droughts in the 1970s and 1980s can be partly seen as a consequence of a southward shift in the tropical belt.[28] By the 1980s, both hemispheres entered into a new warming phase, attributed to an enhanced greenhouse effect (see Chap. 26).

Notes

1. Edwards, 2010.
2. E.g., Hopkins and Moran, 2009; Slonosky, 2015.
3. E.g., Hopkins and Moran, 2009; Slonosky, 2015; Burnette et al., 2010; Baker et al., 1985.
4. E.g., Wilson, 1985.
5. E.g., Przybylak and Vizi, 2005.
6. Fleming, 1999; Anderson, 2005.
7. E.g., Naylor, 2015.
8. Edwards, 2010.
9. E.g. Dupigny-Giroux and Mock, 2009.
10. Edwards, 2010.
11. Schurer et al., 2014.
12. Callendar, 1938.
13. Revelle and Suess, 1957.
14. Schlesinger and Ramankutty, 1994.
15. Bindoff et al., 2013.
16. Raible et al., 2016.
17. Krämer, 2015; Luterbacher and Pfister, 2015.
18. Klingaman and Klingaman, 2013; Post, 1977.

19. Wood and Overland, 2010.
20. Nordli et al., 2014.
21. Thompson et al., 2015; Schlesinger and Ramankutty, 1994; Delworth and Knudson, 2000.
22. Schubert, 2004.
23. Cook et al., 2009, 2014. The once common view that farmers of the 1920s were ploughing already submarginal land has since been called into question—see Cunfer, 2005, and Sylvester and Rupley, 2012.
24. Worster, 1979; Hurt, 1981.
25. Brönnimann et al., 2009.
26. Brönnimann et al., 2004.
27. The role of food supplies and starvation has become an increasingly prominent feature of the history of the Eastern Front in World War II, as in Collingham, 2012.
28. Brönnimann et al., 2015.

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CHAPTER 26

Global Warming (1970–Present)

Stefan Brönnimann

26.1 Climate Data

Atmospheric temperature measurements provide strong documentation of climatic changes since 1970. In addition to meteorological stations of national weather services and other agencies, worldwide projects of the International Geophysical Year (IGY) in 1957/8 and First GARP [Global Atmospheric Research Program] Global Experiment (FGGE) in 1978/9 helped put in place a global atmospheric climate observation system.[1] The former initiated global networks of radiosondes, carbon dioxide measurements, and total column ozone measurements as well as establishing a system of World Data Centres. The latter brought the widespread use of satellites as platforms for Earth observations (see Chap. 38). However, the Global Climate Observing System (GCOS)—the first observation network dedicated to the analysis of climate trends—only came online in 1992, with the United Nations Framework Convention on Climate Change (UNFCCC).

Meteorological observations from the Earth's surface remain the principal source of information for global temperatures and precipitation back to 1970. Nevertheless, constructing global mean land temperatures from station data faces issues of coverage and representativity, and each individual time series needs to be homogenized for non-climatic artifacts (see Chap. 9).

Satellite measurements have now gone on long enough to provide another basis for calculating global climatic trends. Satellite data are used, together with radiosondes, for assessing temperature trends in the free troposphere and stratosphere. They supplement ship and buoy data for deriving sea-surface

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temperatures and marine winds, and they provide information about atmospheric composition. Satellite data are also used in so-called reanalysis datasets, which combine actual observations with weather forecast models in order to obtain a comprehensive estimate of atmospheric conditions every six hours.[2]

26.2 Climate Trends

From 1970 to 2017 global temperatures (land and ocean) increased by ~0.9 °C (see Fig. 26.1).[3] The rate of warming has not been constant: global temperatures increased more steeply during the 1990s and since 2011 than during the period in between. Nor has the warming been spatially uniform: the continents have warmed faster than the oceans and higher latitudes have warmed faster than lower ones (see Fig. 26.2). The Arctic has warmed particularly rapidly owing to feedback processes such as ice-albedo feedback and feedbacks involving clouds and water vapor.

Atmospheric warming since 1970 has a clear vertical structure as well. In the Arctic, warming has been strongest near the ground, where feedback processes operate most strongly. In the tropics, by contrast, the warming has been greatest at an altitude of ~10 km, owing to increased evaporation at the surface, which releases heat as the water condenses into clouds. Globally, the increase in temperature in the upper troposphere is at least as strong as at the surface (Fig. 26.1), although trends derived from weather balloons still present some uncertainty and high interannual variability. The stratosphere cooled from the 1970s to the mid-1990s owing to the increase in greenhouse gases and loss of ozone (Fig. 26.1). This cooling was interrupted by sharp warming spikes following major tropical volcanic eruptions (see the example of Pinatubo below). The stratospheric cooling has stopped since the late 1990s for reasons that are not fully understood.

Trends in precipitation are much less clear than those in temperature and more difficult to establish. From 1970 to 2015, precipitation increased over mid-latitude land areas and in the inner tropics, while decreases are found in subtropical regions (Fig. 26.2). However, such trends are noisy and usually do not stand out from interannual variability.

Not only has mean climate changed, but also extremes. Around the world since the 1950s, there have been more heatwaves and fewer cold nights. Changes in other types of extremes are more difficult to establish, but there are indications that heavy precipitation events have intensified. The frequency of tropical cyclones has not changed, although there is evidence for intensification of Atlantic hurricanes.[4]

Global warming since 1970 has also affected the cryosphere. Northern hemispheric snow cover has decreased since 1970. Satellite data of sea-ice cover, which reaches back to 1979, demonstrates a particularly rapid decline of Arctic sea-ice extent: record minima were set in autumn 2007 and then again in autumn 2012 (Fig. 26.1). Ice thickness also decreased, while the melting season grew longer. Both the Greenland and Antarctic ice sheets lost mass during the past two decades for which data are available. The majority of glaciers worldwide have been retreating, particularly since the 1980s. As a consequence

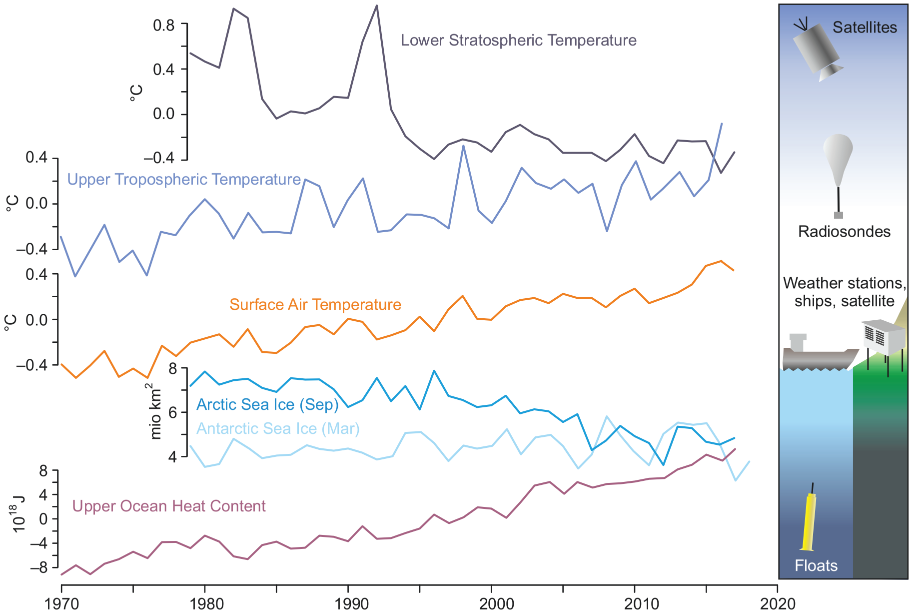

Fig. 26.1 Annual time series of lower stratospheric temperature (TLS/MSU Data, from RSS), upper tropospheric temperature (300 hPa, RICHv1.5, Leo Haimberger, Univ. Vienna), land and ocean surface air temperature (NOAAGlobalTemp; all series are anomalies with respect to 1981–2010). Arctic and Antarctic sea-ice extent (NSIDC) and upper ocean heat content (0–700 m, from NOAA; anomalies 1981–2010). The right panel shows the platforms used

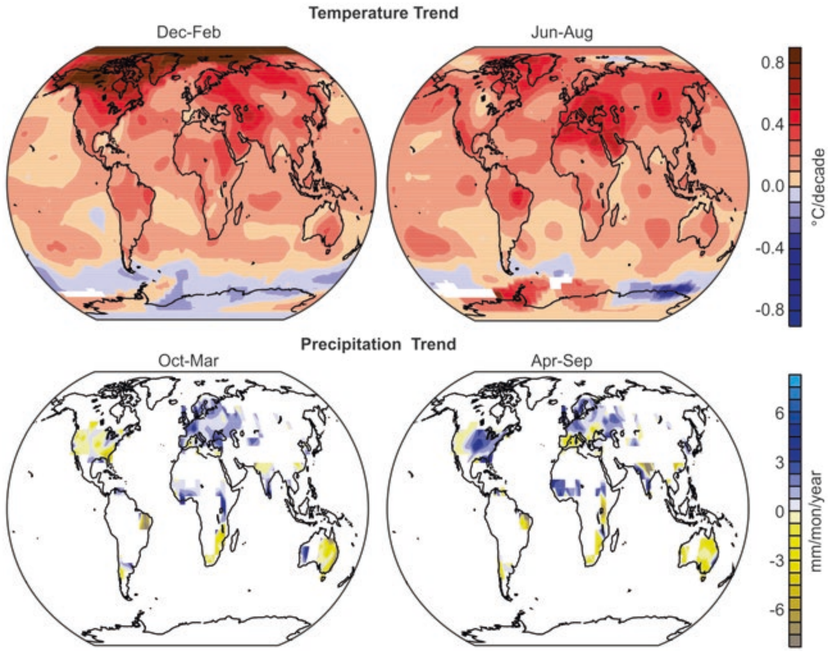

Fig. 26.2 Trend of (top) temperature (NASA/GISS) from 1970 to 2016 and (bottom) precipitation (NCDC) from 1970 to 2015 in boreal winter (left) and summer (right)

of both warming and meltwater influx, global sea level has risen by ~10 cm since 1970.[5] Moreover, upper-ocean heat content has risen considerably during the same period (Fig. 26.1). Until recently, Antarctic sea-ice extent in autumn slightly increased, owing possibly to anomalous atmospheric circulation induced by the Antarctic ozone hole in spring and summer (see below). However, 2017 saw low sea ice.

In contrast to thermodynamic variables such as temperature, ice volume, or ocean heat content, dynamic variables related to atmospheric circulation have changed relatively little. Since *c.* 1980, the tropical belt has widened and mid-latitude storm tracks have shifted poleward. The most prominent tropical circulation cells—the Pacific Walker circulation and the meridional Hadley circulation—strengthened until around 2013. Surface wind speeds have decreased, arguably due to increased surface roughness.

Global climate models that incorporate these climatic forcings (greenhouse gases, tropospheric aerosols, solar and volcanic activity, and land use change) have effectively reproduced these observed trends in surface temperature (see Chap. 13). These models indicate that most of the global surface temperature increase since 1950 can be attributed to greenhouse gases. Up to the late 1980s, the increase of tropospheric aerosols (small liquid or solid particles suspended in the air) counteracted some of the greenhouse gas-induced warming, a phenomenon known as "global dimming." Air quality measures have reduced aerosol emissions in most parts of the world, contributing to a "global brightening" since around 1990.[6]

26.3 Atmospheric Composition Change

Human emissions began to significantly alter the global atmosphere in the 1950s; by the 1970s, air quality had become a global environmental concern. In May 1985, scientists from the British Antarctic Survey discovered rapid stratospheric ozone loss over Antarctica.[7] This so-called "ozone hole" comes from emissions of chlorofluorocarbons (CFCs) that reach the stratosphere and release chlorine. During each Antarctic winter, temperatures drop low enough to form clouds. The surfaces of the cloud particles transform chlorine into its reactive forms. When the sun rises in the Antarctic spring, these species photolyze and destroy ozone molecules, depleting the Antarctic ozone layer. The 1987 Montreal Protocol and subsequent amendments banned CFCs and other ozone-depleting substances. However, owing to the long lifetime of these compounds in the atmosphere, stratospheric ozone levels continued to decrease, reaching a minimum in the mid-1990s. Recovery of the ozone layer is now underway.

The ozone hole affected atmospheric circulation in the southern mid- to high latitudes by enhancing westerly airflow in spring and summer. This is the likely reason that surface temperatures did not increase over Antarctica during the 1970–2000 period and that Antarctic autumn sea-ice extent even increased.

Despite the global decline in atmospheric aerosols, they remain regionally important. A cloud of haze and pollutants frequently forms over the Indian Ocean and the Indian subcontinent during the dry season. The phenomenon is known as the "Asian Brown Cloud" (ABC).[8] The cloud consists of aerosols with a large contribution of black carbon. The cloud adversely affects the health of a very large population living in the region. One of the main sources of the ABC is biomass burning (for domestic cooking, land clearance, and agriculture); another fraction comes from fossil fuel burning. The ABC alters the vertical temperature structure, heating the middle troposphere. Claims that these aerosols affect the Indian summer monsoon and tropical cyclones remain controversial.

26.4 Climatic Events

The period since 1970 has brought many noteworthy climatic events. These illustrate climatic variability on an interannual to multiannual timescale. A subjective but representative sample of events follows in this section.

26.4.1 The Sahel Droughts of the 1970s and 1980s

Droughts in the Sahel, particularly in the early 1970s and mid-1980s, have been among the most significant and deadly precipitation anomalies of the past half-century. The first drought, from 1968 to 1973, brought hundreds of thousands of fatalities and destroyed a way of life for millions of pastoral people. A combination of further drought and conflict during the early 1980s brought even higher excess mortality, particularly in Sudan and Ethiopia. These droughts also led to large economic losses, mass migration, and possibly irreversible land degradation.

The Sahel droughts were likely caused by a change in the meridional (north to south) temperature gradient across the tropical Atlantic, which weakened the West African Monsoon. Several factors may have contributed to this phenomenon, including aerosol-induced cooling north of the equator, internal variability in Atlantic sea-surface temperatures, and remote effects from the tropical Pacific and Indian oceans. Feedbacks through interactions of vegetation, soil, and atmosphere possibly prolonged the drought.

26.4.2 Change of European Winters around 1990

A sudden change in European winters and springs occurred between 1987 and 1989: spring snow cover decreased, and springs began earlier in the year. In 1990, a series of winter storms hit Europe (storms Daria, Herta, Vivian, and Wiebke). These events were accompanied by an increase in the North Atlantic Oscillation index, which measures the strengths of the Azores high and the Icelandic low, the two main quasi-permanent weather systems affecting European winters (see Chap. 23). Most of this change was related to internal variability of atmospheric circulation. However, climate models reproduce a small part of this phenomenon in response to changing sea-surface temperatures, greenhouse gases, and volcanic aerosols. The North Atlantic Oscillation returned to first normal and then negative conditions starting in the mid-2000s.

26.4.3 The 1991 Pinatubo Eruption

The 1991 eruption of Mt. Pinatubo, the biggest volcanic eruption of the twentieth century, affected the global atmosphere and climate. As the eruption occurred during the Space Age and at a time when model capabilities were already developed, its atmospheric effects have been well documented, clearly reproduced in atmospheric models, and scientifically well understood. The Pinatubo effects lasted around one to three years. The eruption produced a 1.5 °C increase in global average temperatures in the lower stratosphere, where volcanic aerosols absorbed outgoing longwave radiation (see Fig. 26.1). The aerosols also scattered the incoming sunlight. At the ground, global cooling followed, reducing average temperatures by as much as 0.3–0.5 °C. The cooling of the ocean surface affected both upper-ocean heat content and sea level. The reduction in net surface shortwave radiation decreased evaporation, slowing down the global hydrological cycle, while the change in the land–sea temperature contrasts led to a weakening of monsoon circulation.

26.4.4 The El Niño Events of 1982–3 and 1997

El Niño is an episodic warming of the eastern equatorial Pacific lasting one to two years. It is accompanied by a weakening or reversal of the Walker circulation and a shift in tropical convection. El Niños (and their opposites, La Niñas) have significant impacts on temperature and precipitation around the world (see e.g., Chap. 34). After the mid-1970s, El Niño events became more frequent than in the previous half-century. Two particularly strong events occurred in 1982–3 and 1997. The event of 1982–3 raised public awareness of the phenomenon, leading to the installation of an observation network and new research into understanding and forecasting El Niños. The second, even stronger, event of 1997 generated a peak in global mean temperatures the following year. In Indonesia, this El Niño brought severe drought and massive forest fires.

From 1998 to 2014, El Niño events became rare while La Niña events became more frequent, meaning more heat was stored in the tropical Pacific. This shift may explain part of the supposed slowdown in global warming from 1998 to 2014, sometimes termed the "hiatus." Another part of the "hiatus" might also come from observational biases related to the incomplete spatial coverage of temperature measurements described above.[9] Other explanations include heat uptake in the Atlantic and Southern oceans, and an increase in small volcanic eruptions.[10] A strong El Niño event occurred again in 2015.

26.4.5 Subtropical Droughts and Mid-Latitude Heatwaves in the New Millennium

The years since 1997 have brought exceptional droughts to various parts of the globe. From 1998 to 2004, a wide region of the northern subtropics from the Pacific to the Middle East suffered from droughts. The combination of a cool tropical Pacific (a La Niña) and a warm tropical Atlantic possibly triggered these droughts. At about the same time, from 1995 to 2009, Australia suffered from record drought conditions known as the "Big Dry" or "Millennium Drought." This drought has been related to a shift of westerly winds and a poleward extension of the southern edge of the Hadley cell. From 2010 to 2015, the USA was affected by a sequence of droughts triggered by anomalous sea-surface temperatures.

Several epochal heatwaves have also occurred since the turn of the millennium. The 2003 heatwave in Europe led to average summer (June–August) temperatures up to five standard deviations above the long-term mean.[11] The 2010 heatwave in Russia, which brought forest and bog fires and ruined wheat production, again changed the map of temperature records. The US heatwaves of 2012, the Australian heatwaves of 2009 and 2013, and the 2010, 2015, and 2017 Pakistan heatwaves likewise set new records at many sites. Heatwaves are predicted to become even more frequent and more severe in the future.

Notes

1. Edwards, 2010.
2. Edwards, 2010; Brönnimann, 2015.
3. Stocker, 2014.
4. Ibid.
5. Stocker, 2014.
6. Wild, 2012.
7. Farman et al., 1985.
8. Ramanathan et al., 2007.
9. Karl et al., 2015.
10. Brönnimann, 2015.
11. Note that anomalies for the summer of 1540 were of the same order, see Wetter et al., 2014.

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PART III

Climate and Society

CHAPTER 27

Climate, Weather, Agriculture, and Food

Sam White, John Brooke, and Christian Pfister

27.1 Introduction

Most analysis of climate change impacts and adaptation begins with food. Climate directly influences the life and growth of plants and animals on which people depend. Historically, the greatest and most immediate impacts of climatic change usually came from harvest failures during bad weather. Other human consequences attributed to climate change, ranging from economic dislocation to disease (Chap. 28), conflict (Chap. 29), and migration (Chap. 31), typically followed from disruptions to food supplies.[1]

Nevertheless, as ongoing studies have demonstrated and as this chapter will explore, the links among past climate change, weather, agriculture, and food supplies were often complicated and contingent. They depended on specific monthly and seasonal patterns in temperature and precipitation, not just general trends. Even within the same climate, particular environmental and social factors could spell the difference between survival and famine. The effects of weather on agriculture and food supplies cannot be understood apart from the fragility and resilience of societies, states, and economies. This chapter will outline research on the history of climatic change, weather, agriculture, and food supplies from the Neolithic to modern times, with a focus on Little Ice Age (LIA) Europe. A historical perspective informed by well-researched examples can help us make sense of when and how climate and weather have played

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an important role in agriculture and food in the past, and may again in the present century of global warming.

27.2 The Role of Climate and Weather in Food Production

In the widest sense, climatic change has influenced food production in three ways. First, it has defined the *potential* for agriculture and pastoralism. The relative warmth of our current Holocene epoch enabled the cultivation of plants and pasturing of livestock, which was difficult or impossible during the long Ice Ages of the Pleistocene. Over the course of the Holocene, broad shifts in regional temperature and precipitation influenced what crops could grow, and where populations settled into permanent agriculture or instead practiced shifting cultivation or pastoralism. The shorter climate fluctuations of recent history influenced local decisions about what fields to plant or leave fallow, and political decisions about which lands to conquer, colonize, and tax.

Conversely, climatic change has also defined *limits* to agriculture and pastoralism. Certain types of food production—in climatically marginal regions, on marginal plots of land, or using marginally suitable crops and practices—relied on climatic regimes that could and did come to an end when climates changed. The most famous case study remains the Greenland Viking colonies, supposed to have perished or emigrated once LIA cooling made their already difficult pastoral ecology unsupportable.[2] However, this popular parable of climate change and maladaptation might also stand in for any number of unrecorded local decisions made across centuries and millennia to abandon unsustainable land use in the face of changing temperatures or precipitation patterns.

Third, and most significantly, historical climate change has shaped actual and perceived *risks* to food production. Beyond the margins of cultivation or pastoralism, where climate posed absolute limits to these activities, most populations experienced climatic change as a change in the frequency and magnitude of weather extremes and related disasters that affected their livelihoods, whether these were droughts or floods, frosts or heatwaves. Perhaps the most important concept of historical climate change impacts is that small changes in climatic forcings—such as the orbital, solar, and volcanic forcings responsible for the LIA (see Chap. 23)—could lead to significant changes in the frequency and severity of extremes.

One way to visualize this concept schematically is to depict the expected range of some climate variable as a bell curve, as in Fig. 27.1a. Most societies would have been adapted to conditions in the middle of the bell curve but not to its extremities, as illustrated by the shaded portions in the figure. Climate change, represented by a shift of that bell curve in one direction, would lead to a much greater increase of extreme events beyond the bounds of adaptation (Fig. 27.1b), until societies eventually transformed their food production practices to suit the new climatic conditions (Fig. 27.1c). Therefore, the speed and

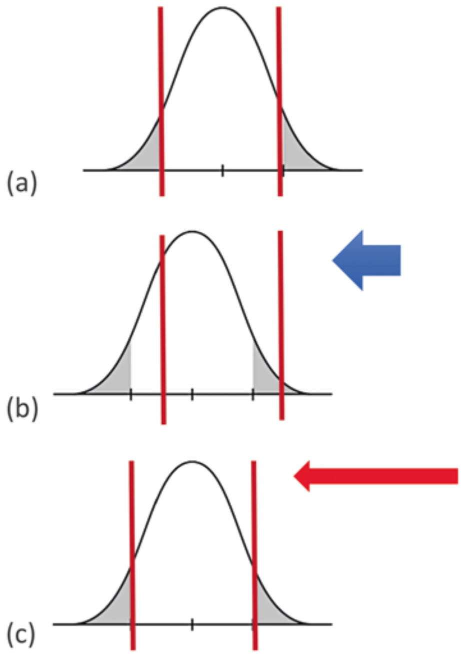

Fig. 27.1 In the top image (a), the bell curve represents an average distribution of temperatures in a given climate, the red lines indicate the limits of adaptation to temperature extremes, and therefore the shaded areas beyond the lines indicate the frequency of events beyond the adaptive capacity of the system. In the middle image (b), the distribution of temperatures has shifted to the left, indicating a cooler climate; however, the adaptive limits of the system have not yet adjusted. Now the frequency of cold events beyond the limits of adaptation is much higher than before, as indicated by the area between the shaded section and the red line on the left side. Over time, the system will adapt to accommodate the shift in the frequency of extreme cold events, as shown in the bottom image (c). In practice, the speed and capacity of this adaptation depend on both human and environmental factors.

magnitude of land use and institutional transformation—often by learning from disasters—shaped the human impacts of extreme events just as much as the speed and magnitude of climatic change.[3]

Clearly, not all climatic challenges to food production have come specifically from climatic *change*. Even in the absence of significant change, nature-induced disasters and year-to-year *variability* have always posed risks. In Europe, there have always been cold springs and wet summers; the Mediterranean and Middle East have always faced occasional droughts; Indian and Chinese farmers have always coped with occasional years when the monsoons failed; and so on. And clearly, not all threats to food supply have even come from weather and climate. Marauding armies, extreme poverty, excessive taxes, and misguided ideologies have been just as responsible for scarcity and famine throughout human history.

Nevertheless, a growing body of climatic and historical research makes a strong case that climatic changes and extremes have had significant effects on agriculture and pastoralism, with important human consequences. Concern over global warming has made this research ever more salient. It remains important to remember that the connections among climate, weather, food production, and human impacts are complex and contingent. Recognizing this fact, most scholars have become increasingly cautious and sophisticated in their analysis of causation. On the other hand, it would be equally naïve to dismiss the role of historical climate variability as simple determinism or as a distraction from contemporary anthropogenic warming. Past cases of climate-driven shortages and famine not only help us better understand history, but also help clarify the environmental and human circumstances of climate change vulnerability and resilience in the present age.

27.3 Climate Change and the Origins of Agriculture

For most of our species' history, humans lived in a colder, drier glacial epoch. Climatic conditions and fluctuations during this period probably made agriculture and concentrated food gathering difficult or impossible. Humans lived in small bands, many pursuing large game adapted to tundra conditions in much of Eurasia and North America.

As the last ice age gave way to the Holocene epoch, environmental conditions were transformed (see Chap. 15). As temperatures and sea levels rose, food availability shifted from grasslands to estuaries and woodlands. Throughout the world, hunter-gatherer bands settled onto these high-productivity locations and acquired the tools and technologies of the so-called Mesolithic, designed to exploit the "broad spectrum" of resources in these emerging environments. As they made increasing use of plant foods, these Mesolithic societies initiated the cultural and evolutionary changes that would lead to plant and animal domestication, and eventually to agriculture.[4]

From *c*. 10,900–9700 BCE the Younger Dryas cold period interrupted this transition. Then as the warming of the early Holocene resumed, societies in separate regions around the world made a gradual transition to a diet of domesticated plants and animals.[5] There remains considerable debate about how these domestications occurred, how quickly they spread, and what role climate played.[6] Domestication appears to have been a gradual process that could not occur during periods of more intense climatic stress, such as the Younger Dryas. However, it also appears that milder climatic stress, such as occurred during glacial meltwater crises of the early Holocene, could drive populations to intensify use of certain plants and animals, accelerating the trend toward cultivation.

The domestication of key crops and animals during the Early Holocene occurred in two regions sharing a particular set of environmental circumstances: South-West Asia and North China. Both were home to large-seeded grasses whose qualities made them relatively easy to domesticate, and both are located in the semiarid belt of the northern mid-latitudes. Hunter-gatherer exploitation of wheat, barley, lentils, pigs, sheep, and goats dated back at least to the Bølling-Allerød warming, and "management" of these species on a path to domestication began as the Younger Dryas cold was coming to an end. Yet full-scale village agriculture did not take hold until after another short cooling event at 8200 BCE, during a subsequent 1500 years of high precipitation, which Bernhard Weninger and colleagues have termed the Levantine Moist Period.[7] Village farming, with a fully formed pottery tradition, may have appeared in Northern China even before the Fertile Crescent. Excavations at Cishan, on the edge of the Loess Plateau north of the Yellow River, have revealed established villages with millet agriculture by 8000 BCE.[8]

The Middle Holocene, *c.* 6000–3000 BCE, brought both new domestications and in some regions the consolidation and intensification of agriculture.[9] Following another abrupt global cooling event *c.* 6200 BCE, the earth enjoyed a continued "optimum" of warmer temperatures for about two millennia. Thereafter, the monsoon rains that once reached far into North Africa, the Middle East, and Northern China began to retreat—a retreat that accelerated during the fourth millennium BCE. Some scholars have hypothesized that the cooling, drying climate of the era forced populations to concentrate into more fertile river valleys, promoting irrigated agriculture and the emergence of the first states and empires.[10]

27.4 Climate, Food, and Crisis in the Ancient and Medieval World

Among the climate history research to receive the most public attention in recent years have been studies of climatic change, famine, and collapse in ancient and medieval civilizations. Researchers in various fields have identified episodes of significant fluctuations in temperature and/or precipitation that overlap with written or archaeological evidence of famine, migration, and political disruption. There can be little doubt that climatic change had an impact on food production during ancient and medieval times. In some cases, the evidence for climatic change and the overlap with human crisis are far too strong to dismiss as mere coincidence. Unfortunately, the paucity of historical sources often makes it difficult to establish exactly how and why climate and weather influenced agriculture and food supplies, much less whether or how they caused societies to collapse.

For instance, during the past two decades, much attention and controversy have focused on evidence for abrupt cooling and drought across the Northern Hemisphere around 4200 years ago. Work by Harvey Weiss and colleagues at Tell Leilan (Syria) found evidence of marked aridity coinciding with the abandonment of agriculture; their discovery was followed by similar evidence of environmental and cultural change in other parts of Eurasia and North America. Nevertheless, written descriptions of the event are scarce and inconclusive, and not all archaeological sites spanning 2200 BCE reveal the same climatic changes or human impacts. Therefore, some archaeologists and historians have remained skeptical about the impacts of this so-called 4.2 ka event (see Chap. 16).[11] Likewise, since the idea was first proposed decades ago, scholars have found increasingly firm and precise evidence for a major drought in the eastern Mediterranean during the Late Bronze Age crisis of the twelfth century BCE. In this case, much more written and archaeological evidence has come to light attesting to migration, warfare, and political crisis, particularly in the Hittite Empire of Anatolia. It is reasonable to imagine a scenario wherein drought undermined agriculture and weakened commerce, taxation, and armies, leaving Late Bronze Age cities vulnerable to hungry marauders and invaders. However, the historical record is scarce and ambiguous enough that it remains open to interpretations other than climate-driven crisis, much less a crisis in agriculture or food production in particular (see Chap. 16).[12]

Other well-known case studies of climate-driven crisis can present similar problems of interpretation, including the collapse of classic Maya city-states in the Yucatan (ninth century CE), the abandonment of Ancestral Pueblo ("Anasazi") sites in the south-western USA (thirteenth century CE), and the fall of Angkor in Cambodia (fourteenth–fifteenth centuries CE). In all three cases, increasingly accurate and precise climate reconstructions and archaeological investigations have demonstrated the close correlation between major droughts and human crises. In all three it is reasonable and even compelling to imagine scenarios of climatic change leading to agricultural crisis, famine, and conflict. There are high-resolution precipitation reconstructions and some further archaeological and written evidence to support such scenarios. We can also identify the mechanisms behind the climate triggers proposed in each example: reduced Intertropical Convergence Zone (ITCZ) migration in the Yucatan, the El Niño Southern Oscillation (ENSO) in the American South-West, and weak monsoon rains in South-East Asia (see Chap. 2).[13]

Nevertheless, it remains difficult in such cases to establish exactly how climate influenced agriculture. There are few or no detailed accounts of particular weather phenomena or their effects on crops and animals, nor records of harvests, taxes, and tribute. In all of these cases, it is very likely that local conditions, contingent factors, and human decisions played a key role in the chain of events leading from climate to crisis—but these can be difficult to reconstruct without more evidence and detailed examination.[14] Moreover, precisely because these cases involve major conflicts and migrations, it can be hard to distinguish the role of climate from the role of these social and political crises. These and other stories of climate-led collapse in remote civilizations can serve as parables for the dangers of global warming and environmental change. However, climate historians need to work from examples with more abundant evidence in order to draw precise conclusions about human vulnerabilities, resilience, and adaptation.

As demonstrated in Tim Newfield's study of the 530s CE (Chap. 32), more detailed climatic and historical evidence may support but can also complicate links among climate, weather, agriculture, and human impacts. In this instance, advances in paleoclimate and historical research support the thesis that major volcanic eruptions brought drought and exceptionally cold summers across the Northern Hemisphere. In some regions, notably the Byzantine lands of the eastern Mediterranean, contemporary evidence attests to famines and migration, evidently arising from weather-induced crop failure. However, other parts of the world evidently experienced similar climatic anomalies without corresponding famines or mortality. The reasons why some regions proved more vulnerable than others could relate to particular weather patterns, choices of crops and livestock, or economic and political institutions.

A second case study in this volume, on the Great Famine of the 1310s, illustrates how the growing volume of written evidence in certain countries by late medieval times can help resolve these uncertainties (Chap. 33). Using high-resolution climate data along with institutional and narrative sources, Phil Slavin is able to demonstrate how a climatic shift brought particular weather, resulting in particular types of damage to crops and livestock. At the onset of the LIA in Europe, changing patterns of atmospheric circulation over the North Atlantic brought several years of exceptionally heavy rain to northwestern Europe, rotting grains, spoiling hay and fodder, and promoting diseases among sheep and cattle. Moreover, Slavin uses economic indicators from the period to illustrate the role of social and political conditions—particularly poverty and warfare—in amplifying the effects of agricultural failure. Such detailed examples may help establish models and hypotheses to be applied to analogous historical cases where similar records are lacking.

Research on imperial China is opening another window onto climate and food production during ancient and medieval times. Advances in regional climate reconstruction and historical research have made it possible to identify specific climatic events, past weather patterns and extremes, and their impacts on agriculture and society (Chap. 17). Although the most detailed records of weather and harvests do not begin until the Ming (1368–1644 CE) and Qing (1644–1912 CE) dynasties, scholars have gathered enough qualitative evidence to reconstruct climatic trends, natural disasters, and food production at multidecadal resolution. This research clearly demonstrates the impact of colder climatic phases and some major volcanic eruptions on harvests, and their correlation with periods of famine and political crisis in early imperial China.[15]

Chinese records can also shed light on climatic change and nomadic pastoralism. On the one hand, researchers have found that times of colder, drier climate correlated with more invasions by pastoral nomads into imperial China, suggesting that climatic change pushed pastoralists out of marginal lands.[16] A more detailed study by Middle East historian Richard Bulliet has made a similar case for the Turkic invasion of Iran during a period of regional cooling in the eleventh century CE.[17] On the other hand, a recent study has come to just the opposite conclusion for the Mongol invasions of the thirteenth century: that a period of exceptionally mild climate encouraged grass growth, fueling Mongol herds and cavalry as they conquered most of Eurasia.[18] Further research by Tim Newfield indicates that major livestock plagues in medieval Eurasia tended to follow climatic anomalies, such as droughts and cold winters.[19]

As these examples indicate, most research on climatic change and food production across the ancient and medieval world has focused on disasters and crises. Much work remains to be done on eras of relatively benign or stable climate and their influence on history. For instance, it has become increasingly clear that the height of the Roman Empire coincided with a relatively warm climate and few major temperature anomalies or droughts (Chap. 16). Further research has explored the effects of climatic amelioration on agrarian settlement and imperial revival during phases of Byzantine history.[20] Climate historians still have the task of analyzing whether and how such phases of climate played a role in agricultural productivity, population growth, and imperial power.

27.5 The Little Ice Age (LIA)

LIA Europe has received the greatest share of historical research on climate, weather, and agriculture. As described in Chap. 23, the LIA roughly describes several centuries of lower average temperatures that preceded the onset of global warming. As the most recent climatic fluctuation before global warming, and one of the largest in written history, the LIA presents the most numerous and detailed historical case studies and models.

In Europe, the LIA is conventionally dated *c.* 1300–1850 CE. It is particularly identified with several periods of advancing Alpine glaciers, and with decades of cold winters and summers during the early fourteenth, late sixteenth–seventeenth, and early nineteenth centuries. The worst years, with respect to cold and to agricultural disasters, usually followed large tropical volcanic eruptions. The LIA in Europe was not consistently cold. Decades of relatively moderate climate allowed populations to recover and agriculture to expand, only to face new crises during years or decades of unfavorable weather and climate. Even during those decades of the most rapid cooling, it appears that only a few careful observers such as the Lucerne scientist Renward Cysat (1545–1614) grasped the longer-term variations.[21] What we can identify in hindsight as climate change, the people of the time tended to perceive as a series of “unnatural” occurrences that disrupted essential activities of food production.

In general, Europe presents three major zones with different climatic vulnerabilities. In Northern Europe, the main limiting factor for agriculture was (and still is) the short duration of the growing season, particularly the risk that severe autumn or spring frost would destroy the harvest. During the worst decades, LIA cooling could rapidly shift the limits of viable agriculture and pastoralism in the region, at least where populations, crops, and livestock proved unable to adapt. Studies have identified the retreat of human settlements and agriculture in parts of Scandinavia and Scotland during periods of cooling in the fourteenth and seventeenth centuries. This research indicates that as the frequency of harvest failures rose, populations abandoned the most marginal land as too risky.[22] Those who remained in more marginal regions put themselves at risk of devastating harvest failures during successive cold years, as in the case of the Finnish famine of the 1690s.[23]

The Mediterranean region was most vulnerable to spring droughts, which could ruin the staple crops of winter wheat and barley. During the late sixteenth and seventeenth centuries, both natural proxies and narrative evidence indicate that southern Spain and Italy were more prone to flooding, while the north-eastern Mediterranean was more prone to drought (see Chap. 23). This "seesaw" pattern meant that most droughts affected only one region or the other. However, decades of exceptional cold and precipitation anomalies, such as the 1590s–1600s, could ruin harvests across the Mediterranean. Isolated freezing winters could also have major impacts. For instance, in 1709 southern France lost not only its crops of winter wheat and barley but also vines and olive trees in the frost; the latter had to be replanted and could not bear fruit for several years.[24]

Agriculture in Western and Central Europe was vulnerable to several seasonal patterns: wet autumns, cold springs, and wet midsummers. Christian Pfister has termed these "Little Ice Age-Type Impacts" and has demonstrated that they were most common during the coldest periods of the LIA, especially *c.* 1570–1630. Using a model based on Swiss temperature and precipitation indices, his research has demonstrated that such weather patterns affected most sources of food and animal feed, resulting in disastrous, widespread crop failures.[25] Cold periods in March and April thinned the grain crops and sapped the hay stocks, leaving cattle to starve and run out of milk. Cold, wet summers damaged food supplies in several ways. Continuous rains lowered the flour content of grains and rendered them vulnerable to mold infections and infestations of grain weevils (*Silophilus ganarius*), leading to the loss of grains (and later potatoes) in winter storage. Hay harvested during persistent rain loses most of its nutrient content, which affects milk production in the subsequent spring. Cold spells in September and October lowered the sugar content of wine; and they shortened the period of pasture, putting more demands on the hay supply. Late summer and autumn wet spells reduced the area that could be sown and lowered the nitrogen content of soil.[26] Most importantly, the simultaneous occurrence of rainy autumns with cold springs and wet midsummers in subsequent years had a larger cumulative impact on agricultural production and food supplies.[27]

The years from 1569 to 1573 present one of the most extreme examples of climate-induced harvest failures in LIA Europe.[28] All regions of the continent were swept into this crisis, starting with northern and central Italy, then Eastern Europe, and the Baltic in 1569, and then Central Europe by 1571. An advection of warm air in November 1570, in combination with several days of persistent rain, brought disastrous flooding throughout Western and Central Europe.[29] The winters of 1571 and particularly 1573 were extremely long and severe, bringing the freezing of large European rivers and most lakes in the Alps as well as the Baltic Sea from Denmark to Estonia.[30] Following three successive harvest failures, grain prices in Central Europe reached their highest point between 1550 and 1877.[31] As usual with subsistence crises prior to the age of railways, landlocked regions cut off from imports were worse affected than cities on the coast.[32] Famine and malnutrition were rife; mortality surged and the number of births fell. Authorities chased out beggars and vagrants searching for food; and there was a resurgence of prosecutions against witchcraft and weather magic, just to summarize a few of the economic and cultural consequences (see Fig. 27.2).[33]

The worst years of the LIA killed not only crops but also livestock, whose deaths could have more enduring consequences for food supply. During the 1590s, for instance, the southern Balkans and Anatolia suffered unusually cold winters and one of the worst droughts of the past millennium. Steady population growth and Ottoman imperial policies during the preceding century had encouraged the spread of agriculture and pastoralism into marginal semiarid lands. The extreme weather of that decade led not only to crop failures, but also outbreaks of disease among exposed and hungry sheep and cattle. Imperial supply routes to major cities and to the Ottoman army on the Danube frontier compounded the spread of epizootics throughout the empire and into Central Europe. Anecdotal evidence suggests that most sheep and cattle in Anatolia and the Crimea died. Similarly Central and Western Europe suffered two of the worst outbreaks of rinderpest (cattle plague) in early modern history following two of the worst winters of the LIA, in 1709 and 1740 respectively. These outbreaks were carried by cattle on long supply routes from the Russian steppe and were probably spread by armies on campaign in the War of Spanish Succession (1701–14), the Great Northern War (1700–21), and the War of the Austrian Succession (1740–8). Such epizootics compounded agricultural failures during LIA-type events, particularly in famine-prone regions. The death of livestock destroyed not only an alternative source of food but also the labor of oxen and horses for plowing and transportation, for years to follow.[34]

Beyond their immediate role in subsistence crises, economic historians have long debated the influence of climate and weather on prices and economies in

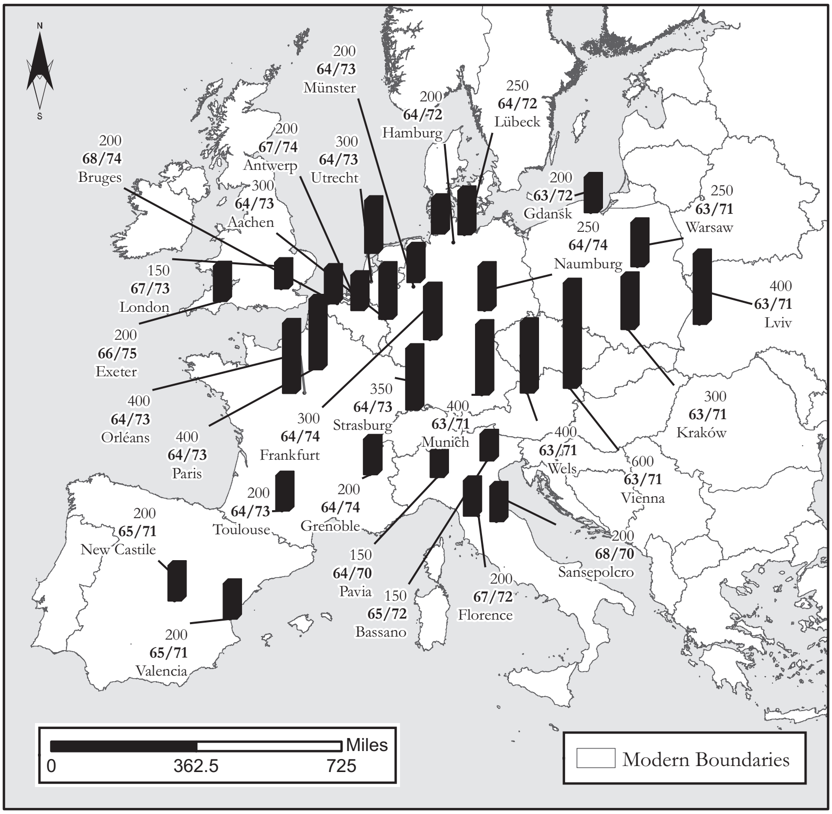

Fig. 27.2 The crisis of the 1570s across Europe. The map illustrates the approximate percentage increase (top number) in grain prices in a number of European cities and regions, from the year of lowest grain prices to the year of highest grain prices (numbers in bold), within the period 1563–76. In most of the cities sampled here, grain prices peaked during the early 1570s at two to four times the prices of the early to mid-1560s. (Based on Abel 1974)

general. Views have ranged from versions of climate determinism (such as correlating sunspot cycles to economic cycles) to outright skepticism. Several recent studies have identified significant impacts from year-to-year variability and particularly runs of bad harvests on food prices and real wages in LIA Europe. In Central Europe, there is also evidence that medium-term climatic downturns, such as during the late sixteenth to mid-seventeenth centuries, helped drive periods of persistent higher average food prices.[35]

Relationships among climate, agriculture, and prices clearly depended on demographic, political, and institutional contexts. The most important of these was the growth in population, especially during the late fifteenth to early seventeenth centuries. Agricultural productivity and economic opportunities in most of Europe did not rise in step with the number of new people. Prices rose, particularly prices for food, spurred on by growing demand and by the influx of American silver. Real wages declined precipitously. The average height of European men actually fell during the late sixteenth and early seventeenth centuries, in a sign of declining nutrition.[36] Case studies across Europe demonstrate similar patterns of rising poverty and inequality, and declining standards of living. The deceleration of marriage and fertility rates reconstructed from parish registers also indicates shrinking opportunities and declining health for a large segment of the population.[37]

Areas of more diversified agriculture or better access to markets could prove more resilient in a crisis, while isolated, landlocked regions might go hungry. For instance, nearly all of England suffered harvest failures and high prices during the climatic downturn of the mid-1590s, but only isolated northern parts of the country suffered full-blown famine.[38] Daniel Krämer's study of Switzerland in the wake of the 1815 Tambora eruption illustrates how malnutrition in this small country could vary enormously from one canton to the next, depending on geographic and economic circumstances (see Chap. 35). At first, the worst affected populations were those hit by frosts and crop failures, but by the second year of the crisis it was landless laborers who suffered most owing to unemployment, disruptions to the grain market, and soaring food prices (up to 600%).[39]

Above all, as Geoffrey Parker has demonstrated, the worst suffering and highest mortality during the LIA did not follow directly from climatic impacts on agriculture, but from the "fatal synergy" of climatic extremes, food shortage, and conflict. Wartime taxes and requisitions fell heavily on already hungry peasants. Conscription into armies and flight from violence disrupted the work of farming. Invading armies might steal or destroy what food remained. It is almost certainly no coincidence that the most deadly events of the late sixteenth to seventeenth centuries across the globe—including the Celali Rebellion in the Ottoman Empire, the Thirty Years War in Germany, and the Ming–Qing transition in China—combined extreme weather and warfare.[40]

Throughout this period some states and economies gradually developed the capacity to cope with a growing population and subsistence crises. In England and the Netherlands, for instance, improving markets and effective public famine relief began to cut down on the frequency and mortality of subsistence crises by the early seventeenth century. However, other parts of Europe continued to witness economic shocks and high death rates during cold decades and LIA-type events. As demonstrated in John Post's comparative studies of the early 1740s, the most important factors were whether countries had efficient markets and effective local relief measures that prevented the sort of famine refugee conditions likely to spread contagious diseases such as typhus and typhoid.[41] As discussed in Chap. 35, the cold years of the 1810s, and particularly the 1816 "year without a summer," brought the "last great subsistence crisis in the Western world" clearly driven by climate.

Advances in historical climatology and climate history research beyond Europe also provide important new insights into the study of climate, weather, agriculture, and food during the LIA. The LIA was not only a period of cool temperatures and unusual circulation patterns in Europe, but also a global event that probably included reduced migration of the ITCZ, more frequent failures of the South and East Asian monsoons, and a number of strong El Niño events. For instance, the recent work of Brendan Buckley and colleagues on droughts and famines in South-East Asia has demonstrated LIA climatic impacts on agriculture in a region previously overlooked by climate historians.[42]

The case study of the 1780s–90s (Chap. 34) demonstrates the emerging possibilities to reconstruct LIA climate anomalies on a global scale and identify particular weather patterns and impacts in various parts of the world. In this case, an initial volcanic eruption in 1783 (Lakagígar) had immediate consequences in Europe, but wider effects soon followed, including ENSO-related droughts in Australia, failures of the Nile flood in Egypt, weak monsoon rains in South Asia, and anomalous cold in Japan—each with serious repercussions for agriculture. Building on this kind of research, scholars should gain a greater understanding of particular environmental and climatic vulnerabilities to food production in past centuries.

Moreover, research beyond Europe provides further insights into human and historical circumstances of climate-related impacts on food production and society. Records of Ming and Qing China demonstrate many of the same patterns in climate-related subsistence crises, economic and political disruption, and gradual adaptation as found in early modern Europe. There is both qualitative and statistical evidence of similar LIA-type events in China—what historian Timothy Brook has termed "sloughs"—during which parts of the country suffered from higher food prices and more frequent famines, and imperial dynasties often experienced turmoil and rebellion. Over time, and accounting for changes in population density, Chinese agriculture diversified and adapted to the LIA, and by the eighteenth century the relationship between climatic fluctuations and food prices weakened.[43]

On the other hand, historical research into other parts of the world illustrates diverging patterns from those in LIA Europe. For instance, Japan has been raised as a counter-example to the climate-driven disasters typical of the seventeenth-century general crisis.[44] Its civil wars of the sixteenth century had kept population relatively low, and political unification after 1600 brought peace and stability, meaning that agriculture and the economy continued to flourish during the LIA climate of the early to mid-seventeenth century. During the eighteenth century, however, population growth and limited arable land put many Japanese at risk of hunger, particularly when climatic downturns brought successive harvest failures. Although the economy of Tokugawa Japan (1603–1868 CE) was highly integrated and urbanized by early modern standards, the country was isolated from new industrial technologies and international trade. Parts of Japan suffered major famines during the 1780s, 1830s, and 1860s—all decades of unusually cold summers that ruined the rice harvest (see Chap. 34).[45]

27.6 Beyond the Little Ice Age

A number of factors have mitigated the impact of climate on food production since the LIA came to an end during the nineteenth century. These include improvements in crop varieties and agricultural practices, better fertilizers and irrigation, improved transportation and infrastructure, and more efficient global markets. On the other hand, this has also been a period of colonialism, growing global inequalities, and many large international conflicts. Moreover, the very rapid warming of recent decades (see Chap. 26) has begun to create new problems for food production and availability. Across the globe famines have become more rare, but many regions remain at risk, and a large share of the world's population remains chronically undernourished.

During the late twentieth century, influenced by the work of Amartya Sen, discussions of famine risk largely shifted from a focus on "food availability decline" (FAD) to "food entitlement decline" (FED). This change of paradigm moved attention away from environmental factors and their influence on food supplies to problems of poverty and political or social marginalization. Since the beginning of the twenty-first century, global warming has refocused some attention back to climate and its impacts on food production and availability. Moreover, scholarly discussion of global warming impacts and adaptation has begun to adopt the concepts of "vulnerability" and "resilience," which help bridge the language and concerns of FAD and FED.[46]

Altogether, it seems reasonable to conclude that weather and climate have remained one of several important factors in episodes of severe malnutrition and famine. Clearly economic and political factors—extreme poverty and inequalities, and lack of democratic accountability—have largely determined which countries remain vulnerable to outright hunger. However, climatic events have remained central in the occurrence of famines and major disruptions to food supplies.[47] For instance, the Irish famine of the 1840s would not have happened apart from the island's high population density, potato monoculture, and disenfranchisement under British rule. However, cold, wet weather in 1845 also helped spread the fungus *P. infestans*, determining the timing and extent of the fatal potato blight. Similarly, China's Great Leap Forward famine—the largest in modern history—had its origins in a drought and harvest failure, even if political suppression and economic chaos were clearly responsible for most deaths by starvation and related diseases. As Mark Tauger has argued, even Sen's classic case study for FED, the Bengal famine of 1943, arose at least in part from weather-related disasters and crop blight.[48] And it appears that extreme weather played an important role in the occurrence of famine in continental Europe and the global spread of Spanish Flu during World War I.[49]

None of this is to excuse the political and social conditions that gave rise to those famines; yet it is misleading to write climate and weather out of the picture altogether.

In other cases, crises in agriculture and pastoralism have come from natural climate variability aggravated by anthropogenic environmental change. This has been particularly true in semiarid regions, because as Michael Glantz and colleagues have argued, "drought follows the plow": that is, temporarily moist conditions permitting an expansion of arable land or pasture will sooner or later turn dry again. For instance, the American Dust Bowl of the 1930s was only one of many recurring droughts to hit the Great Plains in recent centuries. What made this drought a human disaster was the extension of wheat cultivation during the preceding decade, which probably aggravated drought conditions and erosion and left more farmers vulnerable to crop failure during the hard economic times of the Great Depression.[50] Other dust bowl events and agricultural failures in semiarid regions of Australia, Canada, the Soviet Union, and the African Sahel during the twentieth century followed a similar pattern.[51] In the case of the Sahel famines of the 1970s and 1980s, anthropogenic aerosol pollution may have aggravated regional drought conditions (see Chap. 26). Furthermore, parts of the world during the twentieth century remained vulnerable to ENSO fluctuations and their associated weather patterns, particularly in Latin America, the Pacific, and South-East Asia (see Chap. 26).

Accelerating global warming since the 1980s has raised the possibility of more abrupt or extreme climatic change, beyond the adaptive capacity of the current food system. On the one hand, it seems unlikely that climate change will so reduce food production as to threaten global food shortages in the next few decades. Food supplies have risen faster than population since the early twentieth century. The considerable share of global food production either wasted or devoted to beef production should leave significant spare capacity for human food supplies. In the short term, moreover, warmer climates and CO_2 fertilization may raise, rather than lower, global crop yields in some regions.

On the other hand, global warming presents greater problems for local and regional food security than for global food production. Unprecedented extreme weather and crop failures have contributed to local shortages and to economic and political destabilization. In many parts of the world, agriculture remains a source of rural subsistence, employment, and political largesse. For instance, the record-setting 2010 Russian heatwave not only withered crops in that country, but also disrupted global grain markets, thanks to Russian export restrictions. The resulting spike in prices, coming on top of a regional drought in the Middle East, likely contributed to the Arab Spring uprisings and the outbreak of the Syrian civil war in 2011 (see Chap. 29). In the long term, without swift mitigation, global warming is projected to bring coastal flooding, droughts, crop pests, and stress on crops and livestock. By the late twenty-first century, absent timely adaptation, the resulting damage to crops would more than offset any gains from warming at high latitudes.[52]

27.7 Conclusion: Patterns and Lessons

The growing body of research on historical climate change and food illustrates significant patterns. It is easier to identify the impacts of year-to-year climate variability than long-term change. Climatic change has usually had the greatest impacts on food production in marginal environments and on economically or socially marginalized populations. Damage to food supplies may come from isolated extreme events or gradual climatic shifts. However, the worst subsistence crises have usually arisen from runs of bad years or seasons following closely one after another—often a consequence of large tropical volcanic eruptions—or from a combination of harvest failures and war. Pastoralism was usually less vulnerable than agriculture to short-term weather disasters, but it could fail catastrophically during extreme events, depriving farmers of manure and labor as well as animal protein. Further research, building on further progress in paleoclimatology and historical climatology, will no doubt refine and enlarge these findings. What remains more challenging, and more urgent, is to make use of such findings to achieve insights relevant to contemporary problems of global warming and food production.

Notes

1. Mauelshagen, 2010, 84–85.
2. Diamond, 2005; Barlow et al., 1997; Dugmore et al., 2012.
3. Pfister, 2011.
4. For introductions to the Mesolithic and the role of climate in the origins of agriculture, see Mithen, 2004; Rosen, 2007; Munro, 2004; Stiner et al., 1999; Smith, 2001.
5. Gerhart and Ward, 2010; Richerson et al., 2001; Sage, 1995.
6. Larson et al., 2014; Price and Bar-Yosef, 2011; Fuller et al., 2012; Larson and Fuller, 2014. For general reviews, see Barker, 2006; and Bellwood, 2004.
7. Weninger et al., 2009, 14–17; Nesbit, 2002; Zeder, 2011; Larson et al., 2014; Abbo et al., 2010.
8. Fuller et al., 2011; Crawford, 2009; Lu et al., 2009; Barton et al., 2009; Liu, 2004; Nesbit, 2002; Weninger et al., 2009; Zeder, 2011; Larson et al., 2014; Abbo et al., 2010.
9. Larson et al., 2014, SI, Table S1; Gross and Zhao, 2014; Fuller et al., 2011; Nicoll, 2004; Marshall and Hildebrand, 2002.
10. For an overview of the topic see Anderson et al., 2007; Weninger et al., 2009; Kuijt and Goring-Morris, 2002; Simmons, 2007; Liu, 2004; Hole, 1994; Butzer, 1995; essays in Anderson et al., 2007.
11. Original discovery in Weiss et al., 1993. Studies and discussion in response to Weiss in Dalfes et al., 1997. Subsequent review of climate and archaeological evidence in Danti, 2010.

12. For recent reviews of climate and the LBA crisis: Kaniewski et al., 2015, and Cline, 2014.
13. Overview of these and similar examples in Diamond, 2005. For further investigations see e.g., Turner and Sabloff, 2012; Benson et al., 2007; Buckley et al., 2010.
14. See, e.g., contributions in Iannone, 2014.
15. See especially Yin et al., 2015, 153–56; Zhang et al., 2010.
16. Fang and Liu, 1992.
17. Bulliett, 2009.
18. Pederson et al., 2014.
19. Newfield, 2015.
20. Haldon et al., 2014; Xoplaki et al., 2016.
21. Pfister, 2005, 33; Pfister, 2013.
22. Gissel et al., 1981, 69, 94, 103, 122, 142, 177–178, 240; Dybdahl, 2012; Parry, 1978; Dodgshon, 2005.
23. For recent studies, see e.g. Holopainen and Helama, 2009, and Lappalainen, 2014.
24. Lachiver, 1991; Monahan, 1993.
25. Pfister, 1988.
26. Pfister, 1984.
27. Pfister, 2005.
28. Pfister, 1988.
29. Champion, 1863; Pfister, 1999; Glaser, 2013.
30. Pfister, 1999; Glaser, 2013.
31. Studer, 2015. Prices measured by the amount of silver per unit volume in Zürich.
32. Abel, 1974; Pfister, 2015, 70–93.
33. Behringer, 2003.
34. White, 2011; White, 2014.
35. Pfister, 2005; Bauerenfeind and Woitek, 1999; Landsteiner, 1999.
36. Original study of prices in Phelps-Brown and Hopkins, 1957. General accounts of silver, population pressure, and inflation in Davis, 1973, 88–124, and Miskimin, 1977, 20–82. On height, Nikola and Joerg, 2005.
37. E.g., Le Roy Ladurie, 1974, 11–145 (especially 51–83); Skipp, 1978; White, 2011, 52–77, 104–122.
38. Appleby, 1978. See also Hoyle, 2010.
39. Krämer, 2015.
40. White, 2011; Parker, 2013.
41. Post, 1985.
42. Buckley et al., 2014.
43. Brook, 2010; Yin et al., 2015, 153–63.
44. E.g., Parker, 2013.
45. See Arakawa, 1955 for the original study of weather during these famines. For the wider historical context, see e.g., Totman, 1995.
46. Sen, 1981; Mauelshagen, 2010, 92–97.
47. Ó Gráda, 2009, 1–25.
48. Tauger, 2003.
49. Krämer et al., 2016.
50. Cunfer, 2005; Cook et al., 2014.

51. Glantz, 1994.
52. Overview of global warming impacts on food production and food security in Porter et al., 2014, 485–533.

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CHAPTER 28

Climate, Ecology, and Infectious Human Disease

James L. A. Webb

28.1 Introduction

Climate has had a profound influence on evolving patterns of human disease. From the early eras of human history to the present, climate forces have been determinative in establishing the ecological parameters within which human beings and the pathogens that afflict us have coexisted. As early human societies became more complex, population densities increased, and networks of exchange thickened, possibilities for the transmission of pathogens broadened. Over the past few millennia, previously discrete zones of disease transmission became integrated, with devastating demographic consequences.

Shifts in climate phases—between eras of warming and cooling or between eras of increasing or diminishing precipitation—have had significant impacts on human communities. At some times and places, climate shifts have provoked transformations in patterns of land use and thus the environments for animal and insect vectors that could transmit disease. At other times and places, climate change has provoked transformations in regional balances of political power. Some of these changes, in turn, have forced migrants into new environments and exposed them to diseases and nutritional stresses that have compromised their health.

At shorter timescales, extreme seasons and unique weather events have disrupted agriculture and created food shortages that promoted the transmission of disease. Floods, earthquakes, volcanic explosions, droughts, and unseasonal freezes have wreaked havoc on human communities. These threats remain of great concern, even as over the past century or two human beings have developed technologies and medicines that are able to limit or mitigate some of the

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consequences of disease transmission. The long-term result of these achievements is that human beings in many areas of the world—even in an era of anthropogenic global warming—are now less susceptible to infectious disease than at any earlier point in human history, and this trend toward greater security is likely to continue. This remains true even as newly emerging and reemerging disease threats attract the attention of researchers trying to estimate the future health impacts of climate change.

This brief chapter presents a synthetic overview of the relationships between climate, ecology, and human disease over time. It draws upon research in diverse fields, including historical climatology, epidemiology, ecology, and biomedicine. It emphasizes that our biomedical and ecological understandings of disease processes and the widespread use of effective medicines and vaccines have substantially changed the nature of the threats from infectious disease in many areas of the world. This historical contextualization is important to consider when evaluating future disease scenarios.

28.2 Climate Forces and the Ecological Parameters of Disease History

Over the immensely long eras during which our ancestors walked the earth, the forces of climate shaped and reformed the natural world. Over the roughly 200,000 years of the human past, geophysical processes created eras with starkly different temperature zones and levels of carbon dioxide; shifted patterns of global distributions of flora and fauna; dramatically raised and lowered the level of the oceans; and lavished or scanted the freshwater resources upon which our ancestors depended. Climate change has successively configured and reconfigured the earth's ecological zones as all forms of life have continued to evolve, including the pathogens that cause human illness and death.

Research in the genetic and molecular sciences has shown that humans and our hominin ancestors were afflicted with infectious diseases from the very earliest times, and that humans continue to suffer from some of these infections to the present day. The long chains of infections are sometimes referred to as heirloom diseases, either because they have been passed down from one generation to the next (as in the case of various herpes viruses) or because transmission was possible between primates and humans (as in some forms of hepatitis).[1] Yet other heirloom pathogens, such as intestinal worms probably first acquired from eating the meat of wild animals, have gone on to infect human beings and domesticated animals such as pigs, dogs, and cats.[2]

Many infections have proven to be remarkably resilient. They have continued even through intermittent, recurrent crises of dwindling resources and through transitions between Ice Ages and eras of global warming. The ancestors of many infectious pathogens such as mumps, chickenpox, and smallpox originated as zoonoses—that is, infections of non-human animals that jumped species only in the past several thousand years and then evolved to become human infectious diseases without non-human hosts. Measles, a pathogen that was once a zoonosis, emerged as human disease about 1000 years ago from the cattle virus that caused rinderpest. Other infectious pathogens continue to emerge from animal hosts. Influenza epidemics, powered by novel recombinations of swine and avian viruses, appear seasonally; once they produce illness and death, and their survivors develop specific immunity, they become self-limiting. Other originally zoonotic diseases, such as HIV, evolved into human scourges only in the past several decades.

Climate forces set the ecological parameters for the survival of the multitudes of pathogens that have caused human disease.[3] Two essential biophysical parameters—precipitation and temperature—have had a determinative influence on global distributions of protozoa, bacteria, viruses, and their various hosts, whether insect, rodent, domesticated and wild animal, or human. Over millennia, humid and drying phases of climate reorganized the zones in which diseases could be transmitted. Consider, for example, the case of the Sahara. During a humid era that peaked *c.* 7000–4000 BCE, the Sahara was a land of vegetation and lakes. The decisive drying out of the Sahara that followed brought transformations in ways of life, as climate migrants were forced either north or south into moister zones. This climatic shift created conditions that prevented the transmission of certain pathogens. In the Sahara, aridity and extreme daily temperature variations produced a healthier human environment than in sub-Saharan Africa. Today, as throughout history, warm and humid environments enable the transmission of the greatest number of diseases.

In a broad biogeographical sense, cold temperatures set the northern and southern limits within which most pathogens can survive. The ecology of contemporary malaria offers a good example. The mosquito species that host falciparum malaria parasites could survive during the summer season even above the Arctic Circle, but even summertime Arctic temperatures would be too low for malaria parasites to reproduce in their guts. There is no falciparum malaria transmission in the extreme North. Similarly, the zone of malaria transmission has never extended into the Antarctic, because mean temperatures there fall below the threshold for mosquito reproduction as well as the reproduction of the parasites in mosquito guts.

28.3 New Pathogens and Centers of Transmission

The rapid end of the last Ice Age and start of the warmer Holocene era about 12,000 years ago, followed by rising aridity in southern Eurasia and North Africa from *c.* 4000 to 3000 BCE, established some of the baseline ecological conditions that allowed for the flourishing of seed-based agriculture. In this sense, climate forces ushered in the age of modern humanity. The different lateral bands of climate that ring the earth—the tropical, subtropical, temperate, and Arctic and Antarctic zones—have been relatively stable since *c.* 3000 BCE (see Chap. 15).

In the river basins of North Africa and southern Eurasia, those who farmed eventually produced food surpluses that allowed for impressive increases in human numbers. The farming communities also supported populations of insects, rodents, and dogs who lived off the stored food supplies and human wastes. The early phases of animal domestication took place in the same regions, and newly acquired zoonotic infectious diseases greatly contributed to human morbidity and mortality.[4] The early river basin diseases such as whooping cough, mumps, chickenpox, rubella, and smallpox jumped from animal species and accommodated themselves to human hosts. They spread from infected persons to healthy persons without an intermediary vector or host, much as the common cold does today. Many of these pathogens—particularly smallpox and measles—could have an extraordinarily destructive power when introduced to epidemiologically naïve populations.

The greater population density of these farming communities facilitated new levels of exposure to infectious pathogens. In regional hinterlands with uneven population densities, these pathogens circulated intermittently. Everywhere, they hit the non-immune populations hardest, and these tended to be the youngest generations and newest immigrants. Although the farming communities were repeatedly hard hit, they became "disease-experienced" in the sense that the survivors of the lethal diseases generally gained a life-long immunity to them. This immunity provided them with an epidemiological advantage over surrounding populations, which helps to explain the expansion of "river basin cultural zones" into the surrounding hinterlands.[5]

A similar process probably took place in tropical Africa, where the first farmers cultivated yam tubers rather than grain seeds. As in the river basin societies of North Africa and southern Eurasia, the surplus in food calories allowed for increasing populations of farmers. Yam farmers first expanded into rainforest areas, where ecological conditions were propitious for the proliferation of a species of particularly efficient malaria-transmitting mosquitoes. The high densities of village farmers and vector mosquitoes allowed for the intense transmission of falciparum malaria. Those who survived their first encounters gained a partial immunity that accorded them an epidemiological advantage over hunting and gathering peoples. Over time, these "disease-experienced" communities expanded throughout West and West Central Africa in an unfolding demographic process known as the Bantu expansions.[6]

In tropical Africa other lethal pathogens continued to cross from wild animals into human communities and their herds of livestock. Seasonal weather conditions modulated transmission of some pathogens, such as trypanosomiasis (also known as sleeping sickness), a deadly infection transmitted by the bite of *Glossina* flies from wild animal reservoirs to human communities and livestock. Outbreaks of sleeping sickness were in part a function of abundant rainfall that promoted the growth of bush habitat in which the flies bred.[7]

In the Americas agricultural practices developed first in the Mesoamerican and Andean regions, supporting larger population growth in those centers of civilization. However, these regions contained few large animals suitable for domestication or farming, sparing human populations the same onslaught of zoonotic diseases as in North Africa and Eurasia. American populations were nevertheless subject to the forces of climate, and severe and protracted droughts in the early centuries of the second millennium CE are thought to have brought about the collapses of the Mayan civilization in what is today Guatemala and the Hohokam civilization in what is today the state of Arizona.[8]

28.4 Processes of Epidemiological Integration

The growth of agrarian empires brought raids against vulnerable neighbors and warfare against regional rivals, as well as new trade relationships. The increases in political violence and long-distance commerce were key motors for the epidemiological integration of Eurasia. "Natural disasters" almost certainly had a role in these processes, but the relationships between many epidemic diseases and climate, weather, and ecological change are difficult to establish with certainty. Such is the case with the Plague of Justinian, an epidemic of the bubonic plague in the sixth century CE that created havoc in the Byzantine world. It is possible that this sixth-century event was linked to a volcanic explosion that cast an enormous volume of dust into the atmosphere and caused the failure of harvests. In this view, extreme weather conditions created food shortages, a subsequent famine, and a heightened biological vulnerability to pathogens. It is also possible that the epidemic contributed to the inability of the population to harvest crops (see Chap. 32). Natural disasters and weather anomalies in earlier eras are difficult to invoke with precision as a direct cause or intensifier of infectious disease, because the evidence is frequently suggestive rather than definitive.

In some cases, climate events may have helped to determine the timing of epidemic outbreaks. A catastrophic bubonic plague epidemic ripped through Europe in the mid-fourteenth century and smote European populations in intermittent waves for centuries thereafter. New research findings have established a correlation with wet spring seasons in China. This new evidence supports an alternative, climate-based explanation for the recurrent plagues that may replace the previous consensus that plague continued to circulate in black rat populations in Europe. The new climate-based interpretation argues that maritime trade (rather than overland caravans) introduced the plague bacillus, borne into Europe by gerbils (rather than rats). In this view, long-distance trade, rather than extreme weather events, may have been the primary mechanism of diffusion across Eurasia, although wet spring seasons contributed to larger populations of the gerbil reservoir of the pathogen.[9]

Extreme weather events such as drought, cooling from volcanic explosions, flooding from high rainfalls, and unseasonal frosts could wreak havoc on harvests, and one of the most frequent impacts was famine. Shortages of food caused nutritional stress and reduced the resiliency of the sufferers, who were more liable to fall ill, particularly to diseases associated with poor sanitation.[10] When shortages induced migrations, famine refugees suffering from contagious diseases could introduce infections to new populations.[11] The number of unusual weather events increased during climate shifts such as the Little Ice Age that afflicted Europe and North America from the fourteenth through the mid-nineteenth centuries (see Chap. 23) and the period of low rainfall along the western Sahel from the seventeenth until the mid-nineteenth centuries (see Chap. 20).[12]

The voyages of discovery and conquest, initiated by Christopher Columbus, unleashed an epidemiological disaster in the New World.[13] The Old World pathogens, once introduced across the Atlantic Ocean, had an even more destructive demographic impact on New World populations than had the bubonic plague in Europe or elsewhere in Eurasia (even though the millennia-long process of epidemiological integration in Eurasia had itself been a profoundly destructive process). In the first century following European contact, the Old World pathogens reduced the American peoples—none of whom had acquired any immunities to the invaders—to roughly 10% of their pre-contact population sizes.[14]

Many of these virulent pathogens were viruses rather than bacteria or protozoa, and they were transmitted directly from person to person, without an intermediate non-human vector or host. Smallpox wrought the most damage as it tore through densely populated areas of the Americas. The principal limitation of these epidemics—including smallpox, measles, chickenpox, and mumps—was population density, because these viruses left survivors with lifetime immunity to reinfection. In the case of low population densities, the viruses ran out of non-immunes to infect and became self-limiting, disappearing for a time only to flare out of control among later generations born without immunity.

A severe drought in the mid-sixteenth century struck the highlands of Mexico, which suffered severe epidemics in 1545–8 and 1576–8. The highland epidemics have generally been attributed to typhus, a disease caused by *Rickettsia* bacteria transmitted by fleas or ticks.[15] A recent reassessment of the sixteenth-century highland epidemics and later outbreaks in the seventeenth, eighteenth, and early nineteenth centuries, however, suggests that the epidemics may have been caused by indigenous hemorrhagic fevers.[16] The mid-sixteenth-century drought may have brought a rodent host into contact with a highland population weakened by crop failures and the excessive labor demands of Spanish colonists.[17] Otherwise, climatic conditions in the New World appear to have played a minor role in the viral epidemics caused by Old World pathogens, although extreme weather events, as always, could increase the susceptibility of the affected populations to more severe encounters with disease.

Climate and weather had other effects on vector-borne disease. Mosquito-borne diseases such as falciparum malaria (a protozoal infection) and yellow fever (a viral infection) first emerged in tropical Africa.[18] Unlike the person-to-person infections described above, these mosquito-borne diseases could only spread to regions with similar climates. For example, yellow fever and its principal vector, *Aedes aegypti*, were transferred laterally into the Americas, and became established in the same tropical latitudes. Weather conditions played a pivotal role, because rainy seasons produced denser populations of vector mosquitoes, and the density of the vectors was a critical variable in the intensities of transmission. Another major variable was the immunological status of the populations. The survivors of yellow fever infections gained a life-long immunity. The survivors of falciparum malaria gained some degree of acquired immunity that did not protect them from future infections but did lessen the severity of those infections. Most malarial deaths occurred at the first encounter.[19]

28.5 Biomedicine, Emerging Diseases, and Climate Change

Over the past two centuries, advances in biomedicine and improvements in standards of living have greatly reduced the incidence and mortality of infectious disease among populations in economically advanced states.[20] Some programs for the control of infectious diseases in economically less-developed states have also had major successes. In recent decades, global health initiatives have dramatically reduced childhood deaths through immunization programs across the world. Deaths from the scourge of malaria are now largely restricted to tropical Africa, where major efforts are currently underway to reduce transmission.[21]

These developments have coincided with a rapid increase in passenger air travel that has facilitated the global diffusion of pathogens. The greatest concern is for the spread of viral pathogens such as influenza that can be transmitted via human respiration, because our ability to make vaccines and administer doses at the population level falls far short of what is needed. This concern, however, is largely independent from the anticipated increase in extreme climate events that are expected to accompany anthropogenic forcing of climate change.

There are also major concerns that global climate change will increase the transmission of vector-borne diseases. The West Nile virus, introduced into the United States in 1999, has been found in a large number of mosquito species, and it is likely that global warming will extend the range of many of these species and may increase transmission. These possibilities are real, although at present the total number of people affected is small. There is no antidote or vaccine for West Nile virus, although insecticides, screens, and repellents are highly effective. The greater health concerns are that warming may increase the transmission of mosquito-borne diseases such as malaria, dengue fever, and chikungunya fever. In tropical Africa, where transmission rates are highest, continued warming will likely extend the range of the vector mosquitoes to higher altitudes in mountainous regions of eastern and central Africa, although some experts believe this concern is overblown.[22]

Further vulnerabilities come from rising sea levels and storm surges, which could compromise the integrity of coastal water and sanitation systems. Failure of sanitation systems and subsequent pollution of water supplies with fecal matter has in the past set off large-scale epidemics, such as in mid-twentieth-century New Delhi.[23]

28.6 Conclusion

The relationships between climate change, ecological change, and human infectious diseases are complex, and our understandings of these relationships will continue to be refined by the development of new data and perspectives from a wide range of investigations.[24] A major challenge will be for researchers to incorporate insights from different disciplinary perspectives. A fuller understanding of the importance of climate in the epidemiological past can only be won from an evolving integration of the biological, social, and historical sciences.

Notes

1. Barrett and Armelagos, 2013, 29–41; Torrey and Yolken, 2005, 14–19.
2. On the tapeworm, see Hoberg et al., 2001; on the roundworm, see Peng and Criscione, 2012.
3. For an impressive effort to synthesize the scientific literature on climate change and its impact on the human past, see Brooke, 2014.
4. Diamond, 1997, 195–214.
5. McNeill, 1976.
6. Webb, 2009, 18–41.
7. This inference is based upon historical evidence from the twentieth and twenty-first centuries. During the era of European colonization of tropical Africa, European colonial governmental policies and medical campaigns that included the forced relocation of African populations also influenced the distribution of sleeping sickness. See Courtin et al., 2008; Hoppe, 1997; Lyons, 1992.
8. The explanations of the social collapses are multicausal and contested. See Redman, 1999; Diamond, 2005; McAnany and Yoffee, 2009.
9. Schmid et al., 2015.
10. The influence of famine conditions could persist for several decades. The Great Famine of 1315–17 and the Great Bovine Pestilence of 1319–20 (which produced a prolonged dearth of dairy products) in England and northern Europe rendered the populations more susceptible to the ravages of the bubonic plague (DeWitte and Slavin, 2013). On the susceptibility to infectious diseases associated with poor sanitation, see Mokyr and Ó Gráda, 2002.
11. Schellekens, 1996; Post, 1984.
12. For a recent discussion of the evidence for the Little Ice Age, see White, 2014; on the western Sahel, Webb, 1995.
13. Crosby, 1972.
14. Stannard, 1993.
15. Nothing is known about the geographical origins of typhus, including whether it is an Old World or New World pathogen (Wolfe et al., 2012, 358).
16. Acuña-Soto et al., 2000.
17. Acuña-Soto, 2002; Marr and Kiracofe, 2000.

18. Bryant et al., 2007; Liu et al., 2010.
19. Webb, 2009, 66–91; McNeill, 2010.
20. In the early nineteenth century, researchers isolated medically active compounds such as quinine, a highly effective anti-malarial that was the first disease-specific drug in the Western *materia medica*. See Webb, 2009.
21. Webb, 2014.
22. Chaves and Koenraadt, 2010.
23. Dennis and Wolman, 1959.
24. The National Academy of Sciences has convened three workshops to explore the relationships between weather events, disease outbreaks, and emerging infections and another workshop to improve our understandings of the relationships between vector-borne disease and environmental and ecological change and human health. See Choffnes and Mack, 2014; Mack et al., 2008; National Research Council, 2001; Lemon, 2008.

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CHAPTER 29

Climate Change and Conflict

Dagomar Degroot

29.1 Introduction

Average global temperatures have risen more than 1 °C since the Industrial Revolution. By the end of the century, according to conservative estimates, they will probably rise another 2 °C. This change will fundamentally reshape many regional environments, and may well destabilize nations already facing profound socioeconomic and technological transformations. Research that connects climate change to conflict has therefore assumed new urgency. Such work has deep roots. Military historians, for example, have long understood that climatic conditions and weather events can alter the course of war. Recently, researchers in many disciplines have revised these narratives by linking historical conflicts to long-term shifts in average weather called "climate change".[1]

The majority of such work investigates whether, and how, climate changes have provoked wars. An expanding literature traces how past climatic shifts or shocks reduced the supply of resources that maintained the cohesion and stability of different societies. Many scholars argue that communities and individuals responded either by seeking new resources or by overturning social conditions they blamed for their plight. Both reactions often led to conflict. Some of this research deduces causation through qualitative methods, by interpreting historical sources and narrating events. However, a growing corpus of scholarship employs quantitative, statistical methods to link climate changes to war. Quantitative and qualitative research alike has proposed diverse links between climate change and conflict across ancient Eurasia, the medieval and early modern world, and even in contemporary agrarian societies. Scholars who

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explore these relationships in ancient civilizations commonly use qualitative methodology, while those who investigate modern societies generally rely on quantitative techniques.

Fewer researchers have considered how climate change has shaped the conduct of wars already in progress. Those who have usually examine the many wars that coincided with the Little Ice Age (LIA), a generally cold climatic regime that, according to some definitions, endured from the late thirteenth to the early nineteenth centuries (see Chap. 23). Scholars have shown that LIA weather affected military strategies, tactics, and engagements across the early modern world. Some have even suggested that military operations on a sufficiently large scale have changed global climate through depopulation, changes in land use, and carbon emissions.

In this chapter, the words "conflict" and "war" are used interchangeably to refer to large-scale inter- or intrastate violence involving actors who claim sovereign authority. Different scholars approach the concepts of "climate" and "climate change" in distinct ways, and their precise definitions dictate how they can be linked to war. The Intergovernmental Panel on Climate Change defines climate roughly as "average weather", or as the statistical reconstruction of the mean and variability of relevant meteorological conditions. However, most studies that link climate to conflict more or less follow the World Meteorological Organization definition, which has set the minimum duration of a climatic regime at thirty years.

Scholars have unravelled how these long-term changes in prevailing weather affect the conditions and conduct of war on both "tactical" and "strategic" levels. In military parlance, tactics relate to the conduct of battle, while strategy refers to the process of manipulating resources and manoeuvring assets so they are best positioned to damage the enemy. Strategies can therefore unfold over longer time periods and larger regions than tactics.[2]

The rest of this chapter begins by surveying some of the most interesting qualitative scholarship that ties climate changes to the origins of war. It then explains how quantitative scholars have used statistical methods to tackle that relationship from a different perspective. Next, it assesses trailblazing studies that examine how trends in prevailing weather influenced the ways in which war was actually fought. Finally, it reviews how researchers have linked environmental repercussions of war to large-scale shifts in global climate. The aim is not to be comprehensive, but rather to sample some of the most interesting approaches in a field that is quickly becoming too big, and too diverse, for easy synthesis.

29.2 Climate Change and the Origins of War: Qualitative Approaches

In recent years, controversial research has tied wars in Sudan and Syria to destabilizing resource shortages. Just before the 2003 outbreak of civil war in Darfur, average annual rainfall declined sharply, resulting in desertification.

Crop failures, disappearing pasture, and vanishing water holes drove Muslim herders into competition with Christian farmers. Then, from 2006 to 2009, the people of Syria endured the most severe drought in that country's instrumental record. As water grew scarce, crops failed, and cattle died on a huge scale. As many as 1.5 million Syrians, out of a total population of just over 20 million, moved from the countryside to the outskirts of already crowded cities. Out of work, desperate, and living in poorly planned crime-ridden neighbourhoods, many refugees were quick to revolt against a brutal regime that had long suppressed such challenges. Using computer simulations, scientists have linked droughts in Syria and Sudan to the regional effects of global warming.[3]

Many people in Syria and the lands that are now Sudan and South Sudan rely heavily on agriculture and pastoralism. Pre-modern societies did too, and therefore we might also expect natural climate changes to have destabilized them. For decades, scholars in diverse disciplines have explored these relationships between climate changes and conflict. Until recently, they have used largely qualitative methods to create narratives that identify probable connections among climate change, weather, resource shortages, and war. In pursuing this research, they have benefited from the many documents that survive to record the causes of wars in literate societies.[4]

In 1982, meteorologist Hubert Lamb explored the origins of war in the first edition of his influential and frequently revised survey of climate history. He concluded that climate change caused the wars and rebellions that divided different phases of the Bronze Age, accompanied the collapse of Rome, ended the European Middle Ages, and destabilized the Ming Dynasty in China. In fact, Lamb included wars within the most direct, "first order" impacts of climate change.[5]

Historians today might cringe at such determinism, and many scholars in other disciplines have been careful not to repeat it. Anthropologist Brian Fagan, for instance, tried to balance environmental and social causes for conflict in his overview of the LIA. According to Fagan, the less predictable weather associated with the LIA undermined harvests and thereby contributed to the outbreak of the French Revolution. Fagan still finds relatively straightforward links between climate change and cultural or economic developments. Nevertheless, he acknowledges that climate change was just one among many destabilizing influences within the *Ancien Régime*.[6]

More recently, geographer Jared Diamond, in his popular book *Collapse*, has sketched similar relationships between climate change and conflict. His focus is on the endogenous causes for the collapse—that is, the depopulation and political unravelling—of different civilizations through time. Diamond adopts a largely Malthusian model for understanding these catastrophes. As populations grow, their societies develop unsustainable relationships with regional environments. Eventually, citizens must compete for scarce resources, and that competition can provoke wars within and between societies. Wars make those societies more vulnerable to exogenous environmental shocks, such as climate change, which can bring about a Malthusian collapse. For example, Diamond argues that overpopulation and endemic wars left the Classic Maya with little recourse when a catastrophic drought heralded the onset of a drier climate. Starvation, disease, and thirst killed millions, while others died in conflicts over increasingly scarce resources. These conclusions have been nuanced but largely supported by more recent, multidisciplinary scholarship.[7]

Narratives and qualitative methodology are tools more familiar to historians, and historians have lately written some of the most compelling studies of climate and conflict. In 2014, for example, John Brooke published *Climate Change and the Course of Global History*, which synthesizes scholarship from many disciplines to survey all of human history. Brooke argues that civilizations collapsed not because their endogenous social and environmental relationships were unsustainable, but rather because exogenous environmental shocks overwhelmed their capacity to adapt. Causal connections between climate change, agricultural disruption, and war repeat themselves throughout Brooke's history. In 2200 BCE, for example, a climatic shock led to widespread droughts that provoked rebellions across Mesopotamia and Egypt. Then, after the world's climate temporarily stabilized, a massive volcanic eruption in approximately 1600 BCE released sulphur aerosols into the atmosphere, which scattered sunlight, cooled global temperatures, and disrupted agriculture. As societies plunged into disorder, the Hittites "panicked" and launched raids that devastated the cities of Aleppo and Babylon.[8] To take another example, Brooke argues that societies around the world unravelled when the relatively warm Medieval Climatic Anomaly (MCA) yielded to the chillier LIA. Droughts of unprecedented severity depopulated parts of what is now Illinois and forced survivors to build fortifications against raiding. Drier weather also afflicted East Asia. Combining with greater warmth in Mongolia and cooling in East Asia, LIA climatic change encouraged steppe nomads to invade China. By contrast, Europe experienced destructive wet weather and cooling (see Chap. 33). The Hundred Years War began as a dynastic struggle but became a "resource war" amid natural disasters shaped in part by a shifting climate.[9]

Few books have done more to bring climate history into the public consciousness than Geoffrey Parker's *Global Crisis: War, Climate Change, and Catastrophe in the Seventeenth Century* (2013). Parker argues that the LIA entered its chilliest phase during the seventeenth century, when overlapping political, economic, and demographic pressures left many countries especially vulnerable to climatic shocks. In many parts of the world, cooling led to storms and historic winters that directly killed thousands of people. Climatic change undermined the production of staple crops around the world, bringing shorter growing seasons, untimely frosts, and unseasonable precipitation (see Chap. 23). Parker estimates a third of the world's population died from malnutrition, famine, and disease.[10]

Parker shows that wars both worsened these crises and were provoked by them. In East Asia, cool, wet weather ruined harvests and drove the Manchus to invade Ming China in search of more food. Across China, the collapse of agriculture encouraged hungry men to join bandit groups, adding to the chaos. A similar "fatal synergy" swept through Europe. Wars drained national resources just as climatic conditions diminished provisions and revenue, and subsequent revolts only added to the turmoil. Parker therefore argues for relatively direct connections among climate change, weather, food shortages, and social disruptions including war.[11]

In *The Climate of Rebellion in the Early Modern Ottoman Empire* (2011), Sam White also investigates the coldest decades of the LIA, concentrating on the eastern Mediterranean. To White, the Ottoman Empire directed an "imperial ecology" that involved the circulation of resources and population on a vast scale. This system functioned smoothly until the late sixteenth century. By then, population growth in marginal territories had made the empire vulnerable to both natural disasters and the destabilizing influence of landless men. When a catastrophic drought and severe winters coincided with major military campaigns during the 1590s, banditry broke out in the Anatolian countryside. The drought eased in 1596, yet bandit gangs continued to band together to form rebel armies. Further drought and freezing weather compounded the economic disruption and population loss caused by the rebellion and drove more Ottoman subjects into banditry. Even after the revolt was finally suppressed, political and environmental shifts slowed the empire's demographic recovery. To White, rebellion and revolt did not follow directly from agricultural failures brought about by drought. Instead, conflict in the Ottoman Empire emerged from a combination of ecological and social pressures influenced by the changing climate.[12] These books by Brooke, Parker, and White represent state-of-the-art thinking by historians who use primarily qualitative methods to link climate change to conflict.

Scholars in many disciplines have concluded that climate change triggered conflict by disturbing agricultural production, especially where unsustainable or inefficient farming practices raised the vulnerability of agricultural systems to exogenous shocks. Severe or sudden cooling shortened growing seasons too quickly, or too profoundly, for farmers to respond; or else shifts in precipitation patterns ruined crops through rot or withering. Without enough fodder to feed domesticated animals, agricultural productivity declined even more (see Chap. 27).[13] Most agrarian or pastoral societies could not long endure such crises. Many people moved out of environments that became less hospitable and joined or displaced people in cities or other countries, creating conditions for conflict. Others blamed their governments for failing to provide relief, especially when those governments were already embroiled in costly wars. Social and economic disruption added to the turmoil of climate change, and, in turn, to popular support for revolution and rebellion. In these narratives, the Syrian civil war is only the latest iteration of a pattern that has repeated itself time and again, since the first agrarian societies.

29.3 Climate Change and the Origins of War: Quantitative Approaches

Other scholars have approached the link between climate change and conflict from an entirely different angle, by using quantitative and statistical methods. These techniques have informed most of the relevant (social) scientific research, and they have produced some of the most controversial and influential articles written on the climate history of war.

David Zhang and other scholars in the Department of Geography at the University of Hong Kong have been pioneers. Since 2005, they have authored numerous articles that connect climate change to rebellions, dynastic transitions, and nomadic invasions in imperial China. Their methods are superficially simple. First, they identify periods of conflict across centuries or even millennia of Chinese history. Next, they quantify only the most reliable information regarding Chinese wars, such as their dates, number of participants, and locations. They then match a long-term reconstruction of average temperatures with the dates of wars in environmentally and socioeconomically distinct Chinese regions. People in each region responded differently when prevailing weather patterns changed.[14]

This technique produces graphs that represent climate change and conflict on matching scales. The authors then use statistical methods to find ostensibly objective and mathematically precise correlations between climate change and conflict across various timescales. In every article of this kind, the results are striking. Zhang and his coauthors found that approximately 80% of wars, rebellions, and dynastic transitions in imperial China took place during climatic regimes that were substantially colder than the early twentieth-century average. Nevertheless, these general statistics mask regional differences, both in the frequency with which conflict coincided with cooling and in the time lag between cooling trends and outbreaks of violence. It turns out that the relationship between conflict and cooling may have been especially strong for rebellions, and for southern China.[15]

Academics in quantitative disciplines have used similar methods to identify correlations between climate change and the frequency of European wars. Such research is possible because Europe, like China, has well-documented and well-researched records of both violence and climate change. In 2010, economist Richard Tol and climatologist Sebastian Wagner created dramatic maps correlating changes in both temperature and precipitation to shifts in the frequency of war in different parts of Europe. They concluded that over the last five centuries cool, wet conditions increased the frequency of conflict in north-western Europe, while warmer, drier weather may have led to more wars in areas of south-eastern and Central Europe. However, the correlations weakened with the rise of industrialization. One year later, a multidisciplinary team published an article in *Science* that introduced new reconstructions of Central European temperature and precipitation trends over the past 2600 years. The team roughly correlated these trends to major wars and migrations in

European history. Another group, led by the geographers of the University of Hong Kong, has recently nuanced and revised this earlier scholarship by suggesting that past relationships between cooling and conflict were actually most dramatic in Eastern Europe.[16]

Other researchers have investigated whether the recent drying and warming of sub-Saharan Africa has led to more frequent civil wars. Africa is a focus for work that connects global warming to modern conflicts because the majority of its more than one billion inhabitants rely on rain-fed agriculture for subsistence and employment. Relationships between agriculture and war in modern Africa may therefore resemble those in pre-modern Europe and China. Earlier quantitative research on sub-Saharan Africa focused entirely on changes in precipitation, and most found that drought correlated with increased conflict. Newer scholarship, notably a 2009 article by lead author Marshall Burke, also examines the socially disruptive influence of rising temperatures. In 2009 and 2010, Burke and his coauthors found a robust correlation between warming temperatures and the frequency of African civil wars, here defined as "the use of armed force between [two] parties, one of which is the government of a state, resulting in at least 1000 battle-related deaths". In 2012, Cullen Hendrix and Idean Salehyan, using a broader definition of war, compared over 6000 instances of conflict with fluctuations in annual precipitation. Then in 2015, Hanne Fjelde and Nina von Uexkull investigated only smaller clashes and found that major negative rainfall anomalies correlated with conflict, given certain socioeconomic conditions. Another article in the same year, this one by lead author Jean-François Maystadt, found strong correlations between drought and conflict in North and South Sudan.[17]

Owing perhaps to its pressing relevance in a warming world, statistical research that connects climate change to African civil wars has generated considerable controversy, even among quantitative scholars. In 2010, Halvard Buhaug questioned the methods Burke and his coauthors used to establish their correlations. In a series of letters, Burke and his colleagues convincingly rebutted most of Buhaug's criticisms, yet admitted that correlations between warming and civil war have grown much weaker since 2002. More recently, Mathieu Couttenier and Raphael Soubeyran found little correlation among climate change, drought, and the outbreak of civil wars in sub-Saharan Africa. In 2012, a study by lead author John O'Loughlin examined no fewer than 16,359 conflicts in sub-Saharan Africa between 1990 and 2009. By accounting not only for socioeconomic but also geographic factors that contributed to violence, O'Loughlin and his coauthors concluded that conflicts generally become less common in wet conditions. Nevertheless, they discovered no correlation between drought and war, and it is drought that global warming is projected to exacerbate in parts of Africa.[18]

There is great value in detecting robust correlations between human and environmental trends. However, some scholars have made sweeping and unsustainable claims about causation that are based solely on the presence of overlapping trends in the histories of war and climate change. For example, in 2007, Zhang and coauthors concluded that correlated trends in average temperature and the frequency of war show that "war–peace, population, and price cycles in recent centuries have been driven mainly by long-term climate change". In fact, overlapping graphs cannot adequately challenge the causal links identified by generations of historians, anthropologists, and archaeologists, many of whom have placed primary emphasis on political, economic, social, or cultural forces.[19]

This is especially true given the many uncertainties that bedevil the correlations that scholars have found between climate changes and the outbreak of war. For example, it is difficult to know what element of a conflict should be statistically matched with climate reconstructions. Do statistics suggest that climate change causes conflict if it overlaps with the beginning of a war, or is it enough to find that climate change coincides with an entire war, as Burke does? Moreover, quantitative reconstructions of military history cannot easily incorporate long and complex wars, such as the Thirty Years War. That war can be considered either a single conflict or a series of distinct wars. Researchers must subjectively decide how to categorize wars of this kind, and these messy choices will alter their supposedly objective statistics. Buhaug pointed out that scientists have also used arbitrary numbers to decide when violence amounts to a war. Worse, graphing wars by quantity can also lead scholars to misrepresent changes in qualities. The First and Second World Wars can be recorded as only two wars, for instance, yet their material and human costs dwarfed those of any previous conflict. Overall, quantitative methodologies force researchers to use subjective techniques to smooth over complexities that are more easily accommodated within qualitative approaches. Ostensibly "scientific" methods are therefore not necessarily more accurate than the narratives developed by humanists or scientists with humanistic leanings.[20]

There are more problems. Even long-established and supposedly reliable "facts" about past wars can be overturned by new scholarship. Yet natural and social scientists do not always recognize that historians or archaeologists engage in dynamic and evolving disciplines. Tol and Wagner, for example, used a now-defunct website for their statistics on past wars, while Zhibin Zhang cited historical scholarship published in 1939. It can be equally problematic to link regional wars to global climate, as David Zhang and his colleagues have done, because global climate trends can manifest themselves in counter-intuitive ways at the level of local, short-term activities. Finally, even if the correlations that researchers have identified between war and climate change really do accurately represent the past, they can be interpreted in many different ways. Perhaps it is not cooling that provokes war, but rather social structures that increase the susceptibility and instability of societies in the face of environmental changes. From this perspective, the causes of war are not primarily environmental, but rather political, socioeconomic, or cultural.[21]

Fortunately, scholars who reconstruct correlations between cooling and conflict have started to explore the reasons behind these correlations. For example, in 2007 Zhang led a study that linked climate change to war by examining the effects of cooling on food production. Zhang and his coauthors summarized scientific research that identified connections between shifts in average temperature, agricultural production, and the fates of different societies. Like other animals, humans usually migrate when ecological stress overwhelms their ability to adapt. However, as Zhang and his colleagues pointed out, migration across political boundaries often results in war. In 2010, Zhang and fellow geographer Harry Lee introduced a conceptual model based on these principles. In the model, cooling hampers agricultural production, raises food prices, and ultimately leads to war, famine, and population decline.[22] In 2011, Zhang and colleagues employed new analytical tools and a more complex model that built on causal links already identified by (qualitative) historians. In this model, climatic cooling alters bioproductivity, reducing agricultural production and per capita food supply. Once again, less food leads to social disturbance, migration, and famine, which in turn cause war, epidemics, malnutrition, and population decline. Zhang and his colleagues conclude that climate change is the ultimate culprit behind most of the major crises in human history.[23]

Two other articles of 2010 are notable for finding causal connections between climate change and historical conflicts in China. Like David Zhang and his colleagues, Zhibin Zhang and a multidisciplinary group of international researchers concluded that lower temperatures hindered agriculture in ways that increased unrest and provoked wars within China. Ying Bai and James Kai-sing Kung, by contrast, concentrated on the climatic stimuli that spurred other peoples to invade China. They matched 2000-year graphs of precipitation indicators to invasions of China by nomadic peoples of Central Asia, Mongolia, and Eastern Europe. Bai and Kung first calculated the decadal frequency of nomadic invasions of China. They then used a control that accounts for attacks by the Chinese state on nomadic peoples, and a model that compensates for the path-dependency of repeated wars. For each decade in their study period, they identified the percentage affected by drought, and then they compared this figure with their decade-by-decade statistics of nomad invasions. From this, they determined that dry conditions ruined the livelihoods of nomadic peoples and drove them to invade China. Wet conditions could be perilous for Chinese citizens around the Yellow River, but they seem to have had little effect on nomad aggression.[24] Their methodology has drawbacks. Bai and Kung had no access to precipitation reconstructions, and they were therefore forced to employ records of droughts and floods as a proxy for changes in rainfall.[25] Accordingly, flood data used by Bai and Kung relies heavily on levee breaches along the Yellow River, which might have been caused by inadequate levee maintenance, rather than environmental changes beyond human control. Like floods, droughts can also follow from complex relationships between environmental conditions and human practices. Nevertheless, Bai and Kung decided that drought and flood records provide sufficiently strong clues of real fluctuations in precipitation across China and its surroundings.

Quantitative scholars have tried to establish similar causal connections in European history, although their efforts have been controversial. Even more disputed are findings that link the causes of recent sub-Saharan conflicts to climate change. In 2010, Alexandra E. Sutton and coauthors argued that by not including case studies, previous attempts to establish correlation between African wars and climate change have actually revealed very little about causation. In the following year, an article by political scientist Ole Magnus Theisen concluded that socioeconomic, political, and demographic conditions—not climate change—caused African conflicts. Yet not long thereafter, Theisen published a rigorous statistical analysis of links between climate change and war within Kenya. This time, he found that high rainfall anomalies correlated with conflict, while droughts made violence impractical. By contrast, recent qualitative and quantitative research suggests clear causal links between drought and climate change in Syria and Sudan. Different responses to precipitation anomalies in very different places suggest that controversy over relationships between climate change and African wars is, at least in part, a consequence of the sheer social and environmental diversity of modern Africa. We can expect temperature and precipitation anomalies to have different effects in different African regions, further complicating possible links between climate change and conflict. That is why quantitative scholars of Europe and China have usually examined relationships between climate change and war in distinct regions.[26]

Statistical research accounts for most of the recent scholarship on the climate history of war. In a recent special edition of the journal *Climatic Change*, Solomon Hsiang and Marshall Burke surveyed fifty such papers. They conclude that there does seem to be a clear current and historical relationship between climatic change and conflict around the world. In an online appendix, they also argue that statistical misconceptions have led some researchers to either overestimate or falsely dismiss correlations between climate change and war. However, they find no consensus on the mechanisms for these correlations. They survey a range of possible explanations, from the poorly understood psychological effects of weather to the destabilizing influence of inequality in the face of shared environmental risks. Ultimately we can expect different clusters of social and environmental influences to bridge climate change and conflict in different regions, although it is likely that resource shortages usually play a central role.[27]

For historians working with written evidence, the human motivations and actions that shape historical causality may appear too complex to reduce to correlations. Moreover, some scholars have pointed out that disasters can bring out not only the worst, but also the best, sides of humanity. For example, by quantifying the outcome of nearly 8000 natural disasters since 1950, sociologist Rune Slettebak concluded in 2012 that the kind of destructive weather made more likely by climate change, particularly drought, actually reduces conflict. Political scientist Erik Gartzke has suggested that twentieth-century warming was associated with a worldwide trend towards peace, since industrialized nations are more likely to be integrated, democratic, and therefore less eager for war.[28] Environmental historian John McNeill has argued that epidemics and natural disasters have historically united societies more often than they have driven them apart, and since at least the eighteenth century, they have encouraged international sympathy and support. Objections raised by political scientist Thomas Bernauer follow a similar vein. In a series of articles, Bernauer and coauthors admitted that climatic and other environmental changes may, under the right conditions, provoke conflict. However, they have insisted that such "neo-Malthusian" links are not necessarily systematic or unconditional, and that they are invisible in regions like the rapidly drying Aral Sea basin. These are useful calls for nuance and caution in an area of scholarship that, as we have seen, could use both.[29]

Ultimately, diverse methodologies and findings together suggest that climate change can make conflict more likely, but only under particular environmental, political, socioeconomic, and cultural conditions. Societies that are less directly dependent on agriculture are probably less vulnerable to the destabilizing effects of climate change. Moreover, well-organized states are probably less vulnerable to climatic shocks than weak states.

The lack of straightforward connections between climate change and conflict means that these relationships are difficult but not impossible to quantify. That, in turn, raises the value of the qualitative approaches to climate history that are usually favoured by humanists, and especially historians.[30] Nevertheless, statistical tools can provide fresh perspectives on occasionally circular issues of causation. If scholars identify sufficiently precise correlations, they can provide valuable evidence that causal relationships probably unfolded in a particular sequence. Overall, quantitative methodologies indicate that war and climate change may be even more closely entangled than qualitative approaches have uncovered thus far.

29.4 Climate Change and the Conduct of War

In 2014, the Pentagon's Quadrennial Defense Review predicted that climate change would shape both the missions American forces will undertake in a warmer world and the environments in which those missions will play out. However, connections between climate change and the conduct of war are still poorly understood. Because the conduct of every war is distinct, it is difficult to conceptualize and model how actual fighting has been influenced by climate change. For now, this rules out the kind of statistical analysis that has identified probable relationships between climate and the outbreak of wars.[31]

Scholars have worked to overcome these methodological challenges by carefully reconstructing the ways in which global climate change shaped regional environments in wartime. Many of their studies have concentrated on the LIA. Already in 1982, Lamb tied the cooler early modern climate to increased storminess in the North Sea area, and in turn to the gales that devastated the Spanish Armada in 1588. In 1998 anthropologist Fagan leaned on Lamb's research to conclude that the Armada was defeated by storms that were probably caused by climate change. Recently, Parker has blamed the LIA for harvest failures that hindered military provisioning, and for torrential precipitation that thwarted campaigns.[32]

Frigid winters during the Maunder Minimum, a particularly cold phase of the LIA, have been linked to the fate of Swedish campaigns in both the Second Northern War (1655–60) and the Great Northern War (1700–21). While many historians of these wars have ignored the role of climate change, scholars in other disciplines have noted that Swedish armies exploited unusually severe freezing in early 1658 to march across the ice-covered straits that otherwise protected Denmark. By contrast, the extreme winter of 1708–9 weakened the Swedish army invading Russia, contributing to its defeat at Poltava.[33] Multidisciplinary scholars pursuing research of this kind have also shed new light on how cold conditions influenced the campaigns of Napoleon and the fate of German armies in Russia during the Second World War. Overall, such scholarship provides valuable perspectives on relationships between cooler climates, weather, and military operations, but it usually has methodological shortcomings. For example, it rarely explains how climate change that unfolds globally, across decades, can be held responsible for the outcome of fighting at a local level, during just a few months of bad weather. It also does not investigate how climate change systematically shaped the conduct of entire wars.[34]

Environmental historians James Webb and John McNeill have both identified more convincing structural links among climate change, disease, and the ways wars were fought. In *Desert Frontier* (1995), Webb maintained that climate change between *c.* 1600 and 1850 led to drier conditions along the southern frontier of the Western Sahara, which expanded as much as 300 km to the south. As the frontier moved, the tsetse fly, a vector for the disease *trypanosomiasis*, moved with it (see Chap. 28). Horses otherwise prone to the disease were more likely to survive in the Sahel. Alongside sociopolitical developments, these environmental changes disrupted agriculture, encouraged violence, and enabled horse-riding raiders to capture slaves from communities in West Africa.[35]

In *Mosquito Empires*, McNeill argues that from 1620 to 1914 populations born in the Caribbean developed immunity to yellow fever and resistance to malaria. This enabled them to defend their islands against hostile interlopers who lacked such defences. According to McNeill, the Caribbean cooled and dried during the coldest centuries of the LIA, but warmed and grew wetter after around 1750. Because mosquito vectors breed in water and thrive in warm weather, this climate shift increased the recurrence of yellow fever epidemics and enhanced their impact during colonial wars. Droughts had complex and sometimes counter-intuitive influences on the close relationship among humans, mosquitoes, disease, and military campaigns. In regions with reliable streams or piped water, drought limited breeding sites for mosquitoes. In other places, drought encouraged people to store water, providing convenient habitats for mosquito larvae.[36]

In a 2014 article, environmental historian Dagomar Degroot traces the role of climate change in the conduct of three seventeenth-century naval wars between England and the Dutch Republic. Degroot tackles the methodological challenges of bridging long-term global climate change with short-term local military operations by introducing a step-by-step method. First, he establishes probable connections between climate change and the frequency of particular local weather conditions. Second, he relates the outcome of wartime events to those conditions. Only after finding strong enough relationships between military operations and short-term local weather does he claim to identify firm links between climate change and conflict. Degroot uses this method to argue that shifting climatic conditions in the mid-seventeenth century increased the frequency of storms and easterly winds, in ways that benefited the naval tactics and strategies of the Dutch Republic. Whereas England won the First Anglo-Dutch War, Dutch fleets more effectively harnessed shifting patterns of prevailing weather to win the second and third wars.[37]

Historians have also linked changes in prevailing weather to the course of the American Civil War. Already in 1965, Paul Gates argued that a prolonged drought in the Southern states undermined the Confederacy from within. In 2002, Ted Steinberg refined and expanded this climate history. According to Steinberg, poor harvests in the Confederacy led to starvation and disease for Southern troops and their horses. The weakened Confederate armies struggled with poor morale, and had difficulty resisting their Union counterparts. By contrast, favourable weather created ideal conditions for northern agriculture. Northern troops were therefore the best fed in military history, and that probably improved their performance in the field. However, in some respects Confederate forces did benefit from weather and climate. For example, torrential winter rain compromised Union supply routes.[38] These claims link the conduct of war to short-term weather, but not long-term climatic transitions. Recently, Kenneth Noe surveyed the sources and approaches that historians can use to connect the war's fighting to climate change. Scholars are developing methodologies that will unlock new research capable of contextualizing, and perhaps even rewriting, predictions such as those given by the Pentagon last year.[39]

29.5 War and the Causes of Climate Change

Some of the most innovative research into past climates explores not how climate change affected warfare, but rather how those wars altered regional environments and possibly global climate. Recently, geographers Simon Lewis and Mark Maslin have argued that the "Anthropocene"—the proposed new geological epoch dominated by humans—began in 1610, and that it reflected a relationship between conflict and cooling. After Columbus permanently joined the Old and New Worlds in 1492, epidemic disease and colonization indirectly killed more than 50 million Amerindians. Trees spread across a depopulated landscape, pulling carbon dioxide out of the atmosphere. According to Lewis and Maslin, the globe cooled as concentrations of atmospheric carbon dioxide declined, and the subsequent worsening of the LIA was the first clear sign of a human-dominated world.[40]

Lewis and Maslin have built upon the 2003 theories of climatologist William Ruddiman, who connected prehistoric burnings, the advent of agriculture, the Columbian Exchange, and even waves of plague in Europe to changes in global forest cover and subsequent shifts in the world's climate. Some of these transformations in land use were linked to the conduct of war. The links established by Ruddiman have proven controversial, and some have been undermined by new studies that suggest, for example, that soil absorbs carbon dioxide from the atmosphere as it cools. In any case, since the 1950s, the so-called "great acceleration" in humanity's power over the Earth has at the very least resulted in the intensification, or perhaps indeed the emergence, of climate-altering means of fighting war. Despite programmes aimed at curbing its greenhouse gas emissions, the US Department of Defense annually consumes more oil than 160 countries.[41]

29.6 Conclusion

Today, the causes and characteristics of climate change and conflict are closely connected. Using a range of different methods, scholars in many disciplines have shown that these relationships have an ancient history. They have determined that climate change can provoke wars by causing resource shortages. They have found that it can shape the conduct of wars by altering the availability of resources and the features of battlefields. They have even suggested that conflict can trigger climate change by affecting the concentration of greenhouse gases in the world's atmosphere.[42]

Yet consensus about how these relationships actually unfolded has been hard to come by. While scholars have largely established that climate change helped cause conflict by provoking or worsening resource shortages, links between dearth, popular or elite discontent, and societal instability are complex and controversial. Even less certain are connections between an army's supply of food, for example, and its performance on the battlefield, or its susceptibility to the epidemic diseases that so often hobbled pre-modern armies. There is little doubt that today militaries contribute to global warming by emitting greenhouse gases, but past entanglements among war, forest cover, and climate change are much trickier to unravel. Ultimately, the specific circumstances of each war undermine attempts to find universal principles relating climate change to conflict. It is perhaps by unravelling the dizzying complexity of past connections between conflict and climate change that scholars can best contribute to understandings of the present-day societal consequences of climate change, and to projections of life in a warmer world.

Notes

1. Field et al., 2014, 20; Adger et al., 2014, 772.
2. Glete, 2000, 17; Lamb, 1995, 260; Bernstein et al., 2007, 30; Carey and Garone, 2014, 292; Culver, 2014, 312; M.L. Parry et al., 2007.
3. Kelley et al., 2015, 3245; Zakieldeen, n.d., 14; Borger, 2007; Maystadt et al., 2015, 649.

4. Gleditsch, 2012, 3.
5. Lamb, 1995, 287.
6. Fagan, 2000, 166; White, 2014, 350.
7. Diamond, 2005, 175; Turner and Sabloff, 2012, 13,913; Media-Elizalde and Rohling, 2012, 958.
8. Brooke, 2014, 272, 297.
9. Brooke, 2014, 370.
10. Parker, 2013, 45.
11. Parker, 2013, 267.
12. White, 2011, 76, 294.
13. Endfield and O'Hara, 1997, 255; Endfield and O'Hara, 1999, 413; McNeill, 2003, 35; White, 2011, 76.
14. Zhang et al., 2005, 137; 2006, 464; 2007a, 404; 2010, 3746; Zhang and Lee, 2010, 64.
15. Zhang and Lee, 2010, 65; Zhang et al., 2005, 138; 2006, 462; 2010, 3745; 2007a, 407.
16. Tol and Wagner, 2010, 69; Lee et al., 2015, 10; Büntgen et al., 2011, 581.
17. Burke et al., 2009, 20,670; Hendrix and Salehyan, 2012, 35; Fjelde and von Uexkullm, 2015, 444; Maystadt et al., 2015, 657.
18. Buhaug, 2010, 16,478; Burke et al., 2010a, 2; 2010b, E185; 2010c, E103; Couttenier and Soubeyran, 2013, 219; O'Loughlin et al., 2012, 18,344; Sutton et al., 2010, E102.
19. Zhang et al., 2007b, 19,214.
20. Buhaug, 2010, 16,478.
21. Tol and Wagner, 2010, 67; Zhang et al., 2010, 3746; O'Loughlin et al., 2014, 2054; Degroot, 2015, 471.
22. Zhang and Lee, 2010, 63; Zhang et al., 2007b, 19,214.
23. Zhang et al., 2011, 17,298.
24. Bai and Kung, 2010, 972.
25. Zhang et al., 2010, 3746; Bai and Kung, 2010, 971.
26. Büntgen et al., 2011; Sutton et al., 2010; Theisen et al., 2011; Theisen, 2012.
27. Hsiang and Burke, 2014.
28. Gartzke, 2012, 177; Slettebak, 2012a, 163, 2012b.
29. McNeill, 2008, 38; Bernauer and Siegfried, 2012, 227; Bernauer et al., 2012, 1.
30. McNeill, 2008, 40.
31. United States Department of Defense, 2014, 47.
32. Fagan, 2000, 92; Lamb, 1995, 218; Parker, 2013, 322.
33. Brown, 2001, 296; Neumann, 1978, 1432.
34. Winters et al., 2001, 74.
35. Webb, 1995, 87.
36. McNeill, 2010, 4, 59.
37. Degroot, 2014, 242, 272; see also Degroot, 2018.
38. Gates, 1965, 29; Steinberg, 2002, 95.
39. Noe, 2015, 25.
40. Lewis and Maslin, 2015.
41. Ruddiman, 2003, 284, 2007, 137; Hynes, 2011; Zabarenko, 2008; Goodell, 2015; Branagan, 2013.
42. Gleditsch, 2012, 5.

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CHAPTER 30

Narrating Indigenous Histories of Climate Change in the Americas and Pacific

Thomas Wickman

30.1 Introduction

Scholars have told many different stories about the historical responses of indigenous societies in the Americas and Pacific Islands to past changes in climate. The shapes of these narratives matter a great deal. Some scholars start with climate history in the pre-settlement period but neglect the topic of climate change during the colonial and modern era, implying that climate shaped Native societies only in the absence of Europeans. Recent scholarship has connected oral traditions within longstanding Native communities as well as local documentary evidence to the paleoclimatic and archaeological records, creating climate histories that emphasize adaptation and persistence. This latter approach embraces the convergence between place-based indigenous histories and scholarly climate histories.[1]

A conventional narrative structure tracking the climate-related rise and fall of large indigenous societies remains influential, especially with popular audiences, but this approach has several problems. Studies of the pre-settlement past, without the aid of extensive written archives or oral tradition, have been prone to dramatic narrative structures. Causal explanations of collapse—such as the connections between drought and the end of classic Maya cities—tend to make headlines, but they can obscure indigenous resilience. Histories of large societies in ancient North America have also captured the public imagination. The Medieval Climatic Anomaly (MCA, *c.* 900–1300 CE) created conditions for the spread and intensification of maize horticulture, thus helping to explain the rise of indigenous urban sites such as Cahokia or ancestral Puebloan dwellings, as well as rising populations elsewhere on the continent. Subsequent

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droughts and the onset of the Little Ice Age (LIA, *c.* 1300–1850) tested these gains, leading to the dispersal of mound builders and cliff dwellers and prompting migrations to lower latitudes and altitudes. Thus, even though such scholarship effectively persuades readers about the complexity of past indigenous societies, it relegates that kind of story to a time before Europeans, and it assumes that Native societies always have been highly vulnerable to climatic changes.[2]

Innovative recent histories, by contrast, explore the complex interaction of unstable climatic systems, new colonial regimes, and dynamic indigenous societies. As scholars such as anthropologist Julie Cruikshank and historian Natale Zappia have demonstrated, present-day tribes remember some ancient relocations as beginnings, not endings. Tribal histories tend to include elements of creative adaptation and unexpected collaboration with new indigenous neighbors. Environmental stress prompted competition and warfare, but also set the stage for invention, cooperation, and resilience. In some cases, histories of climatic disruption double as stories of ethnogenesis, establishing lineages, supporting land claims, and asserting sovereignty.[3]

One of the greatest strengths of the new scholarship on climate, history, and indigenous peoples is its ability to reveal micro-adaptations and to embed stories of climatic change within detailed local landscapes. As historian Mark Carey has observed, "climate models often have low resolution at local and even regional scales, and this is precisely the scale at which indigenous observations emerge." Oral traditions survey long expanses of time, but reveal a rich history centered on areas that outsiders have viewed as peripheral. Indigenous-authored documents such as legal petitions also reveal nuanced local responses to regional, continental, and global climatic events. "Big histories" of humanity's activities on this planet certainly have a role to play in contemporary debates, but small histories about specific peoples or particular years should be equally important to scholars, activists, politicians, and citizens.[4]

This chapter examines the kinds of stories that scholars have been telling about climate history and indigenous agency. Climate historians structure information into narratives, interpreting a range of oral traditions, pictorial representations, written documents, archaeological findings, and proxy data. As scholars have begun to analyze local indigenous responses to climate, their stories have featured themes of continuous change, survival, and adaptation. If early studies focused on collapse, newer work recovers evidence of resilience and ongoing struggles for power and livelihood.[5]

30.2 Scope

To our knowledge, this chapter is the first synthesis of historiography on climate and indigenous peoples in the Americas and Pacific. The essay focuses on scholarly perspectives and narrative themes, rather than summarizing all Native peoples' experiences. With 567 tribes recognized by the United States alone, there are many climate histories yet to be researched. The chapter brings together the findings of scholars who define their methodologies and institutional affinities in a variety of ways, not just as historical climatology or climate history. Some scholars have produced groundbreaking work precisely because they see themselves first as cultural anthropologists, historical geographers, ethnohistorians, or environmental historians. In the last ten to fifteen years, scholars of all disciplines have become more conscious of global climate change, and their growing concern has broadened and diversified the kinds of approaches and perspectives within the field of climate history.[6]

This chapter reviews scholarship about indigenous peoples' experiences of climatic change in the Americas and Pacific Islands over approximately the last six centuries, encompassing several phases of the LIA (see Chap. 23), examining multiple episodes related to the El Niño Southern Oscillation (ENSO), and entering the present epoch of anthropogenic global warming. It proceeds roughly from north to south, surveying the Arctic and subarctic, Atlantic coast of North America, the American Southwest, Great Plains, Mexico, South America, and the Pacific Islands.[7]

The meaning of "indigenous" often depends on complex local, regional, and global contexts. This chapter focuses on homelands and territories in the Americas and Pacific Islands that were invaded by European colonizers, highlighting indigenous peoples' struggles with both climate and colonialism from LIA encounters to contemporary struggles over fossil fuels. Rising awareness of the unequal burdens of global warming has led many people within threatened communities around the world to explore intersections between climate, history, and indigeneity. Future reviews of historical scholarship in this vein may define "traditional" or indigenous societies much more broadly.[8]

30.3 The Arctic and Subarctic

Long before American and Canadian scientists became interested in glaciers and sea ice, indigenous societies acquired intimate knowledge and experience of Arctic landscapes. The retreat of glaciers has become a symbol of our contemporary climate crisis, but scholars have shown that local populations have oral traditions about dynamic glacial landscapes that stretch back centuries. Oral histories preserve knowledge about past glacial activity that science has subsequently confirmed, thus contributing to glaciology and historical climatology. Yet these stories also have important cultural purposes, expressing beliefs about sovereignty, respect for powerful natural forces, and cooperative responses to climatic challenges.

Julie Cruikshank's path-breaking book on indigenous relationships with glaciers in north-western North America during the late phases of the LIA exemplifies how oral tradition can illuminate climate history. First Nation peoples of the Pacific Northwest tell stories of ancestors who traveled under and over specific glaciers many generations ago. Some recount the first migrations of a clan or tribe to a newly habitable area, where a wasting glacier opened up the shoreline. Other stories warn that glaciers can listen, smell, and watch, so humans must learn how to behave properly in their presence. One such story about a young woman punished by an advancing glacier has a larger political purpose, too, as Cruikshank points out: "the image of the 'woman in the glacier' remains the embodiment of the current Chookanedí clan title to Glacier Bay."[9]

Changes in sea ice have provided another locus for the study of climate and indigenous societies. Anthropologists and Inuit community members do not always define their work as historical, but they are interpreting rapid and complex changes, usually within the broader context of longstanding tradition and ancestral time stretching back centuries and millennia. As anthropologist Claudio Aporta has stated, "sea ice is solid 'ground,' where people live their lives and have a history"; sea ice contains "significant historical places for Inuit," and scholars have to ask highly localized questions, since "specific ice ridges, or ice leads, may have 'a history'." Glacial movements and sea ice melting can obscure or obliterate archaeological evidence of human occupation, which might "only be 'reconstructed' from people's memories." Recent scholarship also charts Inuit flexibility and resourcefulness through phases of both mild and severe weather during the LIA.[10]

Global warming has caused unprecedented problems in Arctic environments that have always been dangerous for people. In the twenty-first century, "the ice is less reliable, ice-related hazards are more frequent, and accidents seem to be on the rise." Indigenous witnesses of the sea ice "are reporting delays in freezing times, accelerating melting times, floe edges forming closer to shore, less solid ice, and shorter ice travel seasons altogether." But Inuit communities want much more than the opportunity to give testimony. By establishing the historicity of their practices and territories, Inuit peoples and scholars have pursued targeted political goals and have informed worldwide debates about climate justice reparations and Arctic sovereignty. For decades, Inuit leaders have organized circumpolar indigenous nations and have articulated innovative political concepts such as the "right to be cold." The volume and sophistication of intellectual work being produced inside and outside the academy related to far northern nations and climate changes promises to shape the study of climate and indigenous societies in profound ways.[11]

30.4 Temperate North America

The story of LIA impacts and adaptations in eastern North America begins in the pre-colonial period. For example, archaeologist William Fitzgerald has argued that Neutral Iroquoians (Atiouandaronk) adapted to a changing climate before the fur trade transformed economic relations in north-eastern North America and long before French colonial settlement. In the fifteenth century, longhouses grew in length, beans became a key dietary component, and white-tailed deer remains were rare at settlement sites. In the sixteenth and seventeenth centuries, "the reliability of the protein-rich but cold-sensitive bean was threatened by the colder climate of the Little Ice Age." Longhouses decreased in length, beans declined within diets, and deer hunting came to compensate by supplying protein in the form of venison as well as hides for warmth. Competition for hunting territories intensified, and therefore signs of "cultural instability and turmoil" did not owe exclusively to the European presence.[12]

While Neutrals sought to retain their territories by adopting a smaller-scale, decentralized survival strategy, other Iroquioan groups migrated. The Susquehannock relocated southward to the Chesapeake area in the late sixteenth century. They survived climatic stresses by relying on a decentralized matrilocal system of clans and kinship networks that ensured distribution of scarce resources. Meanwhile, as historian James Rice has demonstrated, Algonquian societies in the Chesapeake and Potomac held valuable territory by concentrating authority. Centuries of maize production supported the rise of hereditary chieftains, but population growth carried Algonquian societies past "a point of no return." LIA weather introduced new constraints to maize production, and "in response, the people of the Potomac abandoned their relatively egalitarian social and political orders in favor of powerful hereditary chieftaincies supported by a priestly caste" in order to defend favorable maize-growing land from rivals and migrants.[13]

At the far northern margin of maize cultivation, historian Jason Hall has uncovered ways in which the Maliseets of north-eastern Maine adapted to colonization and LIA climate change and continued to cultivate maize on a small but sustainable scale. He argues that European observers—focused on the coast and biased toward male activities—missed how Maliseet cultivators, mainly women, found micro-environments and short-season varieties of maize that could thrive despite the tight frost-free period. Maliseets also coped by consuming a repertoire of other foods, including groundnuts and Jerusalem artichokes.[14] Such stories of local indigenous knowledge are a reminder that Native inhabitants possessed centuries of experience in their homelands, a key advantage over colonizers.

Colonialism, cold, and drought produced competition, war, and depopulation in the Southwest as well, but historians such as Natale Zappia have identified numerous coping strategies, including niche specialization, resource intensification, and increased involvement in regional trade networks. With early LIA conditions, Mojave peoples in the late fourteenth century developed technologies for storing and transporting food more efficiently. Yokut people in southern California selectively burned oak forests to foster acorns and other foraged foods, facilitate deer and elk hunting, and permit smooth travel. Puebloan people drew on "long-standing alliances" and trade relationships with Athapaskans who were hunting the growing bison herds on the southern Plains (see below). By acquiring buffalo robes and moccasins, Puebloans broke from tradition and dressed more appropriately for the severe cold of the sixteenth and seventeenth centuries.[15]

Zappia has brought together a number of origin stories and migration stories from the American Southwest to underscore the ways in which storytellers recall climatic disruption and creative responses in the ancestral past. For example, Lake Cahuilla in southern California began to dry out during the LIA. Cahuilla people migrated westward and witnessed several contractions and expansions of the lake. Traditional Cahuilla stories and songs connect this period of cyclical desiccation to "their own cultural genesis, locating the beginnings of their agricultural traditions in this period." The emigration of the Hohokam people from Pueblo Grande in the fourteenth and fifteenth centuries has been presented as a story of collapse. However, present-day Akimel and Tohono O'odham elders claim their peoples descend from Hohokam emigrants and commemorate those floods and droughts at Pueblo Grande by making a biannual trip to a Hohokam shrine. Such stories exemplify the ability of indigenous communities to transform past crises into lessons of resilience, and to resist narratives of climatic determinism and decline. Similarly, Puebloan people have stayed connected to ancestral villages at Chaco Canyon and Mesa Verde, viewing those sites as sacred points of origin.[16]

Adaptation to prior climatic disruptions only partly prepared indigenous societies for colonial invasions during periods of severe weather. As historian Sam White has shown, Pueblo resistance to Spanish entradas in the American Southwest must be understood within the context of severely cold winter weather. In the Tiguex War over the winter of 1540–1 and the Acoma Massacre of January 1599, conflict arose when Spanish soldiers and Native Mexican auxiliaries stole cotton blankets and turkeys (used for feather coats). Drought and maize shortages contributed to indigenous hostility toward invading soldiers and settlers demanding food. However, "the struggle for warmth, even more than food," framed these early conflicts. Climate and colonialism did sometimes combine to unleash "violence over the land," but climate nearly as often interfered with colonial expansion. Spanish unpreparedness for cold and drought slowed the process of settlement, and accidents of weather and climate made the land appear less valuable for colonization.[17]

European expansion in the Americas faltered at many junctures because of the combined challenges of climatic fluctuations and indigenous resistance (see Chap. 24). Several early colonial ventures in the sixteenth and seventeenth centuries took place during decades of drought or extreme cold. For instance, the Spanish beachhead of Santa Elena (present-day Parris Island, South Carolina) lasted only from 1566 to 1587. Historian Karen Paar has argued that a "period of abundant rain" in the 1570s permitted indigenous communities to create food stores that fueled indigenous resistance, particularly a 1576 uprising by Guale, Orista, and Escamazu. Then a serious drought starting in 1583 prompted many indigenous leaders to shift course and ally themselves with the Spanish. However, the combination of indigenous resistance and adverse climate gave the impression Santa Elena was not worth defending.[18] English encampments at Baffin's Bay, Roanoke, and Sagadahoc never became lasting colonies either, and not just because of inclement weather: mortality crises among settlers and outright colonial abandonment during the LIA often reflected successful indigenous resistance as well. The limited success of

European colonization owed to Native accommodation, and eventually to Native migration, disease, and war. Several scholars have recently examined struggles among indigenous communities and European colonies in the early seventeenth century; historians of early America should carry the story forward through the long colonial period.[19]

For example, there have been comparatively few climate histories of the widespread extreme weather, food shortage, disease, and indigenous rebellion during the 1680s and 1690s. In the American Southwest, a 1680 Pueblo revolt ousted the Spanish from the region for over a decade. The revolt was preceded by a regional drought and famine. Climatic conditions initially favored indigenous rebels, but the return of Spanish colonial rule coincided with terrible weather in the 1690s. In the Northeast, meanwhile, I have argued in a recent article that Native mobility in wintertime presented a challenge to colonial control. At first, the severe cold of the 1690s favored Wabanaki winter raiding parties in north-eastern North America. The Second Anglo-Wabanaki War (1688–99), combined with disease and food shortages, sorely tested colonial settlements in northern New England. Initial defeats prompted English leaders to equip their soldiers with snowshoes, an indigenous technology, in the early eighteenth century. At the heart of the continent, the grand village of Kaskaskia emerged at just this time of climatic stress as well. According to historian Robert Morrissey, Kaskaskia reveals the "power of the ecotone," a territory of edge habitats that were particularly rich and diverse. Possession of this transitional area facilitated lucrative trade between two vastly different ecological zones: prairies filled with bison and fields on one side and forests yielding maize and pelts on the other. Indigenous leaders consolidated rule over tens of thousands of people in Kaskaskia at a time when a diversified economy and food supply likely created an important hedge against climate-related disaster. Such examples illustrate the contingencies and instability of indigenous power during this period of climatic change.[20]

The early and late phases of the LIA also bookend Pekka Hämäläinen's epic narrative of the rise and fall of the Comanche empire on North America's Great Plains. Hämäläinen frames the story of indigenous power in terms of climatic, ecological, cultural, economic, and political variables affecting bison hunts and horse raising. Beginning in the mid-sixteenth century cool, wet weather began to have a "pull" effect, enticing bison onto the Plains and allowing the bison population to grow rapidly. What followed was "one of the greatest [human] migrations in the history of North America." Responding to new opportunities, a number of indigenous societies moved permanently onto the Plains to follow the herds throughout the year. In the eighteenth century, Comanches on the southern Plains combined bison hunting with horse raiding, and consolidated their territories into a vast steppe empire. Comanches hedged against climatic instability by displacing risk onto other indigenous peoples, replenishing their stocks of horses through raids, and acquiring plant foods through trade. When one neighboring community lost horses to winter kill or experienced crop failure from frost or drought, Comanches knew they could obtain steeds or corn from another client. Meanwhile, Comanches calibrated their seasonal mobility to stay within the range of migratory bison herds and to provide sufficient sustenance and shelter for their horses. Such subtle calibrations, though hard to document, remain crucial to understanding Native adaptations to climatic change.[21]

Likewise, historian Theodore Binnema has demonstrated how indigenous peoples on the Northwestern Plains pursued large communal bison hunts during the cold, snowy winters of the LIA. Horses struggled over the longer winters at these higher latitudes: "Cree and Assiniboine bands in areas of the northeastern plains often released their horse herds at the beginning of the winter and collected any survivors they could find in late winter … In severe winters the Blackfoot often tried to rest weak horses by relying on dogs." During these colder months, pedestrian hunters could gather in large groups to use pounds or jumps to catch bison. Indians used fire to protect rich fescue grasslands from forest encroachment, helping secure a key source of winter forage for bison. Nevertheless, both mild and severe winters could present problems. Months of cold and snow in 1788–9 and 1800–1 produced unusually high bison mortality. Yet warm, dry winters "scattered" bison herds; "large bands could not depend on communal hunts and small bands could not kill enough animals to sustain their members."[22]

Adam Hodge has examined the role of climate change during a smallpox outbreak on the Northern Plains from 1780 to 1782. Records of Hudson's Bay Company traders living along the Saskatchewan River include reports of smallpox and starvation among mobile groups of Blackfeet, Assiniboine, Lakota Sioux, and Cree hunters. Indigenous informants showed up at trading posts, reported hunger, and requested provisions. Plains societies also kept winter counts, or hide paintings that registered one or more salient events from each year. Hodge has correlated findings from these different primary sources with available tree-ring data. He tentatively argues that "climate fluctuations in the years preceding the 1780 epidemic decreased bison populations, which in turn increased malnutrition among migratory groups, rendering them more vulnerable to smallpox." Mild winter weather during the winters of 1779–80 and 1780–1 seems to have compelled Native hunters "to search more widely for food," creating fatigue that might have lowered their immune defenses and putting them in contact with neighboring bands carrying the smallpox virus. The return of cold, snowy weather at the end of 1781–2 alleviated food scarcity. The clearest lesson from the case study is that climatic fluctuations in both directions can present challenges to mobile societies, sometimes activating feedback loops between food shortage and disease.[23]

Climate seems to have contributed to the decline of indigenous power on the Plains during the nineteenth century. From 1845 to the mid-1860s, dry weather became the norm, with only a brief, wet interlude in 1850. Comanches prioritized their own access and their horses' access to "forage and water … thus blocking the bison's access to their drought refuges … Already strained by grazing competition and human predation and now left to endure the drought without the vital resources of the river valleys, Comancheria's bison herds collapsed." Comanches may not have recognized the turning point at the time, since bison herds had rebounded after droughts of the 1770s–80s. The crucial problem was not only climate but also the scale of Comancheria by the 1850s: "too many Comanches (and their allies) raising too many horses and hunting too many bison on too small a land base." In some ways, therefore, Hämäläinen has written yet another narrative of the climatically influenced rise and fall of an indigenous empire, but a more richly documented and less climatically determinist story.[24]

Climate history has also contributed to Native American history of the twentieth century. Historian Marsha Weisiger has examined how federal officials and scientists sometimes lacked the local, long-term perspective needed to understand environmental crises in indigenous communities. In the 1930s, the Bureau of Indian Affairs (BIA) and other federal agencies blamed Diné pastoralists for an apparent environmental crisis in Navajo Country. Weisiger used tree-ring evidence to illustrate how natural and cultural factors in the American Southwest came together in the early twentieth century to mislead officials. Severe drought in 1899–1905, followed by extremely wet weather until 1920, had lasting effects in the region, carving arroyos (gullies) into the landscape. New Deal conservationists downplayed natural climate change and blamed Diné sheep and goats, even though the gullies appeared across the southern Colorado plateau and not just in grazing areas. Diné communities had successfully expanded their herds during the rainy period, and these animals did exacerbate desertification occurring in Navajo Country. Weisiger's careful interpretation, however, shows that punctuated climate fluctuations caused the most extreme changes. Federal officials had little interest in Diné local ecological knowledge, and instead promoted a narrative of gradual indigenous degradation of rangelands followed by timely intervention and reform. In 1933, new BIA commissioner John Collier ordered stock reduction and instituted a system of grazing permits, irreparably harming his relationship with Navajo leaders and unintentionally undermining his agenda to promote Navajo self-determination. Weisiger's story is an important cautionary tale, implicitly calling on scholars and officials to take the time to understand culturally specific beliefs and practices in order to support tribes as they find their own solutions to climatic crises.[25]

30.5 Mexico

Colonial Mexico has received detailed examination by climate historians, yet scholarly approaches have varied significantly (see Chap. 19). A "megadrought" in the mid-sixteenth century devastated some indigenous communities. Early studies described its impact as depopulation and even "megadeath." However, two recent studies have examined the contingencies and specificities of climate in colonial Mexico in greater depth at the local and regional levels.[26]

In *Climate and Society in Colonial Mexico*, historical geographer Georgina Endfield has crafted a comparative history of vulnerability and adaptation in three regions of LIA Mexico, revealing a range of coping strategies among indigenous peoples struggling with colonialism and a changing climate. Drawing on archival evidence, Endfield connects sudden events like rebellions with weather and climate, and identifies the cultural resources and political approaches that buffered communities against extremes. The book also considers the "net benefits that might be derived from climatic changes" and "reduction in some risks" over time. Two key periods stand out in Endfield's narrative. In the 1690s, harvests failed, food prices soared, and disease and famine struck many communities. Not by coincidence, it was "one of the most important phases of indigenous rebellion in the entire colonial period." By the middle of the eighteenth century, colonial engineering projects altered waterways and provoked complaints about pollution and unfair distribution. Flooding on these waterways set the stage for dramatic confrontations between indigenous communities and the colonial government.[27]

Indigenous communities in Endfield's three case studies—Oaxaca, Guanajuato, and Chihuahua—dealt with different environmental and political situations, and experienced different outcomes. The indigenous societies of Chihuahua practiced a highly mobile lifestyle, engaged in "more or less continual warfare," and took advantage of climatic fluctuations in order to protect their livelihoods and raid sedentary neighbors. In Guanajuato, the colony's most prolific grain-producing region, successive droughts destabilized indigenous communities; over time flooding became the central point of conflict between indigenous and Spanish residents. In contrast, indigenous residents of Oaxaca coped comparatively well.[28] Although poor residents in Oaxaca suffered occasional food shortages, indigenous communities used a repertoire of coping strategies to avoid the severe crises. They retained a large land base, continued to cultivate subsistence crops, and leveraged specialized skills to generate supplemental income. Needy community members benefited from traditional common funds designed for local relief during food shortages. Residents took legal action to protest unfair water distribution and secure rights to relocate to better land. Oaxacans drew on tradition but also learned new lessons from the extremes of LIA and passed them to new generations.[29]

Historian Bradley Skopyk has made an even more focused study of colonial Tlaxcala in the central Mexican highlands. Drawing on Nahuatl-language and Spanish colonial documents, Skopyk's study highlights indigenous agency and the sustainability of indigenous agrosystems during the LIA, including two early periods of severe environmental stress in 1542–63 and 1595–1625. Indigenous farming techniques and social practices helped mitigate crises, and their carefully monitored landscapes showed the capacity to regenerate. Over the course of the seventeenth century, however, Tlaxcalan farmers created new landscapes of *maguey* (agave) in order to produce *pulque* (an alcoholic drink) on an ever-larger scale. This exposed indigenous communities to market volatility and the natural vulnerabilities of monoculture. In 1680–1710, severe drought and cold weather coincided with a major measles epidemic. The new agrosystem proved less resilient than previous sources of indigenous livelihood, and severe weather resulted in widespread erosion, food shortages, livestock die-offs, temporary abandonment of degraded land, and colonial land expropriation. Moreover, hydrological reengineering during the eighteenth century further exacerbated flooding. Skopyk is able to establish these claims by examining a region in such detail that he knows Nahua place names, the specific contours of the terrain, and the particularities of weather from year to year.[30]

30.6 South America

Many of South America's indigenous communities have lived in regions acutely affected by natural climate variation and current global warming. ENSO events destabilized large indigenous societies like the Moche (*c.* 200–600 CE) on the Pacific coast. Further inland, sharp differences in elevation and a patchwork of micro-climates make it difficult to generalize about Andean experiences of climatic changes. Dry conditions from the twelfth to the fifteenth centuries may have weakened Tiwanaku society, but one study has argued that moderate climatic conditions during roughly the same period (spanning the late MCA and early LIA) contributed to the ascendancy of the Inca Empire. Andean peoples, accustomed to irrigating fields and growing a wide variety of crops, expanded the range of cultivation uphill during warmer times. Agroforestry techniques ensured adequate stores of building material and fuel, which became more crucial with colder weather. Alpacas and llamas likely did well in cool wet weather characteristic of the LIA, providing a buffer for Native herders. In negotiations with colonial officials, moreover, indigenous plaintiffs could cite local environmental knowledge, including of weather patterns and micro-climates, to buttress claims to ancestral lands. Scholars are only beginning to examine the climatic context of colonial South America, such as disastrous droughts and floods that struck the silver mining center of Potosí in 1626, or the avalanche of ice that destroyed the town of Ancash in 1725. With extensive colonial archives and recently available proxy data, as well as rich oral histories and vibrant traditional ecological knowledge among indigenous communities, climate historians studying colonial South America have opportunities for collaboration and many histories left to tell (see Chap. 19).[31]

For nineteenth-century Latin America the most memorable climatic event remains the 1877–9 El Niño. Adjacent regions in South America experienced radically different conditions: rain and floods affected coastal Peru and Ecuador, even as drought devastated the altiplano of Peru and Bolivia. In the arid interior region of north-eastern Brazil, the *sertão*, failures of rainfall during the southern winter (April to September) created severe droughts that deepened during dry southern summers (October to March). Writer and activist Mike Davis has situated the 1877–9 disaster in north-eastern Brazil within global processes of political economy, but at the time many Brazilians of indigenous descent interpreted the events within regional political and historical contexts. Mixed-race *sertanejos* left the dry interior for the coast, and mortality soared as smallpox spread in overcrowded refugee camps. According to geographer César Caviedes, this pattern of migration had deep roots in Brazil. Beginning in the sixteenth century, indigenous people in northern Brazil relocated to the *sertão* in response to Portuguese colonization, and *sertanejos* became "adept at coping with the climatic extremes." Yet once human and livestock populations grew, droughts drove refugees and raiding parties into urban areas. In 1692, for example, indigenous raiders attacked Portuguese settlements during a drought, causing colonial outmigration to Minas Gerais. Droughts in the eighteenth century "became more frequent and more devastating," with the most severe episode lasting from 1723 to 1727. The persistent legacies of these prior instances of migration and violence in response to droughts partly explain why urban distrust of rural peoples again produced suffering among descendants of indigenous Brazilians in the late nineteenth century. The magnitude of the 1877–9 crisis led to multiple kinds of displacement within Brazil. As Caviedes remarks, climatic crises in 1877–9 and again in 1942 also prompted major waves of migration of *nordestinos* to the Amazon basin, indirectly creating new pressures on indigenous communities there.[32]

Since the twentieth century, South America's indigenous populations have coped with the effects of global warming. Mark Carey has documented how a range of stakeholders, including indigenous farmers and shepherds in the Andean highlands, have thought about and responded to glacial melting. During the mid-twentieth century, the problem of melting glaciers brought indigenous community members into more frequent dialogue with national and provincial government officials, as well as glaciologists, engineers, developers, and eventually tourists.[33] Although indigeneity is not Carey's primary interest, he reveals how indigenous communities had coping strategies in place well before the 1940s. Rural residents of the region managed "croplands and pastures that extend far into Cordillera Blanca canyons, right to the edge of glaciers." Yet, as Carey notes, "this rural population actually was less affected by glacier disasters than were the urban residents." Guided by oral traditions and rituals that construed "glaciers and glacial lakes as enchanted or capable of acting out against people," indigenous peoples actively "stayed away from alpine peaks and lakes" and "lived outside hazard zones where floods and avalanches could pass." By taking seriously indigenous ways of knowing and relating to glaciers, Carey reveals "a discursive construction of the Andean environment and its processes." At glacial lakes, indigenous people presented offerings of *rima rima* flowers or threw salt into the water "to tame what they called *chúkaro*, a Quechua term meaning 'raw nature.'" In one sense, the rituals expressed a hope that humans "could help pacify nature so long as this was done according to proper local customs instead of through force or blind transgressions." In another sense, they were a warning: "stay away from the lake."[34]

Carey closely interprets cultural responses to a sudden, climate-related catastrophe: the outburst flood that struck Huaraz, Peru on December 13, 1941. The state-led recovery plan romanticized indigenous knowledge but also marginalized indigenous communities. Spanish speakers circulated stories of rural residents appearing to warn residents of Huaraz about the flood, perpetuating tropes that rural indigenous people were a part of nature, excluded from modern history except when they could critique or interpret unusual events. The flood created opportunities for cooperation, but by destroying the structures that segregated creoles and indigenous peoples, it also raised upper-class anxieties about crime and looting. In the aftermath, some opposed plans to rebuild in the flood's path, citing indigenous practices. Most urban residents, however, envisioned a rebuilt Huaraz as a symbol of "progress and modernity." Actual indigenous communities had a harder time securing relief or reform after the flood. Officials in Lima lagged in responding to indigenous concerns, giving priority to urban constituencies.[35]

Carey has also examined how climate change has brought rural indigenous communities into dialogue with scientists. "Whereas few outsiders had any interest in or control over the country's glaciated mountains in 1940, locals have since lost power and today comprise just one among many stakeholders in the high Andes—and perhaps the least powerful." At times, rural Andeans have been deeply skeptical of glaciologists. Farmers around Lake Auquiscocha, for example, attributed drought to a rain gauge that experts had installed to measure precipitation below melting glaciers. Locals quietly removed the rain gauge then forcibly prevented technicians from reinstalling it, asserting control over their environment. These examples show indigenous Andeans as more than "just passive victims of historical processes beyond their control." Indigenous participation in climate change discussions has not fit neatly into "rigid local versus national, expert versus Indian, or coast versus highland demarcations." Moreover, scholarship such as Carey's raises awareness of indigenous stakeholders in Peru and elsewhere.[36]

30.7 Pacific Islands

Pacific Island societies have also been affected by global changes in average temperatures, including the MCA, LIA, and anthropogenic warming. Yet because the Pacific world is extremely sensitive to ENSO cycles, stories about climatic change and indigenous societies emphasize frequent swings and sudden crises.

Like indigenous peoples in other areas of the world, Pacific Island nations experienced favorable conditions during the MCA, followed by a LIA combination of colder climate, more frequent storms, and a fall in sea level. LIA phenomena presented challenges for all residents in the indigenous Pacific, but societies living on the coastlines of the North, Central, and South American mainland often coped better than islanders because continental residents had greater options to relocate inland. In spite of the vast distances and incredible diversity within the Native Pacific, geographer Patrick Nunn has identified four LIA trends affecting Pacific Islanders beginning *c.* 1300–1400 CE: conflict, decentralization, reduced contact between islands, and new patterns in resource use.[37]

In New Zealand, several noticeable changes have been dated to around 1450, including migration away from the coasts and a reduction in both seafood harvesting and horticulture. Around this time, evidence of intentional fires indicates increased reliance on the edible bracken fern, which Nunn calls a LIA staple food in pre-settlement New Zealand. On some islands in the Pacific, people responded to warfare by taking up residence at hilltop sites and in caves, adjacent to marginal lands for cultivation. Hawaiians seem to have encountered milder LIA conditions, and coped with changes by constructing fishponds. Meanwhile, environmental historian Ryan T. Jones has shown that in the northern Pacific "a strong Aleutian Low storm system fostered a strong oceanic orientation," since LIA climatic patterns increased certain marine mammal populations. Indigenous people participated in their commercial overhunting, and when warmer conditions returned in the late nineteenth century, pressure on these animals increased.[38]

Environmental historian Gregory Cushman has chronicled indigenous responses to repeated La Niña droughts on central Pacific Islands. Oral history from the equatorial island of Banaba tells how the earliest settlers survived the first droughts by following land crabs to limestone caverns with pools of water, and how community regulations ensured water conservation and social welfare during drought. Banabans also looked for weather signs, such as the arrival of *tarakura* (frigatebirds), "which foretell the arrival of small black rain clouds" associated with the reversal of the equatorial current. Increasing Euro-American influence in the Pacific world during the nineteenth century introduced new problems and new options during droughts. During periods of ENSO-related scarcity in the early 1860s, early 1870s, and early 1890s, labor recruiters recruited Banabans and other Pacific Islanders as indentured workers to harvest guano in South America or Pacific atolls. Around half never returned. Later, under Japanese occupation during World War II, indigenous people on Banaba suffered starvation, mass executions, and deportation. The impacts of wartime atrocities were exacerbated by La Niña conditions in 1942. Diasporic pressures make it difficult to keep these stories intact at the turn of the twenty-first century, but leaders such as Raobeia "Ken" Sigrah have been doing just that, against great odds.[39]

Histories of indigenous persistence in the face of climatic challenges have become crucial to twenty-first century Pacific Island nations asserting their sovereignty in the face of new climate crises. Insular societies in the past may have suffered more from climate change and colonialism, as Nunn has argued, because it was difficult to relocate to a large hinterland. Nevertheless, many of these island peoples would have stayed on their traditional lands for cultural reasons. Many present-day Pacific Islanders have explicitly resisted identification as future "climate refugees" in need of assistance to emigrate (see Chap. 31).[40]

30.8 Indigenous Knowledge and Contemporary Research

Scholarship on anthropogenic climate change and the origins of the Anthropocene has been slow to incorporate indigenous knowledge. This apparent reluctance is ironic since this research has highlighted how indigenous peoples transformed environments and possibly altered global climate over millennia, and since traditional stories organize natural and social historical information over long periods of time.[41] In a widely cited essay on climate change and the Anthropocene, historian Dipesh Chakrabarty has explored new convergences between natural and human histories. Many indigenous leaders and intellectuals have long rejected any separation between the two. When indigenous leaders in the twenty-first century hold industrialized nations responsible for altering the global climate, they are often expressing their communities' longstanding convictions about humans' reciprocal relationships with the natural world.[42]

Traditional stories passed down across many generations carry climate histories that go back centuries. Some stories can be connected to evidence from the archives of nature, and other stories can supplement proxy-based climate reconstructions. As Mark Carey has argued, "elders and climate experts in indigenous communities possess knowledge accumulated over many generations that often focuses on areas without any scientific instruments to measure or observe the processes or impacts of climate change." At the same time, tribal storytellers continue educating new generations about how humans have always had profound effects on the natural world.[43]

Some of these stories now incorporate recent urbanization and industrialization. In the nineteenth and twentieth centuries, indigenous communities variously opposed or participated in the fossil fuel economy, and were among the first to feel the disruptions of a warming climate. Energy historian Andrew Needham's history linking Navajo coal mines and electricity production for the city of Phoenix in the 1960s and 1970s is just one story of these rapid upheavals in Indian country. Mark Carey has remarked that scholars "have a record of how societies have been responding" to global warming for at least "a century and a half." Indigenous communities have been an important but overlooked part of that record.[44]

In the twenty-first century, indigenous climate justice activists make up a dynamic and influential trans-national political movement, and scholars and community members are beginning to recover and fashion a usable past for this moment of crisis, protest, and reform. Scholars from outside these communities have an opportunity to enrich public dialogue, activism, and policy by documenting indigenous climate histories; their work should take into account implications for contemporary communities with livelihoods and sovereignty at stake. Or it may be that indigenous scholars will lead the way in writing and synthesizing Native-centered climate histories, building on deep traditions of reflection about environmental change and human responsibility that now interest scholars more broadly.[45]

30.9 Conclusion

In the last decade, an interdisciplinary scholarly field has coalesced around the historical study of climate and indigenous societies. Two major factors have energized this field: advances in historical climatology and indigenous leadership in worldwide debates over responses to climate change. Anthropologists, geographers, and historians have not only connected oral traditions and documentary archives to new tree-ring, pollen, and ice-core analyses; increasingly, scholars in the humanities and social sciences have attempted to bring their interpretive methods in line with the stated values and aims of tribal communities. Working in collaboration or consultation with indigenous intellectuals and political leaders, scholars are finding new ways of telling climate histories.

Humanistic studies can complement climate reconstruction and correct climatic determinist explanations of history, including indigenous history. In some ways, histories of agriculturally oriented Native empires such as the Maya opened the way for the study of climate and indigenous societies. Yet such studies of the rise and fall of indigenous empires have created a template that does not fit all Native societies. Scholars writing smaller, more focused climate histories of indigenous communities have moved beyond old narratives of collapse. Historians, geographers, anthropologists, and archaeologists closely analyze Native ways of knowing, deciding, adapting, and remembering in order to understand history of climate and indigenous peoples as though from the inside. In many cases, printed and archival sources in European languages are rich with information about indigenous activities in the midst of past climatic upheavals. Yet, as the work reviewed here underscores, competence in Native languages may prove essential to understand memories and meanings of historical climate change. Studies relying on oral history and on documents written in Native languages have displayed a special ability to recover stories of indigenous resilience and adaptation. As scholars aim to recover and analyze insiders' perspectives, the history of indigenous responses to past climate changes can be quite different from the bird's-eye view provided by proxy data alone.[46]

Taken together, these smaller histories have diversified the kinds of stories that count as climate history. It is harder than ever to generalize about the effects of the LIA or the El Niño Southern Oscillation. In some ways, local histories about indigenous peoples make it impossible to tell a unified narrative about climatic crises and human responses. Yet the very heterogeneity of these stories should be considered a strength, and work in this subfield promises to invigorate the larger field of climate history in coming years.[47]

Notes

1. For exemplary recent books reviewed below, authored respectively by an anthropologist, geographer, and three historians, see Cruikshank, 2005; Endfield, 2008; Carey, 2010; Cushman, 2013; Zappia, 2014.
2. On Mayan society, see Demarest, 2004; Gill, 2000; Webster, 2002; Haug et al., 2003; Peterson and Haug, 2005; Pringle, 2009. On Cahokia, see Benson et al., 2009; Calloway, 2003, 99, 103. On ancestral Puebloans, see Benson et al., 2007. On the MCA, see also Fagan, 2008; Foster, 2012; Richter, 2011; Anderson, 2001; Jones et al., 1999; Stine, 1998. On the "convergence" and "complementarity" of archaeology and oral tradition, in addition to those cited below, see Crowell and Howell, 2013, 3.
3. Zappia, 2014, 18–40; Cruikshank, 2005.
4. Carey, 2012, 239. For big history, see Brooke, 2014. On narrative, see Endfield and Daniels, 2009; Cronon, 1992.
5. For relevant surveys of global climate history, see Carey, 2012, 2014; White, 2012. For North American climate history, see White et al., 2015. For Latin American climate history, see Prieto and García-Herrera, 2009; Diaz and Stahle, 2007; Cushman, forthcoming. For Pacific climate history, see Nunn, 2007. For a review of historical geography, see Offen, 2014.
6. On cultural diversity, see especially Salick and Ross, 2009. On indigenous knowledge and climate, see especially Green and Raygorodetsky, 2010.
7. For the Caribbean, not covered here, see Cushman, forthcoming. For limited attention to sixteenth-century indigenous knowledge of hurricanes and climatic phenomena in the Caribbean, see Schwartz, 2015, 5–9, 23–4, 36–7; Mulcahy, 2006, 14–16, 21, 34–35, 37, 40, 51.
8. On indigenous activists and tribal members responding to global warming, and the consequences for climate history, see especially Carey, 2012, 239. On traditional peoples and climate change, see Salick and Ross, 2009. For African climate history, see McCann, 1999; Webb, 1995. For Australia, see Anderson, 2016.
9. Cruikshank, 2005, 8, 31, 39. See also Cruikshank, 2001.
10. Aporta, 2011, 9, 10, 16; Kaplan and Woollett, 2000; Crowell and Howell, 2013.
11. Aporta, 2011, 12; Wright, 2014; Bravo, 2009; Wilson and Smith, 2011; Watt-Cloutier, 2015.
12. Fitzgerald, 2012, 37, 38, 39, 41, 44, 46.
13. Rice, 2009, 12, 30–31, 45, 48–49; Halttunen, 2011, 520–21. See also Richter, 1992.
14. Hall, 2015.
15. Zappia, 2014, 32, 36, 38, 42; Carter, 2009, 52, 69–74.
16. Zappia, 2014, 28–29, 35–36; Carter, 2009, 40.
17. White, 2014; Van West et al., 2013; Blackhawk, 2006. See also White, 2015; Spicer, 1962.
18. Paar, 2009; Blanton, 2013; White, 2017.
19. Mancall, 2009, 2013; Kupperman, 2007; Bilodeau, 2014; Stahle et al., 1998; Blanton, 2000, 2004; Grandjean, 2011; Piper and Sandlos, 2007; Parker, 2013; White, 2017.

20. Anderson, 1999, 16–17, 24, 59–61; Carter, 2009, 184–87; Knaut, 1995, 61, 161–62, 183; Ivey, 1994; Blackhawk, 2006; Wickman, 2015; Morrissey, 2015a, 2015b, 2015c.
21. On the way LIA conditions attracted human migration onto the Plains, see Hämäläinen, 2008, 22, 2010, 177; Calloway, 2003, 272. On Comanches' evolving ecological strategy and migration patterns, see Hämäläinen, 2010, 176, 177, 183, 187, 194, 196. On the winter vulnerability of horses, see Hämäläinen, 2008, 240, 2010, 193–95.
22. Binnema, 2001, 19, 21, 24, 32, 47, 48, 49, 50, 141, 142, 143, 153.
23. Hodge, 2012, 366, 368, 374, 376–77, 382–83, 386–87. On winter counts, see also Gallo and Wood, 2015; Fenn, 2014; Therrell and Trotter, 2011; Greene and Thornton, 2007. For a study of Northwest Alaska around the same period, see Jacoby et al., 1999.
24. Hämäläinen, 2008, 296, 297, 361; Jacoby, 2013.
25. Weisiger, 2009, 43–7, 131, 138–40, 163, 239.
26. Stahle et al., 2000; Acuña-Soto et al., 2002, 2004.
27. Endfield, 2008, 96, 127, 154.
28. Endfield, 2008, 8, 13, 112, 126.
29. Endfield, 2008, 15, 66–69, 82–84, 87.
30. Skopyk, 2010, iv, v, 5, 6, 10, 16, 18, 19, 26, 46.
31. Fagan, 2008; Binford et al., 1997; Cushman, 2015, 40–41, 57–63, 66–78; Carey, 2012, 236; Chepstow-Lusty et al., 2009; Miller, 2007, 41–2; Carey, 2010, 35; Gregory Cushman, personal communication, 28 September 2015; Cushman, forthcoming. See also Young and Lipton, 2006.
32. Cushman, 2013, 70; Aceituno et al., 2009; Caviedes, 2001, 100–08. On the 1877–79 crises around the world, see Davis, 2001. On ENSO, see also Fagan, 2008; Sandweiss and Quilter, 2008; Davis, 2001; Glantz, 2001.
33. Carey, 2010, 5, 24.
34. Carey, 2010, 15, 47, 48, 50.
35. Carey, 2010, 36, 42, 50–1, 54–5.
36. Carey, 2010, 4, 5, 15, 40, 44, 177.
37. Nunn, 2007, 121, 136, 140; Goodwin et al., 2014. See also Nunn and Britton, 2001; Jones, 2014b, 126.
38. Nunn, 2007, 137–38, 142, 149. On the northern Pacific, see Jones, 2014a, 2014b, 126, 130.
39. Cushman, 2013, 21, 85–6, 96, 109, 112, 114, 116–17, 230–31.
40. McNamara and Gibson, 2009; Farbotko and Lazrus, 2012.
41. Lewis and Maslin, 2015; Steffen et al., 2007; Ruddiman, 2005.
42. Chakrabarty, 2009.
43. Carey, 2012, 239; Green and Raygorodetsky, 2010.
44. Needham, 2014; Carey, 2010, 5. See also Aijazi and David, 2015; Chamberlain, 2000; Sabin, 1998; Santiago, 1998.
45. Maldonado et al., 2013; Klein, 2014; Grossman and Parker, 2012; Turner and Clifton, 2009.
46. Cruikshank, 2005; Skopyk, 2010.
47. Carey, 2012; 2014.

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CHAPTER 31

Migration and Climate in World History

Franz Mauelshagen

31.1 Introduction

Historians of migration have worked out all kinds of economic and social models to better explain their subject. Chain migration, social capital, and family networks have been very much the focus recently, while climate has remained more or less absent.[1] "Environmental migration," "climate migration," and related concepts such as "environmental degradation" and "environmental destruction" are sometimes mentioned in typologies of migration, or else referred to in concluding remarks about the future of migration.[2] Beyond that, histories of migration occasionally mention harsh weather conditions and failed harvests. In some rare cases, studies refer to the Little Ice Age (LIA) to explain recurring "natural calamities" and "extended periods of malnutrition" that "caused short-term mass migrations and long-term population displacement."[3]

As has been the case with many themes in climate impact research, global warming and the continuing debate about its consequences have created demand for empirical studies on the relationship between climates and migrations. That demand has increased since the IPCC Working Group II, which assesses impacts, adaptation, and vulnerability, expanded their coverage of migration and the amount of scholarship on which they draw.[4] However, social scientists and historians have found it hard to apply concepts such as "climate migration" or "climate change migration." Many regard them as simply deterministic or reductionist. Indeed, they are sometimes used in simplistic ways. But the inability to capture the plurality of reasons and causes for migrations in a single word or attribute is by no means unique to "climate

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migration" and its variants. "Labor," "military," or "chain migration," as well as many other descriptive categories, could be questioned for the very same reason. The difference is that they have long been accepted in disciplinary traditions that neglect environmental and climatic factors. The "rise of the economic paradigm" in late nineteenth- and twentieth-century migration theory has also contributed to that neglect.[5] Even studies in "seasonal labor migration" have taken the meaning of seasonality for granted, most of the time ignoring its complex and diverse environmental patterns that depend on location and the ways in which people interact with the flora and fauna of their surroundings.

Understanding the web of connections between climate history and migration history is by no means an easy task—and by all means more important than a dispute over terminology. However, little of the relevant historiography has been written specifically to address climate migration. Not climate, but the global, has been the trend in the last two decades of migration research.[6] More recently, that perspective has reached out to the deep time of early migrations of our species, *Homo sapiens*.[7] This chapter applies both a global as well as deep-time perspective, but of course it needs to be selective. In selecting and presenting the material, gathered from different disciplines and periods, the emphasis will be on evidence, approaches, and conceptual problems. For this purpose, some case studies will be discussed more deeply than others.

31.2 Climatic Changes and the Peopling of the Earth

Throughout the past 100,000 years, as *H. sapiens* colonized the planet, environmental and climatic conditions changed frequently and often dramatically. During the late Pleistocene Epoch (*c*.2.6 mya–11,700 kya) and the transition to the Holocene, climate oscillated between colder "stadials" and warmer "interstadials" (see Chap. 15). For all but the past few thousand years, most humans have lived as hunter-gatherers. Migration is an essential part of hunter-gatherer lifestyles, in particular that of big-game hunters, and a way they adapt to their environments. However, hunter-gatherers have normally moved within a more or less defined territory. Hence, those migrations that exceeded the normal radius and ultimately resulted in the globalization of the human species call for an explanation. Long-term variation in climate played a crucial role in this development.

Progress in the field of human genetics over the last thirty years has largely confirmed the "Out of Africa" theory. Analyses of human DNA have allowed the distinction of haplogroups (that is, groups of common descent that can be arranged chronologically and mapped geographically). Almost all non-African groups can be traced back to a single African haplogroup.[8] However, multiple-dispersal models still compete with models preferring a single ancestral population.[9] Archeology is also open to both alternatives (see Fig. 31.1).

One or several groups of *H. sapiens* left Africa for the first time between 130 and 120 kya. They passed through the Sahara during a short warm and humid

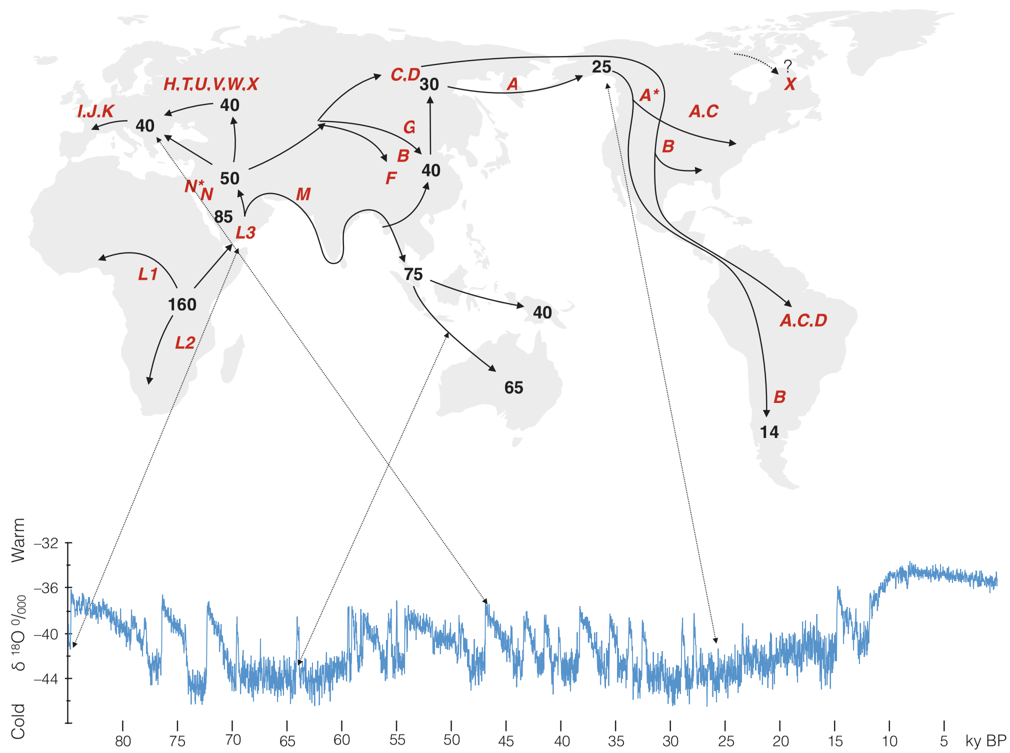

Fig. 31.1 A map of the peopling of the earth by *Homo sapiens sapiens*, showing major haplogroups of mitochondrial DNA (red letters), approximate dating for the peopling of specific continents or regions (black numbers), and geoclimatic clues (indicated by arrows).[10] Migration routes are geographically imprecise and cannot be attributed to identifiable groups of humans. Note that the silhouettes of the continental landmasses looked different from the present at many stages over the past 100 ky, because sea levels were up to 100 m lower than today when ice covered great parts of the Northern Hemisphere during stadial periods of the Pleistocene, e.g. 65 kya, 40 kya, and 25 kya. Geoclimatic clues are paralleled by a graph showing reconstructions of proportions of oxygen-18 ($\delta^{18}O$) per thousand in a Greenland ice core (GRIP) indicating warm and cold periods. The blue line is the data average values for every fifty years.[11]

Table 31.1 Evidence for *Homo sapiens* migrations out of Africa (several sources)[a]

Evidence	*Place/Mapping*	*Dating (kya)*
Archeological		
• *Homo sapiens fossils*	Skhul, Qafez (Israel)	*c.*100
• *Artifacts*	Eritrea's Red Sea Coast	125
• *Stone tools*	Kota Tampan (Malaysia)	>74
• *Liujiang Skull and partial skeleton*	Tongtianyan (China)	70–130
Genetic		
• *mtDNA*	Split between Africa and Asia	~70
• *Y-chromosome*	Split between Africa and Asia	~50
Geoclimatic		
• *Ice cores: temperature reconstructions*	Greenland (GISP2); Antarctica	125 and 85
• *Sediment cores indicating low sea levels*	Red Sea and Gulf of Aden	85
• *Eruption of Mt. Toba*	Sumatra	71–74

mtDNA = mitochondrial DNA; GISP 2 = Second Greenland Ice Sheet Project, which extracted ice cores of 3000 m in length

[a]Data compiled from Wells and Read, 2002; Oppenheimer, 2004; Burroughs, 2005 and the internet presentation "Journey of Mankind" (Bradshaw Foundation and Stephen Oppenheimer: http://www.bradshawfoundation.com/journey/). All dating contains some degree of imprecision (specific to dating methodologies), in particular where ranges are *not* indicated. Climate data from ice cores provide the highest temporal resolution and thus allow for greater dating precision if recombined with the other data in the table.

period and moved into the Levant (based on *H. sapiens* fossils in Skhul and Qafez—see Table 31.1). However, it is unclear whether these Levant migrants survived to contribute to later human populations. During the following cold period that occurred between 100 and 87 kya Neanderthals moved southwards from Eurasia into the Middle East. By that time the Levant line of *H. sapiens* had already died out or they had moved on. It is possible that they took a southern migration route to the Indian subcontinent. A "high-resolution portrait of genetic diversity" among Aboriginal populations of Australia "found that about 2% of genomes from individuals of Papua New Guinea ancestry indicate that their ancestors separated from Africans earlier than did other Eurasians."[12]

A second, more effective dispersal event took place from *c.*85 to 40 kya. This time, *H. sapiens* needed to look for a different exit from Africa, because the Sahara had turned back into desert. Genetic evidence provides a sequence for the subsequent separation of different human genealogies. First, there was the separation between African and Asian populations followed by that between populations in Asia and the Americas. After those two followed the schism between populations of the Middle East and Europe. The dating remains imprecise, but archeological evidence indicates that by around 70 kya *H. sapiens* had ventured as far as Malaysia and China and by around 65 kya had arrived in Australia. In multiple-dispersal models this could be related to earlier outmigration from Africa, while for single-ancestry models a *terminus ante quem* follows for the second exodus from Africa. Sinking sea levels due to glaciation provide a further geoclimatic clue. Ice cores indicate rapidly decreasing temperatures from 85 kya onwards. A group of *H. sapiens* crossing the narrow Bab-el-Mandeb strait across the Red Sea provides the most plausible scenario. As early as 125 kya humans had been settling on the coast of Eritrea, sustaining themselves partly on shellfish. Presumably, the early inhabitants of the seashore reacted to cold conditions by extending their territory.[13] Falling sea levels reduced the exchange of water masses between the Red Sea and the Indian Ocean in the Gulf of Aden leading to strong salinization and deterioration of plankton at the base of the marine food chain. Sediment analysis shows an all-time low of sea levels and of plankton in the Red Sea starting around 85 kya. Therefore, in a plausible scenario, the inhabitants of the Eritrean coast, perhaps under pressure from a shortage in seafood, crossed the Red Sea estuary to the Yemeni coast around that time.[14] Following their exit from Africa, populations continued to move along the shores of the Indian Ocean to India and then to Indonesia over a land bridge exposed by the lower sea levels during the last ice age.

Anatomically modern humans had already reached Borneo and South China *c.*74 kya, when Mount Toba (Indonesia) exploded in an eruption a hundred times greater than that of Tambora in 1815 (see Chap. 35). The ash spread north-west and covered India, parts of the Indian Ocean, the Bay of Bengal, and the South China Sea. Stratospheric aerosols from the eruption brought a six-year-long volcanic winter, and snow and ice covered much of the Northern Hemisphere. Some have argued that these changes in planetary albedo triggered the following stadial, which lasted approximately a thousand years. However, recent computer simulations have raised doubts about this "instant ice age" theory.[15] According to another theory, the Toba eruption drove most humans to extinction and created a genetic "bottleneck," or serious reduction of the human gene pool.[16] However, archeological excavations in Jwalapuram (southern India), where the deposit of ash is 2.55 m thick, demonstrate that humans lived there both before and after the Toba eruption, still using the same stone tools.[17] Clearly, the eruption's impact on the environment was enormous. Owing to sudden cooling and prolonged aridity, tree cover in India was reduced and replaced by savannah and grasslands.[18] These environmental changes must have posed serious challenges to humans, and we simply do not know what strategies they used to adapt and survive.

Homo sapiens migrated into Europe more than 40,000 years ago, supposedly from Anatolia, and soon replaced the Neanderthals.[19] These arrivals are identified with the Aurignacian culture (40–34 kya), famous for its cave paintings and animal figurines.[20] At the peak of the Last Glacial Maximum (LGM) *c.*25 kya, ice shelves extended from Scandinavia to the Baltic Sea Basin, while in Central Europe vegetation was changing from forests to steppe and ultimately to tundra. During the LGM Central Europe became largely depopulated. Humans had to retreat to other ecological niches.[21] Other migrations in the Northern Hemisphere are associated with the warmer climates of interstadials in the Late Pleistocene. Sea levels offer further clues that help clarify the first peopling of the Americas. There are ongoing debates about when people arrived in the Americas. However, it is undisputed that several movements of *H. sapiens* entered by way of Beringia, the land beneath the Bering Sea, which was exposed by the low temperatures and sea levels of the LGM.

31.3 Climate and Migration in Early Agrarian Societies

The transition to agriculture and permanent settlements created new vulnerabilities to climate variability. Paleolithic hunter-gatherers had probably lived in small groups of ten to thirty individuals, sometimes forming seasonally larger groups of up to 100 members. They had relatively egalitarian social structures and a high degree of flexibility in their lifestyles, and used a wide spectrum of food—a kind of insurance policy in hard times. Moreover, their populations were modest—perhaps never more than 10 million globally—and their mobility limited growth. Large-scale migration among hunter-gatherers was not a matter of short-term climatic variability, but of extensive long-term shifts in regional and global temperature and precipitation, which altered flora and fauna and the migration of large game.

In the warming climate of the early Holocene, some hunter-gatherer communities settled permanently in particularly fertile regions. In some cases, these permanent settlements led to the cultivation of domesticated crops and animals that humans came to depend on—in other words, agriculture. However, the transition was not smooth. The Natufian culture of the Middle East developed early forms of sedentism around 14 kya, but they had to revert to a nomadic lifestyle when colder and dryer conditions returned during the Younger Dryas (*c*.12.9–11.7kya).[22] Only after that cold intermezzo and the onset of Holocene warming did agriculture emerge again and become permanent in the so-called Fertile Crescent. The relative stability of Holocene climate certainly provided an important precondition for the spread of agricultural forms of life around the world, particularly to northern latitudes and to the ecological margins of higher altitudes (e.g., in the Andes).

Agriculture supported much larger populations, who spread from these early centers, replacing and eventually marginalizing hunter-gatherer lifeways almost everywhere. Yet agriculture generally exerted a novel kind of "gravity," drawing farmers to stay on the same land, rather than move away. Step by step, agrarian regimes redefined migration—and its general condition—as people became sedentary, sought protection against enemies, and built larger forms of society organized in states protecting their territory against intruders, both human and non-human. Sedentism defined the meaning of settlement and resettlement, and eventually borders—an idea born in agricultural societies. At the same time, agriculture led to new ways of interacting with the climate system (see Chap. 27). It meant that a long-term interaction between humans and local environments was established, and farmers became increasingly dependent on stable seasonal patterns of temperatures and precipitation.

In modern times, agriculture also marginalized mobile pastoralism. Historically, innumerable conflicts occurred between the two lifestyles, partly because they used conflicting strategies in adapting to climate fluctuations. Adapting their annual migratory routes according to weather conditions was a common practice among pastoralists, while farmers were much more bound to the soil. Increasing amounts of land claimed by farmers raised the potential for violent conflict between the two groups. A long-term statistical analysis found meaningful correlations among climate (temperature and precipitation), "nomadic (pastoral) migration," and conflict in Imperial China *c.*250 BCE–1950 CE, particularly between precipitation and the movements of pastoralists (see Chap. 29).[23]

Larger-scale migrations are sometimes related to climatic changes. A recent study of tree-ring chronologies from the Altai Mountains and European Alps has found a synchronous cooling of summer temperatures between 536 and 660 CE. The beginning of that period witnessed an unusual sequence of large volcanic eruptions in 536, 540, and 547. The authors propose the term Late Antique Little Ice Age (LALIA) for the entire period, and they suggest that several population movements—the arrival of the Avars in Pannonia, the Lombard invasion of Italy, the arrival of the Türks near the Black Sea—were related to this climatic event.[24] However, such ideas remain highly controversial (see Chap. 32).

One of the best known and most closely debated cases of climate and migration in agrarian societies concerns the US Southwest during the thirteenth century CE. The ancestors of the Pueblo nations of New Mexico and Arizona, popularly known as the Anasazi, left some of the most impressive remains of pre-Columbian cultures. These were their multistoried masonry dwellings, the so-called "Great Houses," at Chaco Canyon and elsewhere built during a period known as the "Pueblo II era" (*c.*900–1150 CE). The Anasazi had adopted maize agriculture during the early first millennium CE, and also grew squash and beans and bred turkeys. They learned how to manage water and created irrigation systems and a road network linking Chaco Canyon and peripheral villages, mainly for the purpose of wood and food supply.

Chaco Canyon was abandoned in around 1150 CE in the middle of a major drought that lasted from 1135 to 1180 and hit a population that had grown considerably in the preceding decades. Many migrants headed for Mesa Verde (Colorado) where they bunched together in cliff dwellings. However, after another megadrought that occurred between 1276 and 1299, the Anasazi also abandoned Mesa Verde and moved out of the Four Corners region. This final exodus from Chaco Canyon and Mesa Verde left behind the traces of violence.[25] Some researchers do not regard these traces as a consequence of famine and resource depletion, but as signs of social disruption independent of ecological circumstances. Since Andrew Ellicott Douglass (1867–1962), the father of dendrochronology, suggested that the late thirteenth-century drought had been the main reason behind the collapse of Anasazi culture there has always been controversy about the role of climatic fluctuations.[26]

Our knowledge of Anasazi settlements is based on archeology or analogy from present-day Puebloans and their agriculture. While tree rings provide precise dating for Anasazi buildings and records of past droughts, information on Anasazi diet and population size is often more indirect. Anthropologists have recently used computer simulations to model agricultural production based on recent information on production by modern-day Puebloan peoples. One of the earliest studies of this kind concluded that climatic fluctuations would not have had dangerous consequences for maize production; however, those results were disproven in later research.[27] For Mesa Verde, population estimates, simulations of maize production, and deer depletion suggest that Puebloans "experienced substantial subsistence stress." Combined with climate-induced immigration from other regions, which caused an increase in the local population and thus enhanced resource depletion, the picture of climatic and social push factors is as complete as it can be regarding the available evidence.

While dismissing monocausality, archeologist Larry Benson and others have maintained that "climate change including drought was a primary push factor in the reduction or migration of Anasazi populations during the middle-12th and late-13th centuries."[28] Coping strategies such as storage or a temporary return to hunting and gathering failed to bridge multiyear droughts. Thus, according to the present state of research it is very likely that the out-migration of the Ancestral Puebloans from the Four Corners Region occurred in the context of two megadroughts (1135–1180 and 1276–1299), resulting from a weakening or failure of summer "monsoon" rains in the American Southwest.[29]

Nevertheless, there is "no single, simple cause" but rather "a cascade of events" that led to the depopulation of the Four Corners Region in the late thirteenth century.[30] Jared Diamond has told the story of the abandonment of Anasazi settlements in Chaco Canyon as one of "rise and decline." A period of prosperity, emerging from favorable weather conditions, led to an expansion of the population and consumption of resources such as wood, water, and crops. During the eleventh and twelfth centuries, Chaco Canyon became the center of Anasazi culture, connected to a periphery from which it drew ever greater amounts of material resources. Thus, in Diamond's narrative, as social complexity increased the Anasazi left the path of sustainability and headed towards greater vulnerability. The megadroughts and successive bad harvests were "the last straw." It is at this point where Diamond's account diverges from Benson's and Kohler's. For Diamond, climate change was only the *proximate* cause of the collapse of Chacoan Anasazi culture, while the *ultimate* cause was resource depletion. Diamond identifies this pattern throughout his popular history, *Collapse*, to connect the history of societal collapse with the dangers of present global warming.[31] The end of Chaco Canyon points to the problem of path dependency in the development toward more complex social structures, blocking the way back to more efficient and flexible relationships with the environment.

However, Diamond's assumption that the Ancestral Puebloans could have persisted in Chaco Canyon had they only brought their own development to a halt is questionable. The idea that the simpler social structures are always more resilient to environmental crises overlooks that migration was a fundamental part of that resilience (as described above). Moreover, economic history research indicating that wider economic networks reduced the vulnerability of communities to famine might challenge Diamond's view.[32] Connecting markets and resources balances risk, providing a kind of insurance against the caprices of weather and their impacts on harvests.[33]

31.4 Little Ice Age (LIA) Climate Change and European Emigration to the Americas

Periods of continuous cold spells and drought, or an unusual frequency of such climatic conditions during a decade or two, posed serious challenges for agrarian cultures around the world. In many cases people responded to such challenges by moving, as we have seen from the case of Anasazi migrations. Assessing the "push" effects of climate on migration becomes much more challenging when considering periods of climate change lasting a century or more.

Some scholars have claimed that the LIA (see Chap. 23) "had a major impact on migration as agriculture failed in various parts of Europe."[34] Referring to the LIA and its impacts on early modern Europe, the German Advisory Council on Global Change has argued that "climate-induced deterioration in people's living conditions can also be said to have contributed indirectly to the large-scale migrations to the New World."[35] Historical research supporting that bold statement will be hard to find. There is no long-term trend of decline in early modern European economic history; rather a series of ups and downs from the early fourteenth century onwards and a clear upward trend in the eighteenth century, both in terms of population and production. The historiography on transatlantic migration has failed to seriously consider LIA climate change as a potential long-term cause that might have pushed Europeans to the other side of the Atlantic. Instead, European historians have preferred to integrate the story of transatlantic migration into more conventional narratives of poverty in early modern Europe. However, it is questionable whether the history of transatlantic migration can be grasped in purely economic terms, ignoring the vulnerability of agrarian civilizations to climate variability and agrometeorological risks.

Assessing the impact of LIA climate change on European emigration to the Americas requires a meaningful rearrangement of the available evidence. Several problems need to be addressed, starting with that of periodization and timing. The LIA in Europe was not simply one long period of cooling, but several multidecadal phases when unfavorable weather conditions were more common (Chap. 23). The LIA peaked during the first and last decades of the seventeenth century, when the transition to cash crop agriculture in the colonies was only just beginning. European subsistence crises probably only began to make an impact on transatlantic migration during the Late Maunder Minimum (1675–1715). By the time that the effect of short-term climate variability on migration to the Americas starts to become measurable, in the eighteenth century, the worst of the LIA had passed. After some early stagnation in the seventeenth and eighteenth centuries, when African slaves were by far the largest immigrant group, European transatlantic migration peaked only in the mid- to late nineteenth century, once railways and steamships provided the logistics for mass migration for much more rapidly growing industrial populations. Yet the cooling trend of the LIA was reversed after *c.*1860–70, as greenhouse gas emissions from the burning of coal began to influence global climate. More problems emerge with the quest for migration data. Prior to 1800, the statistics are either incomplete or simply missing. This does not necessarily mean that the search for causal links between LIA climate change and transatlantic migration is futile, but clearly there are no straightforward answers.

One obvious approach to solving the puzzle is to look for cumulative effects of climate-induced subsistence crises on emigration. The trajectory of Irish migration to North America in the eighteenth and nineteenth centuries could be exemplary in that it reveals striking coincidences between the peaks of Irish emigration (based on estimates) and climatic extremes in 1717–18, 1725–9, 1740–1, 1754–5, and 1771–5. Scotch Irish migration from Ulster was particularly significant in this context.[36] The "Ulster diaspora" in America had already formed during the seventeenth century. Ulster–American emigration reached an estimated total of 70,000 for the period 1680 to 1750, a figure that more than doubled between 1750 and 1820. The effects of the "great frost" in 1740–1 were particularly severe.

Nevertheless, Irish emigration to North America must be seen in the wider context of population movements preceding or following these famine years. Internal migration predominated, especially people moving away from the countryside hoping to find labor and food in nearby towns or cities. Those who departed from Ireland altogether before the nineteenth century came disproportionately from the Scotch-Irish, Protestant, and Presbyterian minorities. Many headed for the New England colonies and Pennsylvania, which had trade connections with Ireland. Philadelphia became one of the main destinations of chain migration following the 1740–1 famine, as migrants followed the paths of relatives and friends who had already left Ireland in 1728–9. A great proportion of migrants from southern Ireland headed for the Delaware Valley.[37]

There is a further problem relating particular subsistence crises and subsequent migration to the LIA. Subsistence crises are often connected with seasonal variability, or even more short-term extremes or hazards, rather than climatic trends and anomalies of years or decades, much less centuries. Claims of climate-induced migration require appropriate temporal and spatial resolutions, on the regional or local level. Statistical downscaling, based on existing climate datasets of past centuries, rarely leads to reliable correlations for premodern eras.

Large volcanic eruptions, which produce impacts on a hemispheric or global scale, could provide a way around some of these problems. Assessing the impacts volcanic eruptions have on societies, indirectly through their effects on the climate system, still requires data responding to the regional or local level. But their climatic impacts, through injections of sulfate aerosol into the stratosphere, are not in doubt; nor is their role in producing some of the coldest periods of the LIA, in conjunction with orbital and solar forcing and internal climate variability (see Fig. 31.2).[38] Volcanic forcing has become an essential part in the story of the LIA, which makes it easier to link the (often global) anomalies caused by major eruptions with longer-term trends (see Chap. 23).

In that sense, the Dalton Minimum (*c*.1790–1830) is one of the most promising periods for the study of climate and migration. This period brought lowered solar activity as well as several major volcanic eruptions: Lakagígar in 1783 (see Chap. 34), the unnamed eruption of 1809, and Tambora in 1815 (see Chap. 35). A strong La Niña event in 1788–90 followed by a severe El Niño in 1791–3 added to the mix of forcings (see Chap. 34). Estimates are available for migration from various places of origin to North America between 1783 and 1820 (see Fig. 31.3), and these estimates show peaks that correlate well with the three major volcanic eruptions and El Niño Southern Oscillation (ENSO) events above. Yet certainly the French Revolutionary Wars (1792–1802) and, even more so, the Napoleonic Wars (1803–15) contributed to the crises, while the Continental Blockade between 1806 and 1811 hampered emigration from Europe to America.

The 1815 eruption of Mt. Tambora on Sumbawa (Indonesia) and the following "year without a summer" has been a model case since John D. Post published his 1977 book *The Last Great Subsistence Crisis in the Western World*.[40] Not only did volcanic aerosols dim incoming solar radiation and cool global temperatures, but they also caused various feedbacks in the climate system (see Chap. 35). Throughout the summer of 1816, Western and Central Europe suffered anomalous cold and damp conditions. Frosts affected harvests in many places. Figures for Switzerland and Württemberg (southern Germany) prove that transatlantic migration increased strongly in 1816/17—obviously a direct consequence of the agricultural crisis during those years.[41] South-west German emigrants mainly came from peasant or artisan populations, which suffered most directly from the crop failure. In addition to North America, this group also migrated in substantial numbers to Poland and Prussia. When interrogated, many of them mentioned the scarcity of food as their motive.[42]

Migration in 1816–18 also had a larger demographic and economic context. Marked population growth during the late eighteenth century had contributed to the precarious food situation, as had the practice of partible inheritance (the parceling out of estates among heirs) in most of continental Europe. Additionally, the end of the Napoleonic Wars (1803–15) flooded labor markets with demobilized soldiers.[43] On the whole, we are dealing with an ensemble of social and climatic push factors for migration. Nevertheless, these factors alone do not sufficiently explain the migration movements of these years. The worst subsistence crises of past centuries in Central Europe—1570–3, the early 1690s, and 1770–3—had left populations in similar circumstance. Yet potential

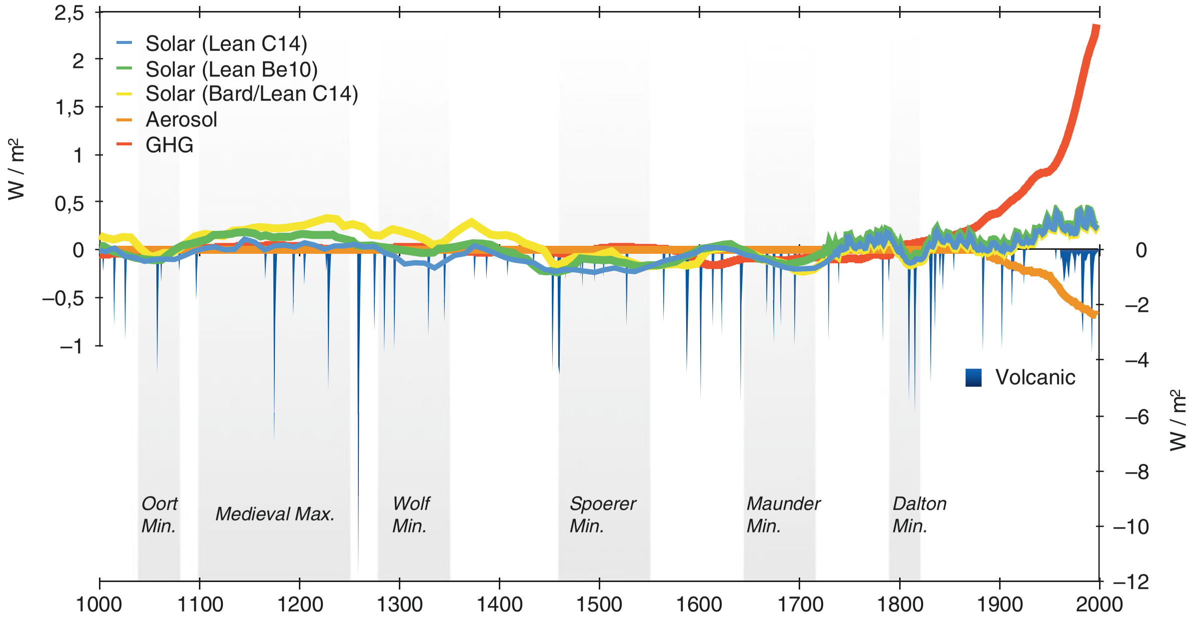

Fig. 31.2 Radiative forcing, 1000–2000 CE, plotted based on data by Crowley, 2000: several reconstructions for solar forcing, greenhouse gases (CO_2), aerosols, and volcanic forcing. Note that scale for volcanic forcing is different from that used for other forcings.

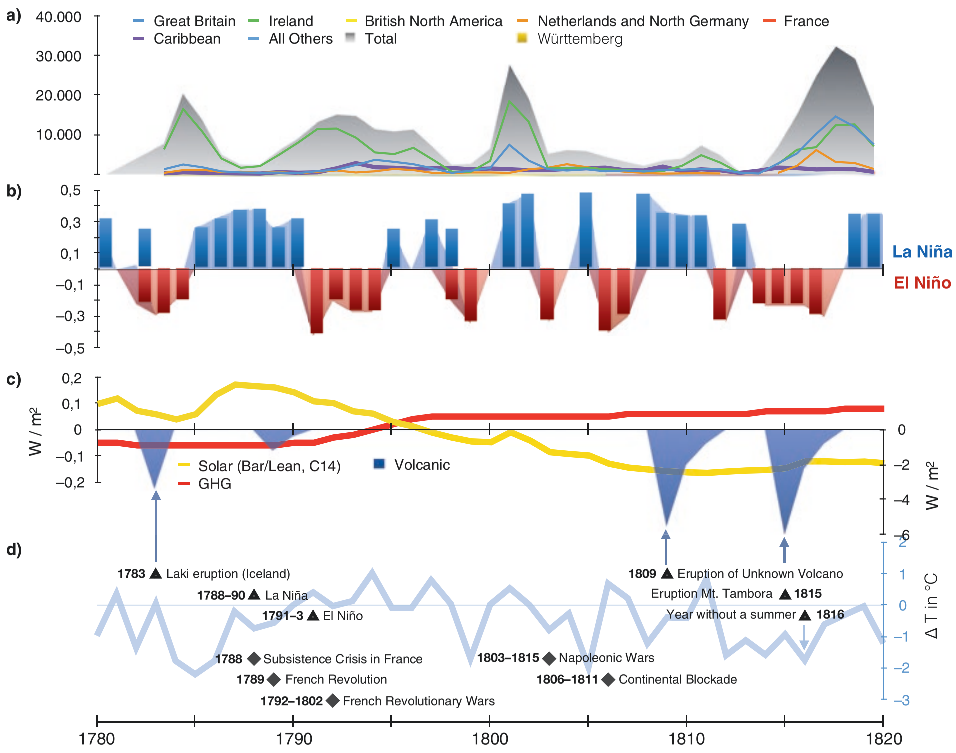

Fig. 31.3 Migration and LIA Climate, 1780–1820: **(a)** Immigration to the United States, 1783–1820, by place of origin (estimates by Grabbe, 2001: 93); **(b)** ENSO reconstruction, 1780–1820: the graph plots the minimum quality adjusted magnitude score attributed to each El Niño or La Niña event by Gergis and Fowler, 2009: Table 9; **(c)** Global Radiative Forcing, 1780–1820, extracted from Fig. 31.2: solar forcing shows the transition to the Dalton Minimum in around 1790. Note that the volcanic forcing for the 1783 Lakagígar eruption was much more significant in the Northern Hemisphere than shown in this graph; **(d)** Timeline of events mentioned in the text, 1780–1820, including volcanic eruptions, ENSO, and historical events, with annual temperature anomalies from 1960–90 averages for Central Europe in the background.[39]

migrants had not had the option of making the long journey overseas. What happened in 1816–18 must be seen in the context of the new organization and momentum in transatlantic migration that had grown up since the late eighteenth century. In addition, farmers were legally granted increasing mobility during this period in many parts of Europe; and last but not least, the attraction of the "New World" had grown over the preceding centuries, creating a strong and persistent pull factor.

31.5 Acclimatization, Forced (Labor) Migration, and Resettlement

Not only climatic events, but also *ideas* about climate shaped transatlantic migration during the colonial period and into the nineteenth century. Europeans were influenced in their decisions about migration by notions of what new climates they would find in the New World and what those climates meant for them. Experiences of unfamiliar environments and concerns about "unhealthy climates," particularly with regard to warm and humid atmospheric conditions in the tropics, led colonists to compel others, particularly Black Africans, to migrate in their place.

Until the late nineteenth century, most migration to the Americas came as forced labor. The transatlantic slave trade was "the largest long-distance coerced movement of people in history."[44] By the early nineteenth century, about four times as many Africans as Europeans had traversed the Atlantic. The Spanish and the Portuguese started the slave trade shortly after reaching the New World. The slaves were sent from Portugal and the Atlantic islands, where African slaves had been taken during the fifteenth century. The first known voyage directly from Africa to the Americas was in 1526. Before 1550 slave ships went to the Spanish Caribbean to sell Africans as forced labor on gold mines, especially on the island of Hispaniola. After 1560, sugar began driving slave traffic to Brazil. Responding to growing demand from Europe, plantation slavery expanded to the eastern Caribbean in the early 1640s and then further westward into the tropical and subtropical regions of North America. Altogether, sugar plantations absorbed more than two-thirds of African slaves.

Initially, Spaniards and Portuguese had coerced Amerindians into working for them on plantations. But indigenous populations declined dramatically during the sixteenth century, as they fell victim to epidemics or violence. European immigration never came anywhere near to meeting the labor demands of colonizers. Only in the mid-nineteenth century did mass migration from Europe overtake the slave trade from Africa. The logistics of that trade, however, depended on intra-African practices of enslavement and traders such as the Vili (north of the Congo), the Efik (in the Bight of Biafra), or the Kingdom of Dahomey willing to sell slaves to European ship captains. The greatest number of slaves were taken from West and Central Africa. Portugal and Spain dominated the trade at first, before British imperial power expanded into the Caribbean and North America. British embarkations outnumbered all others by the end of the eighteenth century. But the end of the slave trade dawned early in the nineteenth century, when Danish legislation declared it illegal in 1802, soon followed by Britain and the United States. The institution of slavery continued to be legal in the US until the thirteenth amendment to the US Constitution in 1865, and it took another twenty-three years before emancipation in Brazil—by far the greatest recipient of African slaves—finally brought the transatlantic slave trade to a halt.

The climate system of the Atlantic, particularly wind directions and ocean currents, had a strong influence on the routes taken by slave voyages in the age of sail. It also shaped the seasonality of the slave trade, which for a long time was assumed to come from the demand for workers in the colonies to harvest cash crops. Recently, however, Stephen D. Behrendt has shown that the seasonal character of the slave trade was defined by both sides of the Atlantic and was therefore coupled with a much more complex ecology of plant growth. The travels of slave vessels required as much coordination with the growing seasons of crops and the demand for labor on the African coast as with the colonies.[45]

The predominance of forced labor migration was highest in tropical and subtropical colonies, where European settlers experienced high death rates from tropical diseases such as yellow fever.[46] Prevailing medical theories in Europe attributed the suffering of white settlers to tropical climates, which hosted supposedly "noxious exhalations."[47] Northern Europeans in particular found climatic conditions very different from those of their home country, and very different from their expectations (see Chap. 37). "People came to America inadequately prepared, physically and psychologically, to cope with the environment they actually encountered."[48] Their experience of unfamiliar climates in the colonies was sometimes biased by unusual extremes—unusual that is by the standards of modern historical climatology. Such extremes caused hardship for most of the first settlements in North America, as well as Australia (see Chaps. 24 and 34).[49]

Settler experiences of such unfamiliar environments generated a far-reaching discourse about climate, both in the colonies and in Europe. These experiences were expressed in pamphlets, travel narratives, and letters sent back to family members who had stayed in Europe. Emigrants began to consider weather conditions and climates in their choices of destination. Promotional publications for the colonies included often idealized descriptions of climate, temperatures, and the annual cycle of seasons, while playing down the dangers of potential hazards such as hurricanes—a practice that continued well into the twentieth century. Moreover, the discourse about climate and weather also included a (transatlantic) exchange of experiences about the success and failure of plants and livestock.[50]

This discourse often circled around the idea of "acclimatization." In France the term *acclimater* (to acclimatize) was used in medical, agricultural, and zoological discourses on colonizing the tropical West Indies. By 1798, the verb had found entry into the *Dictionnaire de l'Académie Française* where it was defined as "to get accustomed to the temperature of a new climate."[51] Early Spanish and English discussion of colonization had introduced the notion of a "seasoning," or adjustment necessary for Europeans to survive New World climates and diets.[52] In France and Britain, throughout the eighteenth and the nineteenth centuries, the theory of acclimatization developed into a science that included transplanting humans, plants, and animals into different climates. "Faith in the malleability of animal and plant form and function typified the French approach to acclimatization, and helps explain why the French attempted to introduce everything from ostriches to yaks and llamas both in their own country and in its dependencies." Acclimatization only lost its appeal after the diffusion of Louis Pasteur's germ theory in the second half of the nineteenth century and progress in parasitological research on tropical diseases.[53]

Climate also played a role in debates about slavery and abolition during the nineteenth century. Based on the alleged impossibility of "white" adaptation to tropical climates, pro-slavery activists in the USA and elsewhere argued that "blacks" and other "non-whites" were better adapted to perform the hard physical labor required to maintain sugar, indigo, or tobacco plantations. Caribbean slave societies also became deeply involved in discourses on acclimatization. For example, Robert Renny, an early historian of Jamaica, declared the entire institution of slavery "even to be natural, to the inhabitants of warm climates."[54]

The idea of pre-adaptation to tropical climates also had some uncomfortable implications for European colonizers themselves, such as the question of whether adaptation to colonial climates would alter their bodies or characters. Misleading reports about the flora and fauna of North America and the shrinking of plants and animals brought into the colonies led the French natural historian Comte de Buffon to conclude that colonists would suffer the same degeneration, as historian Antonello Gerbi has discussed. American diplomats and intellectuals (including Thomas Jefferson and Benjamin Franklin) tried to refute these ideas in their writings during the late eighteenth and early nineteenth centuries.[55]

Ideas about climate and acclimatization influenced colonial population policies beyond the slave trade. Reflecting about a "downriver" extension of their colony in New Orleans in around 1750, French officials hoped to recruit settlers "from the frontiers of Italy and Spain […] because of the similarity of the climate." They also intended to accelerate the peopling of that area by "ordering the passage of two to three-hundred families with their slaves from Martinique [another French colony, in the Caribbean] who are too crowded there. Being accustomed to the hot climate and to the crops of the land they would provide the best means to the other inhabitants to till part of the soil."[56]

But there were many other ways of turning climate into an argument, depending on perspective. After battling down the Trelawny Maroon rebellion in Jamaica, the British deported several hundred Jamaican Maroons to Nova Scotia in the summer of 1796. Settled in Preston, two miles away from Halifax and from the white population of Nova Scotia, the Maroons started petitioning for their removal to a warmer climate almost instantly when temperatures dropped in the following autumn; and they continued petitioning after the harsh winter of 1796–7 that they be allowed to go to a province "more congenial to people of their complexion."[57] In response, Nova Scotia's governor John Wentworth (1737–1820) argued that living in a temperate climate might actually cool the Maroons' "fiery disposition" and help their moral improvement.[58] In the end, the governor's efforts to hang on to the Trelawny Maroons were in vain, as he met with resistance from other British officials and the white population of Nova Scotia. In 1800, only a few years after their arrival in Nova Scotia, the Jamaican Maroons were resettled in Sierra Leone.

Though merely a brief episode, the case of the "Maroons of Nova Scotia" is instructive for two reasons: first, as an example of how discourses about adaptation to a new climate became involved in acts of banishment, a type of forced migration that was rather frequent in the early Atlantic world; and second, as one of the early precedents to later debates on how African Americans would acclimatize to the North when they moved there from the rural South, mostly to the urban centers of the USA, during the Great Migration in the twentieth century.[59]

31.6 Global Warming, Displacement, and Climate Refugees

Industrialization during the nineteenth century brought a transition in global demography, migration patterns, and climate. Populations began to urbanize more than ever and labor migration was dissociated from the primary economic sector, agriculture.[60] The industrialization of agriculture increased food production and made European and North American populations gradually less vulnerable to crop failures. From the mid-nineteenth century onwards, steamships and railways led to integrated commodity markets, bringing cheaper American and Australian foodstuffs to the world, and evening out local and short-term price fluctuations.[61] What one economist has called "Europe's escape from hunger and premature death" supported an unprecedented and sustained growth in European populations, despite emigration overseas.[62]

This escape from the "Malthusian trap" does not mean, however, that climate no longer played a role in migration.[63] Rather it shifted the relationships among climate, weather, and population movements. Even as populations became less vulnerable to subsistence crises, many remained as vulnerable as ever to climate-related disasters, the loss of agricultural livelihoods, or food entitlement deficits when local markets broke down. The shift to global warming, starting in the late nineteenth century, and its acceleration since the 1990s has returned attention to these problems (see Chap. 27).

In fact, global warming has raised concerns about environmental mass migration, which many expect to become a permanent global reality in the twenty-first century.[64] In the wider framework of the United Nations, environmental or climate migration usually surfaces as a humanitarian problem. Population movements are expected to come overwhelmingly from developing countries, which are considered most vulnerable to climate change. One of the reasons for this assessment is their continued reliance on agriculture for employment and income. The wealth of developed countries is expected to make them more resilient to the impacts of global warming.

In other contexts, climate change and migration come up as a security issue. Anthropogenic global warming could generate resource conflicts, which might further exacerbate international migration through feedbacks on people's decisions to move away from their home countries (see Chap. 29). Climate migration scenarios often treat environmental migration as a security problem, particularly for the wealthy and highly industrialized countries of Europe and North America—also among the greatest per capita emitters of greenhouse gases (GHGs).[65]

The international framework of the debate on global warming has created a focus on *out*-migration (or *e*migration, in contrast to *im*migration) and to what degree it is forced. Discussions about the status of migrants in international law, and whether they constitute "climate refugees" with a right to asylum, have been intense and controversial.[66] In the international arena, a sharp line has been drawn between states sharing responsibility for causing anthropogenic climate change, the main per capita emitters of GHGs, and the "victims" of changing climatic extremes and hazards. The main push for climate migration is expected to come from (1) climate-induced gradual environmental changes leading to a shortage in resources, particularly land and water, and to droughts with the possible consequence of famines; (2) rapid environmental changes triggered by meteorological or climatic hazards; (3) flooding of low-level landmasses and the submergence of islands owing to rising sea levels.

Some historical examples for the first pattern have been discussed in the previous sections of this chapter. The other two, meteorological and climatological hazards and the comparatively slow rise of sea levels, often work together. Landmasses are threatened by the complex interplay of melting polar ice, oceanic heat dilution, erosion and subsidence, and natural hazards, operating on different timescales. Global warming poses direct threats to the national sovereignty and territorial integrity of island states.[67] Many islands in the Indian Ocean and South Pacific are elevated only a few meters above sea level and are no more than a few hundred meters wide. The adaptive options of those "sinking islands" are very limited.[68] The consequences of sea level rise are already affecting the livelihoods of many islanders as salt water contaminates soils and groundwater. The bleaching of coral reefs is reducing fish stocks. Tropical cyclones (typhoons), which are expected to become more severe with more energy feeding the interaction between warming ocean surfaces and a warming atmosphere, accelerate erosion. Seven million people live in the twenty-two island states of the South Pacific, including Tuvalu, Kiribati, Vanuatu, and the Solomon Islands. Leaving their homes may be the only foreseeable option for those people, their children, and grandchildren. An Alliance of Small Island

States (AOSIS) was founded in 1990, and negotiations about resettling the populations of sinking islands have already been initiated, particularly in the framework of the United Nations.

Climate trends and projections of temperature and precipitation changes show that the industrial countries of the South Asian Pacific will also be seriously affected by global warming. In fact, after Queensland (Australia) experienced flash flooding in 2011, the township of Grantham became the focus of a community resettlement project.[69] Nevertheless, countries such as Australia and New Zealand are not threatened as a whole by rising sea levels and are considered to possess the adaptive capacity to handle the risks of climate change. In the geography of global warming in the South Pacific they are also expected to become destinations for climate migrants and the resettlement of islanders. Their policies have been dominated by a “wait and see” approach, which contrasts sharply with spectacular campaigns such as the government of Tuvalu’s underwater meeting in 2009.[70]

The Bay of Bengal will become a future hotspot of climate migration with an estimated half-billion people exposed to a variety of environmental problems, both enhanced by climate change and enhancing its effects.[71] Sunil S. Amrith has argued convincingly that projected climate change migration should be seen in the context of the Bay of Bengal’s history: driven by British imperialism in Asia it became “home to one of the world’s great migrations.” An estimated 28 million people crossed the Bay in both directions between 1840 and 1940.[72] Many migrant workers were exploited in land clearances on the South-East Asian forest frontier for the cultivation of rice in Burma, tea in Ceylon, and rubber in Malaya; these clearances brought major environmental changes.[73] The demise of the British Empire after World War II turned most of the inhabitants of the Bay into citizens of independent nations, which came at the price of free movement in the region. Rapid growth and concentration of populations in urban centers around the Bay of Bengal, industrialization, and the damning of rivers brought a new generation of environmental problems. As in other great river deltas around the world, the coasts have been destabilized. Relative sea level rise is influenced four times more by the sinking of the land than the rising of waters, making the coasts more vulnerable than ever to rapid erosion from cyclones. The Bay of Bengal also has its sinking islands, such as Ghoramara, located 150 km south of Kolkata in the Sunderban delta. More trouble for the region is expected to come from a more erratic Asian monsoon, more frequent droughts, and flooding.

Natural hazards usually affect great numbers of people: 4.4 million experienced the destruction of the “millennium flood” in West Bengal (India).[74] When Cyclone Nargis hit the coast of Burma in May 2008, 85,000 people were killed and 2 million displaced. “In one sense, climate-induced migration is nothing new, as each year millions of people in Asia flee their homes to escape flooding. Most of the time, however, these are temporary and short-distance moves. The crisis will come if coastal regions have to be abandoned permanently.”[75] It is expected to hit the low-lying lands of Bangladesh first.[76]

"The stark image of poor people forced from their homes by floods or by sinking habitations haunt the imagery of climate change in the wealthy world," writes Sunil S. Amrith. There is a colonial tradition of seeing Asian migrants as refugees from the misfortunes brought by climate. Severe El Niños in the 1870s and 1890s brought harvest scarcity and famine, particularly in India. Both crises produced additional migration to Burma, Malaya, and Ceylon. British officials and rubber planters took advantage of the surplus of workers and justified "indenture abroad as preferable to starvation at home."[77] British colonial administrators treated South Indian emigrants as refugees from the monsoon, overlooking or denying that emigration was still a choice made feasible by circumstances such as family contacts abroad or the availability of credit. Their perception matched what the anthropologist August A. Grote termed *primitive migration*—a type of migration "influenced solely by physical causes affecting man's existence." Writing in 1877, Grote hypothesized that primitive migration had occurred most frequently in "man's" early history "when he was unprovided with means of his own invention against unfriendly changes in his surroundings."[78] Roland B. Dixon used the term in his migration article in the *Encyclopedia of Social Sciences*, and through William Petersen's influential typology of migration it entered many textbooks on the sociology of migration, and works of demography, ethnography, and other subjects.[79]

In traditional typologies of migration, "primitive migration" is definitely the oldest, perhaps the only, conceptual precursor of what is presently termed "environmental" or "climate migration."[80] There is little awareness about this prequel, but it should give us a lot to think about. Both concepts consider climate or the environment as only a push factor in people's movements.[81] In the absence of adaptive capacity—thought to depend mostly on wealth and technologies to control the forces of nature—the environmental push may become coercive: hence the ideas of "climate" or "environmental refugees."[82] In much of the ongoing debate, "climate change migration" has become synonymous with "forced migration." That, however, risks overlooking that emigration is still a choice, at least most of the time, and depends on a variety of circumstances that allow people to make that choice: for example, social networks they can tap into at their destinations, the financial capacity to travel, or the expectation of obstacles connected with migrating abroad. Attachment to place may originate from family or friendship ties, immobile private property, or other local resources—factors that may exert a certain "gravity" to stay in place.[83] Closed state borders and legal definitions of citizenship also hamper people's movements in the twenty-first century. There is a long history underlying that pattern, but it is not a historical constant.

Underlying the concept of "primitive migration" was the assumption that technologically more advanced societies are better protected against "natural" calamities and the fluctuations of climate. The risk geographies of climate change migration today often seem to follow the same assumption. United Nations policies of adaptation to global climate change are largely based on assessments of technology, financial, and knowledge capital. By these standards, Western industrialized countries are obviously better armed against the consequences of climate change than non-industrialized nations. It is hardly surprising that developing countries are regarded as places where climatic changes are expected to cause major societal instability, perhaps violent conflicts ("climate wars"), but almost certainly mass migration.

It is altogether striking to see the degree to which risk geographies of global warming resemble colonial risk geographies of past centuries.[84] That does not mean that they are to be dismissed altogether, but they could be misleading in that they underrate the resilience of people living in developing countries and overrate that of people living in the developed world. The forced displacement among New Orleans citizens after Hurricane Katrina in 2005 has become a seminal example in this context. Many thousands of citizens who evacuated their homes with plans of a quick return remained displaced after the storm. Unexpectedly, many never returned to live in New Orleans.[85] Similar kinds of post-disaster mobility from metropolitan regions have occurred repeatedly in the USA, as well as in many other countries, often in relation to river floods or other types of flooding caused by storms.[86] Yet the wider public in the West never seems to perceive the domestic victims of meteorological or climatological disasters as environmental migrants or climate refugees.

31.7 Conclusions

The issue of climate-driven migration calls into question the Durkheimian consensus of the social sciences to prioritize social explanations for social phenomena over environmental ones. Climate migration deserves recognition as a research perspective just as much as other generally accepted types of migration such as labor migration or "chain migration," which acknowledges the relevance of family and other ties among people (social capital). Without claiming exclusivity, the concept of climate migration acknowledges the relevance of people's economic *and cultural* interactions with their environment. Without that cultural context, there is the danger of deterministic or reductionist explanations.

Present debates on the impacts of global warming have favored an analytical perspective regarding climate merely as a push factor forcing mass emigration. That perspective has emerged from national security concerns in Western countries fearful of prospective "climate refugees." However, reducing climate to a push factor is too narrow, if not inadequate; and so is the idea that climate migration is forced practically by default. Geographies of future climate change migration have a tendency to resemble imperial risk geographies, merely replacing a bipolar world of metropole and colonies with one divided between developed and less-developed countries. Historians have a capacity to unravel that resemblance and question assumptions underlying mainstream discourse on climate migration and refugees, one being that industrial societies are less vulnerable and less exposed to the threats of climate change. Historians are well advised to apply approaches open enough to allow them to explore the entire variety of human–climate interactions relevant to understanding migration. It is probably from that standpoint that they can make the most valuable contribution to current discussions.

The examples discussed in this chapter are far from comprehensive, but they illustrate the multidimensionality and variety in patterns of migration and their entanglement with climate variability and climate change. On the one hand, whether people have been aware of it or not, the variability of the climate system has interfered with people's movements in one way or another. On the other hand, climate has also been meaningful as a cultural construct—often an ideologically charged one—a dimension that should not be ignored.[87]

The following typology summarizes the range of climate–migration relationships, along both a temporal scale, and the range of physical and cultural connections:

1. *Climatic or hydro-meteorological hazards (various examples)*. Climatic and meteorological disasters have caused displacement in countless cases. People affected by rapid-onset disasters may be left with little choice but to move out of harm's way. Displacement occurs as precautionary evacuation (where early-warning systems are available) or soon after the event. Displacement often becomes permanent, because post-disaster hazards delay return until the displaced have built a new life in another place.
2. *Monthly, seasonal, or annual variability and extremes (Anasazi and other migrations)*. Weather extremes (hailstorms, unseasonable frosts, etc.) or temperature and precipitation anomalies may lead to harvest failures followed by a decline in food availability. In particular, failures of several harvests in a row create stresses on agrarian populations. Complex relations between climate and culture, including cultural practices of food production and coping strategies, mediate between climatic variability and decisions about migration.
3. *Seasonal (labor) migration*. Harvest seasons vary greatly from region to region and crop to crop, creating opportunities for labor migration. Historians of migration have reconstructed several regional labor migration systems worldwide.[88] Many of them were circular, meaning that migrants returned home. Delays in harvests or declines in agricultural production often reduced the demand for labor, making labor migration sensitive to climatic fluctuations during growing seasons. Failures or delays of the harvest created disturbances in the system to which laborers needed to adapt in order to make a living. Future studies might find out in what way. The transatlantic slave trade depended on harvest seasons on both sides of the Atlantic, and the role of climatic variability in this context also merits further study.
4. *Climate change and migration on decadal to centennial scales: cumulative effects*. Assessing the effects of climate change on decadal to centennial scales poses tricky questions of data availability and methodology. Correlations between climate data and migration data may be helpful, as

they might indicate statistical significance; however, correlation alone is never enough to make an argument. It is generally more promising to analyze climate–migration relationships through single events and then to assess the long-term effects mostly qualitatively. Methodological problems of attributing single push events to more long-term climatic changes, however, make it advisable to distinguish between "climate migration" and "climate change migration."

5. *Pleistocene climate change on millennial scales and the peopling of Earth.* Alternation between stadials and interstadials created many opportunities for, and limitations on, migration during the long history of the peopling of Earth. Pleistocene migrations of anatomically modern humans are almost impossible to reconstruct in detail. Nevertheless, genetic, archeological, linguistic, and paleoclimatic evidence allows conclusions about its chronology.
6. *Climate as an argument*: Climate became a standard part of the argument justifying enslavement of indigenous American peoples, forced-labor migration from Africa, and colonial settlement or resettlement. Thus in the geopolitical realm of colonialism, deterministic ideas about climate exerted power over people and their movements. Climate ideas also influenced free choices of destination, as was the case in the settlement of California and the North American Sunbelt during the nineteenth and twentieth centuries.[89]

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Notes

1. Culver, 2012, 131, diagnosed an "absence of climate from migration history."
2. Harzig et al., 2009, 6–7, 134–37; Oltmer, 2012, 120–22; Bade et al., 2011, xxv; Oltmer, 2017, 218–23.
3. Hoerder, 2002, 169, on seventeenth-century China.
4. See McLeman, 2014, 54–56, for a survey on IPCC reports. While the first report in 1990 "did not draw on any scholarly research about migration," later reports improved little by little.
5. Piguet, 2011, 3.
6. Hoerder, 2002; McKeown, 2004; Hatton and Williamson, 2005; Lucassen and Gerardus, 2006; Lucassen, 2007.
7. Manning, 2005, Chaps. 2–4; Lucassen et al., 2010; also Earle et al., 2011.
8. The methodology of tracing early migrations by means of population genetics is best explained by Knijff, 2010. For mtDNA analyses see Cann et al., 1987; Vigilant et al., 1991; Ingman et al., 2000; Oppenheimer, 2004; for y-chromosome analyses see Underhill et al., 2000; Wells and Read, 2002; Burroughs, 2005,

8–10 gives a short survey. Some principal drawbacks are pointed out by Manning, 2005, 23.

9. See the most recent genomic histories of Aboriginal Australia and the peopling of Eurasia by Malaspinas et al., 2016, and Pagani et al., 2016, as well as the summary of their results by Tucci and Akey, 2016.
10. This map is a compilation of similar representations of prehistoric migrations from various sources (Burroughs, 2005, 12, 107; "Journey of Mankind": http://www.bradshawfoundation.com/journey/).
11. Data archived at Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen (http://www.iceandclimate.nbi.ku.dk/data/; last accessed on April 30, 2016). Reference study: Johnsen et al., 2001.
12. Tucci and Akey, 2016, 179; cf. Malaspinas et al., 2016.
13. Marean et al., 2007; McBrearty and Stringer, 2007.
14. Fernandes et al., 2006.
15. Robock et al., 2009.
16. Ambrose, 1998.
17. Petraglia et al., 2007.
18. Williams et al., 2009.
19. Burroughs, 2005, 144.
20. Sirocko, 2010, 71–76.
21. Sirocko, 2010, 77–82.
22. Mithen, 2003, 29–55.
23. Pei and Zhang, 2014. The study does not deal with migration of the farming population.
24. Büntgen et al., 2016.
25. Gibbons, 1997; Diamond, 2005.
26. Benson et al., 2007a, 2007b.
27. van West, 1994; Benson et al., 2007a, 2007b; Kohler et al., 2008.
28. Benson et al., 2007a, 189.
29. Benson et al., 2007a; Kloor, 2007.
30. Kohler et al., 2008, 153.
31. Diamond, 2005, 156.
32. Persson, 1999.
33. Schelberg, 2001 has made this argument in the Anasazi case.
34. O'Neill et al., 2001, p. VIII.
35. German Advisory Council, 2008.
36. Engler and Werner, 2015.
37. Engler et al., 2013.
38. Wanner et al., 2008, 1802–03.
39. Dobrovolný et al., 2010.
40. Post, 1977.
41. Ritzmann-Blickenstorfer, 1997, 49, 125; Hippel, 1984, 175.
42. Moltmann, 1979; for a survey on migration after Tambora see Behringer, 2015, 172–91.
43. Oppenheimer, 2003, 253.
44. David Eltis in his introductory essay to Eltis et al., 2016, online http://www.slavevoyages.org/assessment/essays#. See also Eltis and Richardson, 2010 and Rawley and Behrendt, 2005 for excellent accounts of the history of the slave trade.

45. Behrendt, 2009, 45, refers to Davis, 1962, 279–5 and 294, as well as to Galenson, 1986, 33–37. For the meaning of seasonality for work routines on British Atlantic plantations see Roberts, 2013, Chaps. 2 and 4.
46. Curtin, 1989; McNeill, 2010.
47. Rushton, 2014, Chap. 7, 184–219, 230–31.
48. Kupperman, 1982, 1277.
49. Kupperman, 2007; White, 2015; Gergis et al., 2010.
50. Livingstone, 1999.
51. Académie Française, 1798: "ACCLIMATER. v. a. Accoutumer à la température d'un nouveau climat."
52. Earle, 2012.
53. Osborne, 2000, 139–40.
54. Renny, 1807, 161.
55. Gerbi, 1973, Chaps. 1–4; also Gerbi, 1985.
56. *Mémoire pour servir à l'etablissement de la Louisiane*, Archives nationales d'outremer: C13C1, fol. 9. I owe this example and the reference to Eleonora Rohland.
57. Maroon address to W.D. Quarrell (Esq.), in Campbell, 1990, 53–54.
58. Zilberstein, 2008, 230–31.
59. Morgan and Rushton, 2013, see 118 on the case of the Maroons, and 173 on the general problem of unfamiliar climates and environments that exiles would encounter in many places. For Canada, which was also among the destinations, see Winks, 1997, 311 in particular.
60. Bade, 2000, 2007; Hoerder, 2002.
61. Achilles, 1982, 1991; Persson, 1999.
62. Fogel, 1992, 2004.
63. Brandenberger, 2004.
64. As early as 1975, the proceedings of the Toronto workshop on "Living with Climate Change" stated: "In the past, climate changes have led to mass migrations and to the growth and decay of major civilizations." See United States Congress, 1976, 435.
65. Barnett and Adger, 2007; Barnett, 2003; Lonergan, 1994; Myers, 2005; Podesta and Ogden, 2007; German Advisory Council, 2008.
66. El Hinnawi, 1985; Black, 2001; Bates, 2002; McNamara, 2007; Biermann and Boas, 2008a, 2008b, 2010; Hulme, 2008; McAdam, 2012.
67. Gerrard and Wannier, 2013, part II on sovereignty and territorial concerns.
68. Hummitzsch, 2009, 5; Nicholls and Nobuo, 1998, 15.
69. Okada et al., 2014.
70. Gemenne and Shen, 2009, 28.
71. Leckie, 2014; Price, 2016.
72. Amrith, 2013, 2.
73. See also Hoerder, 2002, 376–80.
74. McLeman, 2014, 124.
75. Amrith, 2013.
76. Shaw et al., 2013.
77. Amrith, 2013.
78. Grote, 1877, 222.
79. Dixon, 1933, 420; Petersen, 1958, 259; examples for the reception of Petersen's terminology are: Berry and Tischler, 1978, 100; Joshi, 1999; and Han, 2005, 27–30.

80. Morinière, 2009 also recognized "primitive migration" as a precursor, though without mentioning Petersen's sources. For a broader discussion of precursors and the disappearance of environmental and climatic factors from migration studies in the course of the twentieth century see Piguet, 2011, 2–4.
81. McLeman and Smit, 2006.
82. Kates, 2000, 14–15. The quote is from Stern, 2007, 128.
83. Rohland et al., 2014.
84. Mauelshagen, 2015, 179–84; Greg Bankoff's sharp analysis of "vulnerability as western discourse" is particularly relevant in this context. See Bankoff, 2001, 29.
85. New Orleans and its surroundings have a long history of disastrous hurricanes and Mississippi floods setting people on the move, see Rohland, 2015.
86. Gutmann and Field, 2010; Lübken, 2014 gives several examples of Ohio River flooding and resettlement.
87. Mike Hulme in particular has emphasized the cultural dimension of climate in the context of global warming discourse: Hulme, 2011, 2015.
88. Hoerder, 2002, 277–305.
89. Culver, 2012.

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PART IV

Case Studies in Climate Reconstruction and Impacts

CHAPTER 32

The Climate Downturn of 536–50

Timothy P. Newfield

32.1 Introduction

The 536–50 CE climatic downturn has a contentious and imperfect history. Its most basic characteristics long eluded consensus and disparate explanations exist for its cause, chronology, geography, and impact. Was this anomaly interregional, hemispheric, or global in scale? Was it a singular vast phenomenon or a complex of near-simultaneous events? Was it terrestrial or extraterrestrial in origin? Was it a cultural and demographic watershed or a minor incident inconsequential for all and unnoticed by most?

Histories of the downturn vary in part because reconstructions of its origin, scope, and severity have evolved steadily since the anomaly was discovered in the early 1980s.[1] Its meaning for scholars of classical Maya Central America, north–south dynastic China, migration-period Scandinavia, the late antique Mediterranean, and other parts of the sixth-century world remains in flux. The written evidence is finite, but interpretations of key passages have differed. Some of the natural evidence, namely from ice, lakebeds, and trees, has proven mutable, and perhaps some of it is still ambiguous. Not only do new ice-core and dendroclimatological studies continue to appear at a good clip, but many

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earlier studies have since been reinterpreted. Some relevant paleoclimate data, including results pivotal to the event's discovery, have been refined, reworked, and retracted.

This is not to say that nothing about the anomaly is known for certain. Far from it. Dozens of natural indices for pre-instrumental temperature and precipitation from around the globe, but the Northern Hemisphere in particular, illuminate the downturn and its causes. It is clear that it was a major episode of cooling, as dendroclimatology has long signaled, and it was possibly, but not necessarily, global in scale. Indeed, dramatic cooling is seen clearly in many proxies north of the equator, but a drop in Southern Hemisphere temperature, severe or not, is less certain. Multimillennial temperature proxies there are few, and uncertainties exist in some of the proxy records assembled.[2] Still, downturn volcanism is archived in both Greenlandic and Antarctic ice, lending the event a global history.

Several recent paleoclimate studies have underscored the downturn's magnitude and extraordinariness. For example, a new bipolar ice-core chronology of volcanism paired with a composite of multimillennial-long Northern Hemispheric tree ring chronologies identified the downturn eruptions as some of the largest of the last 2500 years, and 536–45 as the second most extreme decade of post-volcanic cooling over the same period. Of the sixteen coldest summers north of the equator since 500 BCE (compared to the paper's modern reference period of 1901–2000), six occurred between 536 and 550.[3] A study using Alpine and Altai trees found that the 540s was the coldest decade of the Common Era in the European series and the second coldest since 100 CE in the Central Asian series (with respect to 1961–90). Moreover, the authors of this article established that the downturn's abrupt temperature plunge ushered in an unprecedented period of cooling—a Late Antique Little Ice Age—over large swathes of Eurasia.[4] Another new composite tree ring-based study, but of European summer temperatures stretching back to antiquity, positioned the 536–50 dip as one of the coldest and most dramatic in the series. Over the European peninsula, the decade-and-a-half came in at about 1°C colder than the study's modern reference period (1961–90). Seven years of the departure were well below that mark.[5] Most recently, modeling of the climate forcing of the two largest downturn eruptions implied that they were each comparable to the strongest eruptions of the last 1200 years and that together, over the decade of 536–44, they exercised an impact on extratropical Northern Hemispheric climate upwards of 50% larger than any decade-long cluster of eruptions since 800 CE. North of 30° they were 1.5 times stronger than the combined effects of the large 1809 unknown eruption and 1815 Tambora event (see Chap. 35).[6]

The exceptionality and severity of the downturn are well established. Yet, despite the prominence assigned to the event in "old" and recent paleoclimate studies, it is important to stress that our understanding of it will continue to evolve as more paleoclimate data emerges, existing data is perfected, and the techniques of climate reconstruction continue to develop.[7]

The 536–50 anomaly has attracted a diverse set of scholars. Some are predisposed to assign the downturn considerable historical agency, others not. Often, these differences reflect more the intellectual background from which they have arisen than the current state of knowledge about the downturn itself.[8] Paleoclimatologists, anthropologists, archaeologists, geographers, and popular historians who prioritize paleoclimate data and presume that premoderns were weak and rigid in the face of abrupt environmental change have adopted maximalist interpretations, leaning toward or embracing catastrophism and determinism. Minimalist interpretations, less numerous, are mostly limited to humanists who are shy of natural proxies and tend to write nature out of history.[9] So, at one extreme, the downturn has been privileged as an "epoch-making disaster" and "the real beginning of the modern world," and at the other, it has been disparaged as the "latest Great Disaster theory" and a demographically "marginal event."[10] Moderatist stances acknowledge the anomaly's extent and severity but emphasize its limited duration and the resilience of contemporaries.[11]

This chapter surveys the evolution of research on the 536–50 downturn from the early 1980s to 2016. It presents the written evidence for climatic anomalies over the Mediterranean alongside the ever-growing wealth of relevant ice core and tree ring scholarship, and it highlights changes in reconstruction and interpretation as scholars reworked old data and injected new data. Judgments about its long-term historical significance are mentioned but not assessed: there is space here neither to support nor to refute the numerous roles that this downturn has been assigned.

In line with current evidence, the chapter concludes that the anomaly was a discontinuous complex of phenomena whose effects were extreme but varied across space and time. A cluster of very large volcanic eruptions triggered exceptional cooling and possibly drought across several parts of the globe. This was not simply a "536 event." It was a decade and a half of marked cold, with summer lows around 536, 540–1, and 545–6. It is a testament to advances in paleoclimatology that we must speak now of a fifteen-year anomaly as opposed to an episode of twelve or eighteen months' duration. This volcanic climate forcing led, via its effects on food production, to a pronounced but short-term demographic contraction in several regions of the world. Although most assessments of the downturn privilege written sources for dust veiling around the Mediterranean—the so-called 536 "mystery cloud"—that clouding was but one component of the event. In fact, its centrality to an explanation of the multiple temperature plunges registered in the world's trees or the violent volcanism catalogued in ice between 535 and 550 is debatable.

32.2 Texts

Five contemporary and independent accounts of the dimming of the sun around 536 survive from the Mediterranean region. Four were fundamental to the original formulation of the 536–50 downturn in the early 1980s; all five have underpinned reconstructions and histories of the event since 1988.[12] The scholar Procopius—who spent 536 in Italy, Tunisia, and possibly Turkey, and 537 in Italy alone[13]—observes in his lengthy history of Justinian's wars that in 536/7 "the sun gave forth its light without brightness, like the moon, during this whole year." He continues, "it seemed exceedingly like the sun in eclipse, for the beams it shed were not clear nor such as it is accustomed to shed."[14] Similarly, but from Rome, the senator and consul Cassiodorus, in a letter to his deputy variously dated to late 536, 537, or mid-538, speaks of the dimming of the moon and of the sun having lost its "wonted light" and appearing "bluish" as if in "transitory eclipse throughout the whole year" without the might to produce shadows at noon. He writes of "strange" weather with, as he puts it, "a winter without storms, a spring without mildness and a summer without heat." In short, it was unusually cold and dry with a "prolonged frost and unseasonable drought."[15] The Constantinopolitan administrator John the Lydian in his work on signs and portents written in the early 540s reports the sun dimming "for nearly a whole year" in 535/6, although it has been suggested this date is a simple mistake for 536/7.[16]

The churchman John of Ephesus, who lived in southeastern Turkey (Amida) and traveled much before settling in Constantinople in the early 540s, also describes the event in the second section of his ecclesiastical history which survives in the third part of the late eighth-century compilation of the so-called Pseudo-Dionysius, a chronicler of the Zuqnin Monastery near Amida. In this work, the sun is documented as "covered with darkness" for eighteen months in 530/1, and the sun's rays visible for only two or three hours a day "as if diseased."[17] The twelfth-century chronicle of Syriac Patriarch Michael the Great, which made use of this text, includes a nearly identical passage, although the daily sunlight is stretched to four hours and the date is corrected to 536/7, presumably to John's original.[18] Lastly, the so-called Pseudo-Zachariah Rhetor, a Syrian monk who likely compiled his history in the third quarter of the sixth century somewhere in southeastern Turkey (probably also Amida), observes the darkening of the sun and moon from March 24, 536 to June 24, 537: "the sun began to become dark at daytime and the moon by night."[19] He also refers then to the Mediterranean in an "awkward phrase" usually translated as "stormy with spray"[20] but which could be read instead as "clouded by moisture" or "confused by wet clouds."[21] Pseudo-Zachariah as well notes that the 536–7 winter in Syria was severely cold and unusually snowy, causing birds to die.[22] Other texts document difficult weather at the time but not veiling. Notably, Marcellinus Comes' Constantinopolitan continuator remarks that 536 saw "excessive drought" that destroyed western Asian pastureland and forced the migration of 15,000 people from modern-day Iran to Syria.[23]

These accounts, truncated as such, have been taken "as is" with few qualms. The exception is John the Lydian's passage, which Arjava demonstrated was often read too selectively.[24] Unlike the other sources, this John offered an explanation and range of the sun's dimming.[25] The sun became dim, he writes, "because the air is dense from rising moisture." This moisture "evaporated and gathered into clouds dimming the light of the sun so that it did not come into our sight or pierce this dense substance." John also tells us the aqueous phenomenon was European in scope; Persia and India, he specifies, were not affected.[26] As discussed below (see Sect. 32.7 "Collapse and Resilience"), Arjava employs John's remarks, alongside Pseudo-Zachariah's vague comments about a stormy or cloud-covered Mediterranean, to argue that mystery clouding was circumscribed, tropospheric (that is, in the lower atmosphere), and not volcanic in origin.

But just how much should we make of John's interpretation? The Byzantine may have been well informed about current events in Persia but likely not in India,[27] and he was present in neither to witness clear skies firsthand. He may also spare Persia and India sun dimming since he conceived of them as being dry, or at least drier than Mediterranean Eurasia: "India and the Persian realm and whatever dry land lies toward the rising sun were not troubled at all." In any case, his understanding of the cause of the sun's dimming, whether his own or another's,[28] need not be accurate.

There is then the East Asian evidence, which requires closer attention than it has been given or can be given here. In the eastern region between the Yangtze and Yellow Rivers, for example, there are reports of drought, early frost, and snow in 536, and then very unusual summertime cold, frost, and snow in 537. Particularly adverse conditions are reported in 536 for Ching state, south of Shandong peninsula. The eighteenth-century encyclopedic compilation, *Gujin Tushu Jicheng*, contains references to a dire drought in 537 in Gansu, Henan, Shanxi, and Xi'an provinces. There is also a hint of atmospheric clouding, since sources from southern China report that Canopus, the second brightest star, could not be seen at either the spring or fall 536 equinoxes. Additionally, the early seventh-century *Nanshi* chronicle refers to "yellow dust" that "fell like snow" in 536 and 537. In the latter year, it "filled scoops when picked up." The dust was almost certainly Gobi sand (not volcanic ash), but this signals that 536 and 537 were unusually dry.[29] Further droughts are cited in 542, 543, 547, and 550.[30]

In the Japanese *Nihon Shoki*, likely compiled between 681 and 720 from earlier sources, there is a brief mention of people "starving of cold" and hunger in summer 536. It also includes references to the necessity of public granaries in "preparation for evil years," grain distribution to regions underserved by granaries, and the construction of new granaries to deal with "extraordinary occasions."[31] The thin *Silla Annals* of Korea's Samguk Sagi, from the southeast of the peninsula, record the winter blossoming of peach and plum trees in 540, and (presumably extraordinary) snowfall in spring 541, but nothing else potentially relevant for the years 535–50.[32] The *Koguryo Annals* of the Samguk Sagi, which concern a large region on either side of the Yula and Tumen Rivers, report this unusual blooming but not the snowfall. Importantly, this text observes in 536 that "due to a severe drought during the spring and summer officials were dispatched to relieve the suffering of the people." Following this drought, and a plague of locusts, there was famine in 537.[33]

Read separately or together, these passages suggest something atmospherically and climatologically unusual during and after 536. It is hardly clear, however, whether the Mediterranean clouding was linked to events reported in China, Korea, or Japan, or to European accounts of food shortage addressed below. From the written sources alone, it remains altogether unknown whether sun veiling extended far beyond Byzantine territories. Yet support for vast volcanic dust veils and climatic impacts emerges when the written evidence is combined with high-resolution tree ring-based indices for sixth-century temperature and precipitation.

32.3 Tree Rings

Multiple dendroclimatological studies identify an unusually cold-dry anomaly between 536 and 550. Some studies consider several indicators of temperature and precipitation, including tree ring width (TRW), maximum latewood density (MXD), cell wall thickness, and the variability of stable carbon and oxygen isotopes ($\delta^{13}C$ and $\delta^{18}O$). Tree ring-based climate reconstructions have commonly isolated 536–50 as one of the coldest periods of the last several millennia. Many of these studies find temperature declines of 1.5–4 °C below their referenced instrumental series for one or more years of the downturn. Thin growth rings as well as one or more rare frost rings, which indicate growing-season freezing, are not uncommon across the roughly fifteen-year period. Such poor growth is often related to impacts of major volcanic eruptions on climate and associated sudden drops in temperature.[34] Mature trees at high altitudes or high latitudes archive these drops best. Low elevations specimens, in contrast, speak to precipitation. Relevant dendroclimatology has emerged at a rapid rate and has revealed a severity and abruptness lost in lower-resolution climate proxies. High-resolution tree ring studies illustrate that the downturn exceeds the magnitude and the temporal and spatial scope of the anomaly suggested in the written evidence.

Too many relevant tree-based studies have appeared to discuss them individually here. Table 32.1 summarizes twenty-eight of these publications. The vast majority survey thousands of years of climate and simply mention (or depict) the 536–50 downturn as a truly extraordinary but brief climate departure. Baillie authored the first studies to integrate tree ring data into the discussion of a 536 event (5). In his 1991 and 1994 papers, he drew on published tree ring material concerning northern Sweden and California (1, 3). He also introduced an unpublished TRW series of bristlecone pines from Nevada that showed exceptionally poor growth in the late 530s and 540s—with nadirs at 536–7, 540–1, 546–7, and 552–3—and compiled a composite of fifteen oak TRW series from England, Ireland, Germany, and Scotland that revealed 536–50 as an extreme trough, with lows at 536 and 540–1 and recovery in 537–8 and 546–7. In Irish oaks, 540 was identified as the worst growing year of the last several millennia.

Baillie's work has been confirmed repeatedly in reassessments of European and US data and in new series from these and other regions. The 536–50 cooling stands out in 1500- and even 7500-year-long chronologies. Multiple and varied analyses of all but two of the more than ten tree ring series encompassing the downturn show it as an exceptionally pronounced period of temperature and/or precipitation anomaly.

Naturally, there is some variation among chronologies and analyses. Most series (about 85% of those in Table 32.1) are chiefly temperature sensitive. A few (e.g., 12, 14, 20, and 24–25—three of which come from Qinghai Province, China) specifically concern precipitation, and neither the degree of deviation nor the years identified as most extreme are always the same. Most studies consider TRW alone. One recent study (24), however, demonstrates the array of measurable parameters. Ring width, cell-wall thickness, and cellulose $\delta^{13}C$ and $\delta^{18}O$ were assessed with specific attention to the 530s and 540s in three multi-millennial larch series from Russia's northern Krasnoyarsk Krai, northeastern Sakha Republic, and Altai Republic. TRW minima were established in the northerly Krasnoyarsk and Sakha chronologies at 536 and 541, and in the high-altitude Altai chronology at 536 and 539. Exceptionally thin cell walls were visible in the Sakha series at 536 and 541 and in the Altai series at 536 and 537. Cell-damaged frost rings could be seen in the latter at 536, 537, and 538. Pronounced $\delta^{13}C$ declines, telling of a cold but moist growing season, were visible at 536 in the Krasnoyarsk and Sakha series. Krasnoyarsk $\delta^{13}C$ values remained low until the 550s, with a 538 minimum, while Sakha values showed respite at 537 and another plunge at 541. Altai $\delta^{13}C$ values hardly varied. Exceptionally diminished $\delta^{18}O$ values were uncovered at 536 in the Altai series, indicating a very cold growing season, but $\delta^{18}O$ remained steady at Krasnoyarsk and Sakha. Taken together, this data indicates multiple unusually short growing seasons during the downturn and June–July temperatures dipping well below the referenced instrumental series (by up to 4 °C in the Altai series).[35]

One explanation for the variation in the years of extreme temperature departures is that TRW is less sensitive than MXD to sudden cooling and TRW may give an extended response to cold events.[36] Furthermore, not all tree species respond equally to climatic phenomena, and high-latitude chronologies—as opposed to high-altitude ones—seem to give a sharper and lagged response to sudden cooling.[37] Still, in all but two studies surveyed (3, 24), 536 marks the downturn's onset.[38] One study of pines from Finland (8) illustrates in particular how abrupt the event could be. The series identifies the July of 535 as the warmest of the last 7500 years and the 535–6 interannual transition as the second most extreme since at least 5520–5519 BCE. There is also some discrepancy regarding moisture. While the northern Siberian Krasnoyarsk and Sakha chronologies (24) register cold-wet conditions, Central European and central Chinese series (12, 14, 20, 25) tell of a cold-dry downturn.

Two other growth minima center around 540–1 and 545–6 CE. In multiple series, many of the intervening and subsequent years show growth minima as well: notably 537, 539, 541, 542, 543, 544, 547, and 549. Some studies

Table 32.1 Twenty-eight dendroclimatological studies (1990–2015) relevant to the 536–50 downturn

	Location	*Span*	*Parameter*	*Observations*
1	Sweden, Norrbotten County	500 CE–1980 CE	TRW, MXD	April–August 536 5th coldest in series, 1.5 °C below SIM; summer cold trough late 530s & early 540s.
2	Sweden, Norrbotten County	500 CE–1980 CE	MXD	July–August 536 2nd coldest in series at 2 °C below SIM; multiyear cold period around 540.
3	USA, California State	1 CE–1980 CE	TRW	June–January 536, 535, 541 2nd, 3rd & 4th coldest, 3.13 °C, 3.07 °C & 2.93 °C below SIM; 542–61 coldest 20-year stretch, 1.95 °C below SIM.
4	Chile, Los Lagos Region	1634 BCE–1987 CE	TRW	Extreme poor-growth period (December–March temperatures) *c.* 540.
5	Composite European Series & USA, Nevada	See text	TRW	See text.
6	Mongolia, Zavkhan Province	262 CE–1999 CE	TRW, MXD	Frost rings, MXD evidence exceptional cold at 536; TRW evidence, August–July temperatures, 536–45 cold trough, nadirs at 536 & 543; TRW minimum at 543; respite 538.
7	Russia, northern Krasnoyarsk Krai	212 BCE–1996 CE	TRW	June–July 536 4th coldest in series (estimated at 3.5 °C compared to average instrumental observation period (1933–89) temperature of 9.6 °C); 533–52 3rd coldest 20-year period in series.
8	Finland, Lapland Regions	5520 BCE–1999 CE	TRW	July 536 1.78 °C below SIM; 541–50 4th coldest non-overlapping 10-year period, 1.17 below SIM; 542–51 coldest decade of last 4000 years, 1.33 below SIM; July 535 warmest, 6.17 °C above SIM; 535–6 2nd most extreme interannual fluctuation.
9	Sweden, Norrbotten County	5407 BCE–1997 CE	TRW	Severely cold June–Augusts around 540; multiple frost rings & TRW minima; 1 of 6 coldest short periods in series.
10	Russia, north Krasnoyarsk Krai	431 BCE–1996 CE	TRW	June–July 536 5th coldest in series (estimated at 3.7 °C compared to average instrumental observation period (1933–89) temperature of 9.6 °C, or 2.8 °C below SIM); cold trough spanning late 530s & 540s.
11	Sweden, Norrbotten County	5407 BCE–1997 CE	TRW	Exceptionally cold June–Augusts between 536 and 553; lows at 536, 542, 544–5, & 550.
12	China, Qinghai Province	326 BCE–2000 CE	TRW	536 first year of decade plus of low May–June precipitation.

(*continued*)

Table 32.1 (continued)

	Location	*Span*	*Parameter*	*Observations*
13	Sweden, Jämtland County	2893 BCE–1998 CE	TRW	Several very low summer temperatures between 536 & 550; minima at 536, 539, 542, & 544.
14	China, Qinghai Province	515 BCE–2000 CE	TRW	Several years (July–Junes) of very low precipitation in 530s & 540s.
15	USA, Arizona State	266 BCE–1997 CE	TRW	534–43 6th coldest 'short period' in series at 1.34 °C below SIM.
16	Norway, Troms County	320 CE–1994 CE	TRW	Exceptionally low July temperatures in mid 530s–540s, some of the deepest plunges in series.
17	Austria, Tyrol State	5125 BCE–2000 CE	TRW	Trough of cold May–Septembers 536–52; lows at 545 & 549.
18	USA, Arizona, California, Nevada	3000 BCE–2002 CE	TRW	Remarkably cold 'warm seasons' in 536, 537, 541, 542, 543, 545, & 547; cold trough 536–47; frost rings 536 & 541; 2/5 sixth-century frost rings & 6/7 sixth-century ring-width minima took place between 536 and 550.
19	Sweden, Norrbotten County	500 CE–2004 CE	TRW, MXD	Sharply cold April–Augusts in mid 530s & 540s; multiple lows in range of 2 °C below SIM.
20	Central European Composite Series	500 BCE–2000 CE	TRW	Dry April–Junes in northeast France, northeast & southeast Germany & cold June–Augusts in Austrian Alps; cold-dry lows *c.* 537, 542, 545, & 550.
21	Finland, Lapland Region	5500 BCE–2000 CE	TRW	536 one of the five coldest Julys in series at more than 3 °C below SIM; summer 542 nearly as cold.
22	Sweden, Norrbotten County	500 CE–2008 CE	TRW, MXD	Several sharply cold May–Augusts mid 530s & 540s; lows 536, 542, & 545. 1 of coldest short periods in TRD and MXD series.
23	Sweden, Norrbotten County & Finland, Lapland Region	5510 BCE–1999 CE TRW, 1 CE–1997 CE MXD	TRW, MXD	Summer 542 2nd coldest over last 2000 years in TRW & MXD series, 5th coldest in TRW series; summer 536 less frigid, 36th in TRW series; yet 536 1 of 10 coldest years 1–1000 CE in MXD series.
24	Russia, north Krasnoyarsk Krai, northeastern Sakha Republic, Altai Republic	See text	TRW, MXD, CWT, $\delta^{13}C$, $\delta^{18}O$	See text.
25	China, Qinghai Province	2637 BCE–2011 CE	TRW	Extremely dry July–Junes mid 530s & 540s; follows drier short periods in late 300s & late 400s; last short dry period for 600 years.
26	USA, California, Nevada	2575 BCE–2006 CE	TRW	Exceptionally cold July–Septembers mid 530s & 540s.
27	Austria, Upper Austria State	88 CE–2008 CE	MXD	Sharply cold July–Septembers around 540; especially light ring at 536.

(continued)

Table 32.1 (continued)

	Location	*Span*	*Parameter*	*Observations*
28	Composite European Series (ES), Composite Northern Hemispheric Series (NS)	1 CE–2000 CE (ES), 500 BCE–2000 CE (NS)	TRW, MXD	1.6 < 2.5 °C drop June–August 536, 1.4 < 2.7 °C drop June–August 541, against preceding 30 years in ES with lows at 536, 541, 543, 544, 545, 546, 549; in ES 536–40 2nd coldest run of June–Augusts; in NS 535–50 has 6 of 13 strongest tree-growth reductions 500 BCE–1250 CE & 536–45 strongest decade-long tree-growth reduction (coldest decade) 500 BCE–2000 CE; 536–45 & 546–55 2 of 10 coldest decades in NS.

TRW = Tree-Ring Width; MXD = Maximum Latewood Density; CWT = Cell Wall Thickness; $\delta^{13}C$ = Stable Carbon Isotope; $\delta^{18}O$ = Stable Oxygen Isotope; SIM = Series Instrumental Mean. **1** K. Briffa et al., "A 1400-Year Tree-Ring Record of Summer Temperatures in Fennoscandia," Nature 346 (1990), pp. 437 (Fig. 2), 439. **2** K. Briffa et al., "Fennoscandian Summers from AD 500: Temperature Changes on Short and Long Time Scales," Climate Dynamics 7 (1992), pp. 116 (Fig. 8), 117. **3** L. Scuderi, "A 2000-Year Tree Ring Record of Annual Temperatures in the Sierra Nevada Mountains," Science 259 (1993), p. 1435. **4** A. Lara and R. Villalba, "A 3620-Year Temperature Record from *Fitzroya cupressoides* Tree Rings in Southern South America," Science 260 (1993), p. 1106 (Fig. 3); Cf. R. Villalba, "Interdecadal Climatic Variations in Millennial Temperature Reconstructions from Southern South America," in P. Jones et al., eds., Climatic Variations and Forcing Mechanisms of the Last 2000 Years (Springer, Berlin, 1996), pp. 164 (Fig. 1), 170 (Fig. 5). **5** M. Baillie, "Marking in Marker Dates: Toward an Archaeology with Historical Precision," World Archaeology 23 (1991), pp. 233–238; idem, "Dendrochronology Raises Questions about the Nature of the AD 536 Dust-Veil Event," The Holocene 4 (1994), pp. 213–15. **6** R. D'Arrigo et al., "Spatial Response to Major Volcanic Events In or About 536, 934 and 1258: Frost Rings and other Dendrochronological Evidence from Mongolia and Northern Siberia," Climatic Change 49 (2001), pp. 241–42; R. D'Arrigo et al., "1738 Years of Mongolian Temperature Variability Inferred from a Tree-Ring Width Chronology of Siberian Pine," Geophysical Research Letters 28 (2001), pp. 544–45. **7** M. Naurzbaev and E. Vaganov, "Variation of Early Summer and Annual Temperature in East Taymir and Putoran (Siberia) over the Last Two Millennia Inferred from Tree Rings," Journal of Geophysical Research 105 (2000), p. 7324. **8** S. Helama et al., "The Supra-Long Scots Pine Tree-Ring Record for Finnish Lapland: Part 2, Interannual to Centennial Variability in Summer Temperatures in 7500 Years," The Holocene 12 (2002), pp. 683 (Table 3), 685 (Table 4), 686. **9** H. Grudd et al., "A 7400-Year Tree-Ring Chronology in Northern Swedish Lapland: Natural Climatic Variability Expressed on Annual to Millennial Timescales," The Holocene 12 (2002), p. 663. **10** M. Naurzbeav et al., "Summer Temperatures in Eastern Taimyr Inferred from a 2427-year Late-Holocene Tree Ring Chronology and Earlier Floating Series," The Holocene 12 (2002), pp. 732, 734 (Table 4). **11** H. Grudd, "A 7400-Year Tree-Ring Chronology in Northern Swedish Lapland: Natural Climatic Variability Expressed on Annual to Millennial Timescales," The Holocene 12 (2002), p. 663; Larsen et al., "New Ice Core Evidence," L04708 (Fig. 1). **12** Q. Zhang et al., "A 2326-Year Tree-Ring Record of Climate Variability of the Northeastern Qinghai-Tibetan Plateau," Geophysical Research Letters 30 (2003), p. 1739 (Fig. 3); C. Zhang and Q. Zhang, "Is There a Link between the Rise and Fall of the Tuyuhun Tribe (Northwestern China) and Climatic Variations in the fourth–seventh centuries AD?" Journal of Arid Environments (2016), p. 148. **13** B. Gunnarson et al., "Holocene Humidity Fluctuations in Sweden Inferred from Dendrochronology and Peat Stratigraphy," Boreas 32 (2003), pp. 348–49, 351–52, 355–56; Larsen et al., "New Ice Core Evidence," L04708 (Fig. 1). **14** P. Sheppard et al., "Annual Precipitation Since 515 BC Reconstructed from Living and Fossil Juniper Growth of Northeastern Qinghai Province, China," Climate Dynamics 23 (2004), p. 876. **15** M. Salzer and K. Kipfmueller, "Reconstructed. Temperature and Precipitation on a Millennial Timescale from Tree-Rings in the Southern Colorado Plateau, USA," Climatic Change 70 (2005), pp. 473 (Fig. 4), 476 (Table IV). **16** A. Kirchhefer, "A Discontinuous Tree-Ring Record AD 320–1994 from Dividalen, Norway: Inferences Climate and Tree-Line History," in Mountain Ecosystems:

(*continued*)

Table 32.1 (continued)

Studies on Tree Line Ecology, eds. G. Brill and B. Keplin (Berlin, 2005), p. 225. Though this chronology stretches back to 320, detailed analysis is presented only for 587–980 and 1507–1993 and the severity of the downturn has to be inferred from Fig. 3. **17** K. Nicolussi et al., “Holocene Tree-Line Variability in the Kauner Valley, Central Eastern Alps, Indicated by Dendrochronological Analysis of Living Trees and Subfossil Logs,” Vegetation History and Archaeobotany 14 (2005), pp. 221–34; Larsen et al., “New Ice Core Evidence,” L04708 (Fig. 1). **18** M. Salzer and M. Hughes, “Bristlecone Pine Tree Rings and Volcanic Eruptions Over the Last 5000 yr,” Quaternary Research 67 (2007), pp. 62 (Table 2), 63 (Table 4), 65 (Table 6), 66. **19** H. Grudd, “Torneträsk Tree-Ring Width and Density AD 500–2004: A Test of Climatic Sensitivity and a New 1500-Year Reconstruction of North Fennoscandian Summers,” Climate Dynamics 31 (2008), p. 853. **20** U. Büntgen et al., “2500 Years of European Climate Variability and Human Susceptibility,” Science 331 (2011), pp. 580, 581 (Fig. 4); Kostick and Ludlow, “Dating of Volcanic Events,” p. 16 (Fig. 1). **21** S. Helama et al., “A Chronology of Climatic Downturns through the Mid- and Late-Holocene: Tracing the Distant Effects of Explosive Eruptions from Palaeoclimatic and Historical Evidence in Northern Europe,” Polar Research 32 (2013), p. 15866 (Fig. 2). **22** T. Melvin et al., “Potential Bias in ‘Updating’ Tree-Ring Chronologies Using Regional Curve Standardisation: Re-Processing 1500 Years of Torneträsk Density and Ring-Width Data,” The Holocene (2013), p. 371 (Fig. 5). **23** P. Jones, “Cool North European Summers and Possible Links to Explosive Volcanic Eruptions,” Journal of Geophysical Research: Atmospheres 118 (2013), p. 6263. **24** O. Churakova et al., “A Cluster of Stratospheric Volcanic Eruptions in the AD 530s Recorded in Siberian Tree Rings,” Global and Planetary Change 122 (2014), pp. 145–49; O. Churakova et al., “Siberian Trees: Eyewitnesses to the Volcanic Event of AD 536,” Pages Magazine 23 (2015), pp. 64–65. **25** B. Yang, “A 3500-Year Tree-Ring Record of Annual Precipitation on the Northeastern Tibetan Plateau,” PNAS 111 (2014), p. 2906. **26** M. Salzer et al., “Five Millennia of Palaeotemperature from Tree-Rings in the Great Basin, USA,” Climate Dynamics 42 (2014), p. 1524 (Fig. 6). **27** M. Klusek et al., “Multi-Century Long Density Chronology of Living and Sub-Fossil Trees from Lake Schwarzensee, Austria,” Dendrochronologia 33 (2015), pp. 46 (Fig. 4), 47. **28** M. Sigl et al., “Timing and Climate Forcing of Volcanic Eruptions for the Past 2500 Years,” Nature 523 (2015), pp. 547–48, Extended Data Table 5 (e.g., 28) identify another low in the early 550s. The year 538 is a "respite" or good growth year in most (but not all) studies; and some chronologies identify respites in 537, 542–3, and 547–8. The cold trough of 536–50, then, represents a general and significant departure from normal temperature and—at least in western China, southern Russia, and Central Europe— from normal precipitation. It was not a period of consistent poor-growth conditions, but in the vast majority of dendroclimatological studies, it remains *one of* or *the* coldest short periods on record (see, for example, 3, 5, 6, 8, 9, 11, 13, 15, 17, 18, 20, 22, 24, 28). The tree ring-based Old World Drought Atlas, not included in Table 32.1, also demonstrates that climate forcing was not steady. Yet it does suggest that the downturn was by and large dry north of the Alps. The summers of 549 and 550 emerge as rather wet in the atlas, but those of 536, 538–41, 546, and 551 seem to have been very dry.[39] A 2015 study (28), using a composite northern hemispheric tree ring chronology spanning 500 BCE–2000 CE, established the consecutive decades of 536–45 and 546–55 as the first and tenth coldest decades in the series, respectively. The same trees also put six of the thirteen most significant tree-growth anomalies (coldest years) between 500 BCE and 1250 CE within the limits of the downturn. A forthcoming study reconfirms these findings.[40]

Of course, this dendroclimatology presents challenges. Most tree rings that provide a temperature signal come from high-altitude or high-latitude sites—that is, thinly populated regions far removed from written descriptions of dust veils and famines. Temperature signals obtained from trees are more homogenous than precipitation signals and can be regionally representative,[41] but there is a dearth of crop-level climate data. The climate signals obtained from trees reveal neither winter temperature nor winter precipitation but only growing-season conditions; yet winter precipitation is fundamental for food production in many parts of the world. Moreover, even though sulfates logged in Antarctic ice cores reveal that the downturn was at times global in scope, at least from 540 (see Sect. 32.5 "Ice Cores"), most of the proxy data comes from north of the Tropic of Cancer and is Eurasian in focus. The available South American dendroclimatology (4), which seems to register a temperature plunge about 540, does little to fill out the downturn's impacts in the Southern Hemisphere. Multimillennial Tasmanian and New Zealand TRW series indicative of November–April temperatures do not register significant or unusual downturn cold, though it has been suggested that they reflect volcanic climate forcing poorly.[42]

Finally, tree ring evidence cannot yet confirm the climate impacts of the Mediterranean mystery cloud described in Byzantine sources. There is still only one truly Mediterranean chronology spatially and temporally consistent with the documented veiling: a floating Constantinopolitan series thought to span 398–610 CE.[43] TRW analysis of that series, however, returned neither a severe 536–50 cold trough nor extreme lows at 536 or 540. Narrow but "non-anomalous" rings are apparent at 537 and 541. These results are not as surprising as they may seem. Low elevation, mid-latitude trees typically tell us about precipitation, not temperature. Rather than failing to indicate major post-eruption cooling, these rings may instead evidence some anomalous post-eruption dryness.[44] In any case, work remains to be done on this series. The authors observe that the date range of the series is not absolute; Aegean trees may experience better-than-average growing conditions in cold anomalies or, as is more likely, fail to register cold anomalies altogether; and this particular chronology may provide a microclimate signal rather than a "broader regional or hemispheric" one.[45] The tree ring series closest to the documented clouding that register the downturn temperature plunge come from the Alps (17, 20, 27–8).[46]

A vast array of tree ring graphs could be presented that demonstrate the abruptness and severity of 536–50 summer cooling. Figure 32.1 presents Christiansen and Ljungqvist's 2000-year-long multiproxy temperature reconstruction for the extratropical Northern Hemisphere (north of 30°) alongside the PAGES 2k Consortium's tree-based temperature reconstruction for Europe. Figure 32.2 presents sixth-century sections of these series as well as composite tree ring temperature reconstructions for Scandinavia and the Alps. The downturn registers clearly in all four series, but there are differences. The PAGES and Scandinavian reconstructions are rather choppy. The hemisphere-wide and Alpine series suggest more sustained low temperatures. In addition, they indicate that the downturn persisted well into the 550s.

32.4 Other Proxies

The fact that tree rings demonstrate a cold trough at the same time that written sources describe clouding and food shortages suggests but does not prove a link. Other archives—including cave formations (speleothems) and ice cores—can offer further information about global and local climate histories.

Studies of stable isotope variability in speleothems offer data on regional climates. Like trees, these cave formations can provide annually resolved proxies of past temperature and precipitation.[47] For example, studies of layer thickness in a speleothem outside Beijing, China, indicative of May–August temperature, and analysis of oxygen isotope variability in a Wanxiang Cave (Gansu, China) speleothem reflective of May–September precipitation, have turned up evidence of rapid climate change during the 530s and 540s. The latter shows a major $\delta^{18}O$ spike around 536, indicating the most sudden and severe drought conditions in the 1810-year chronology.[48] This speleothem may reveal the climate triggers of famine in eastern China in the 530s, as dendroclimatology may the triggers of famine in temperate Europe.

Many less-resolved climate proxies also reveal 536–50 cooling and drying. For instance, an analysis of ice accumulation and oxygen isotope variability in ice cored from Peru's Quelccaya glacier reveals a pronounced cold-dry period lasting about two decades around 540; dendrochronologically dated fossil wood demonstrates that Switzerland's Lower Grindelwald glacier advanced from 527 to 578; a study of alkenone in varved lake sediments in northeastern China shows a marked decline in spring-summer temperatures about 540; and an assessment

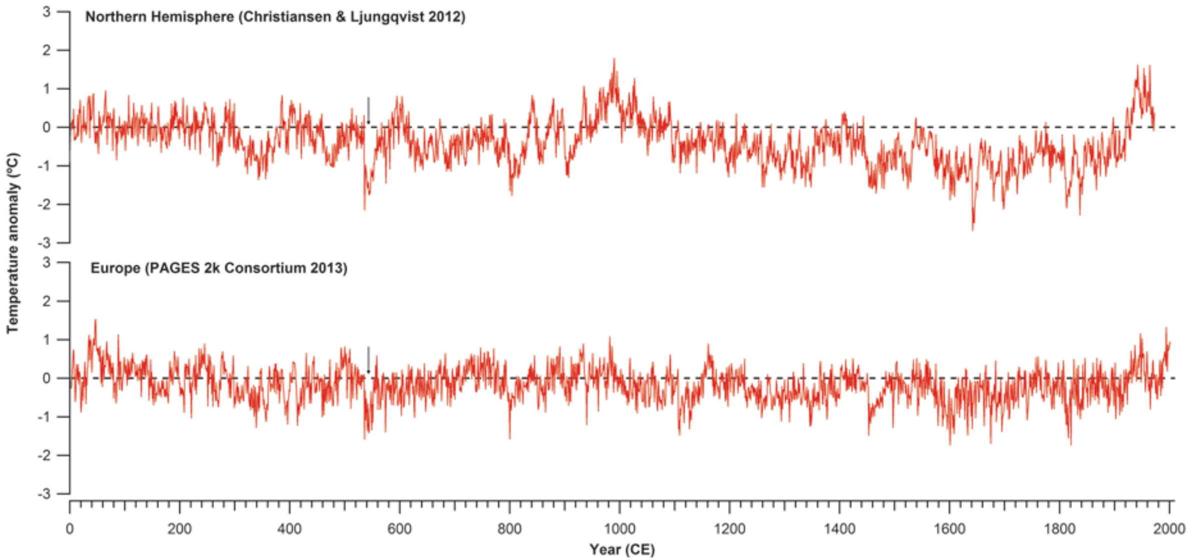

Fig. 32.1 Summer temperature anomalies for the past two millennia. Summer temperature anomalies noted by Christiansen and Ljungqvist (2012) are with respect to 1880–1960. The PAGES June–August temperature anomalies are relative to 1961–90. Five tree-based temperature reconstructions are rolled into the Scandinavian series and four into the Alpine series [the data comes from Büntgen and Tegel (2011)]. These European series reflect June–August temperature anomalies with respect to 1860–2004. The author thanks Ulf Büntgen for sharing this data and Inga Labuhn for drawing these graphs

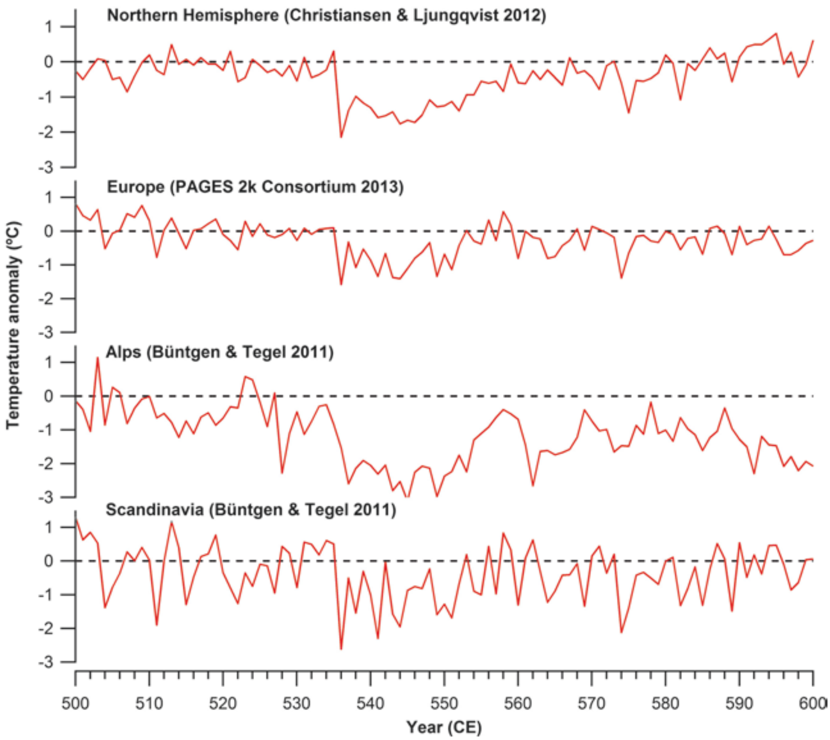

Fig. 32.2 Summer temperature anomalies 500–600 CE. Summer temperature anomalies noted by Christiansen and Ljungqvist (2012) are with respect to 1880–1960. The PAGES June–August temperature anomalies are relative to 1961–1990. Five tree-based temperature reconstructions are rolled into the Scandinavian series and four into the Alpine series [the data comes from Büntgen and Tegel (2011)]. These European series reflect June–August temperature anomalies with respect to 1860–2004. The author thanks Ulf Büntgen for sharing this data and Inga Labuhn for drawing these graphs

of water-table depths in Tierra del Fuego peat bogs roughly indicates a shift from drier to wetter conditions around 550.[49] There are also isotopic assessments of gases trapped in polar ice. For example, analysis of argon and nitrogen isotopes from the Central Greenland GISP2 core (resolved to about twenty years) established a sharp multiyear temperature drop around 540.[50] Although there are uncertainties, work on oxygen isotopes in Antarctic ice suggests that temperature did not fall much over the frozen continent in the mid-sixth century. In fact, it may have risen.[51]

Naturally, poorly resolved proxies are less valuable where high-resolution indices are already available. Nevertheless, in regions such as Central America—where many think the downturn hit hard—low-resolution proxies are all we have.[52] Paleoclimatology in this region has focused on climate trends underlying the so-called Maya classical collapse (750–1000). However, the Maya "hiatus"—a sharp break between the Early and Late Classical periods, spanning about 535–95—has not gone unnoticed. Archaeologically, the period saw a leveling off or decline in stelae and monumental building, and potentially population contraction and settlement desertion. Increasing $\delta^{18}O$ values in a sediment core taken from the Yucatán Peninsula's Punta Laguna in the mid-1990s indicate an "exceptionally arid event" at 585 ± 50 and a study of gypsum horizons in the sediment of neighboring Chichancanab Lake also seemed to reveal a hiatus-era drought about a decade long. Later studies, however, suggested that this drought was not dire.[53]

More recently, an annually resolved study of oxygen isotope variability in a Yucatán stalagmite turned up evidence of severe multiyear droughts (increased $\delta^{18}O$) in the early sixth century comparable to later "collapse"-era droughts. Yet the study fixed these droughts at 501–18 and 527–39, so predating the 536–50 downturn.[54] Analysis of a Belizean speleothem has also identified a drought around 517 (±0.5–3 years).[55] Considering the chronological uncertainties in these records, however, it remains possible that one or more of these arid intervals were linked to the eruption of 539/40. Less firmly dated evidence of sixth-century drought in Central America comes from $\delta^{18}O$ analysis of a roughly resolved sediment core from Guatemala's Salpetén Lake,[56] titanium in a marine core taken off the coast of Venezuela in the Cariaco Basin,[57] and analysis of plant δD in lacustrine cores from the Dominican Republic's Laguna Castilla.[58] Not all of these proxies necessarily reflect the 536–50 downturn. Higher-resolution indices that span the mid-sixth century are very much needed for this region.

32.5 Ice Cores

Assessment of sulfate in polar ice provided the first indications of a mid-sixth-century climate anomaly. While tree rings archive annual changes in growing-season climate, ice layers archive sulfate and tephra from large or local volcanic eruptions. Different dating methods have produced slightly different results for eruptions. Sulfuric acid aerosols are deposited as sulfates months and possibly years after eruptions. Evidence of massive tropical eruptions can appear at both poles.[59]

A study published in 1980 first identified an acid horizon from a major mid-sixth-century eruption in a south Greenlandic ice core, dated to 540 ± 10.[60] A similar horizon was identified at about 535 in the Greenlandic Dye-3 ice core two years later.[61] A few years after that, both of these signals were redated to around 516.[62] Volcanic acid layers subsequently emerged in the GISP2 core at 530 ± 2, in the GRIP core at around 527, and the Dye-3 core at around 530—all too early for the reported 536 clouding.[63] The GISP2 ice core section pertaining to the mid-500s (likely "from A.D. 620 to 545") was lost during retrieval and no relevant signal was detected for several years in other Greenlandic or Antarctic archives.[64]

Then studies in 2004 and 2007 found a major volcanic signal in the Antarctic Dronning Maud Land and Dome-C cores dated to 542 ± 1; and in 2008 Larsen and his team uncovered two significant signals in Dye-3, GRIP, and NGRIP Greenlandic cores at 529 ± 2 and 533/4 ± 2.[65] The latter, it was argued, related directly to the 536–50 climatic downturn. Following a comparison of sixth-and seventh-century volcanic horizons, this team proposed that Antarctic ice core dates be shifted back six years and Greenlandic dates up two to three years, meaning that an eruption possibly accountable for the 536 event would be evident in multiple cores at both poles. Only months later, however, dendrochronologist Baillie proposed that the dates of these newly detected acidities be bumped up six or seven years, which would put major eruptions at around 535 and 539. These eruptions could explain the Mediterranean clouding and the poor growth registered in trees around 536 and 540.[66]

This redating was not immediately accepted. A 2011 study of a new South Pole core dated an "unusually large" eruption to 531 ± 15; and a 2012 study found a major volcanic signal in an East Antarctic core and finely dated it, via the counting of annual ice layers, to late 531.[67] The authors of the first study proposed that a single large eruption was behind their strong 531 ± 15 signal and the 542 ± 17 Antarctic signal identified in 2004, but they wagered that the source event occurred about 535 rather than 539 (the pull of Mediterranean clouding was stronger it seems than narrow tree rings at 540–1). The authors of the latter study agreed that the Greenlandic and Antarctic signals at 533 and 542 referred to a signal episode, as Larsen proposed, but they fixed it a date of 531–3—which meant it could no longer explain either the clouding of 536–7 or the thin tree rings of 540–1.

Then in 2013–15, several studies came out refining both the dating and scale of eruptions identified in ice cores. The first of these found both of Larsen's large eruptions, at around 529 and 534, in new ice cores from Greenland and Antarctica.[68] The second, using additional Antarctic cores, found signals at 543 ± 17 and 515 ± 18 and tied them to Larsen's Greenlandic horizon of 533/4 ± 2 and the 536 event.[69] Another 2014 paper, combining a reappraisal/redating of multiple existing Antarctic cores with several new and existing ones, identified an eruption at 531 as a bipolar "global-scale" event, and the fifth-largest eruption of the last 2000 years—big, but a not insignificant demotion.[70] A 2015 analysis of several Greenlandic cores, which employed Baillie's six- to seven-year bump, then found large sulfate horizons at 535/6 and 539/40. It located the second, but not the first, of these eruptions in Antarctic cores.[71] Most recently, glacier ice from the Western Belukha Plateau in Siberia's Altai Mountains was shown to contain high sulfate levels rather roughly dated at 520 ± 100, 540 ± 100 and 550 ± 10, one of which was assigned to the 536 event. Study of the oxygen isotope variability in this core, indicative of seasonal air temperature, also suggested that the most prominent of these signals was associated with some of the coldest temperatures (lowest $\delta^{18}O$) of the first millennium CE in the region.[72]

32.6 Origins

Soon after a major mid-sixth century eruption was detected in Greenland ice, scholars turned to Byzantine writers to fill out the details of an important climatic event.[73] Once they had connected the acid horizons in ice cores and the narrow and frosty tree rings to historical descriptions of mystery clouding, natural scientists essentially concluded that the phenomenon was volcanic in origin, extended far beyond the Mediterranean Sea, and had an extra-Mediterranean source.

Large, violent volcanic eruptions can inject tens of millions of tons of ash, hydrochloric acid, and sulfur dioxide into the atmosphere. The first and second fall to earth within weeks. The sulfur dioxide, however, mixes with water in the atmosphere to produce fine sulfuric acid aerosols. If these reach the stratosphere, they can dim incoming sunlight on a hemispheric or even global scale for multiple years. In the stratosphere, sulfuric acid aerosols absorb and backscatter solar radiation, warming the stratosphere's temperature but lowering that of the earth's surface. Recent eruptions, far less explosive than those during the downturn, are known to have lowered global temperatures by 0.1–0.4 °C for upwards of three years, with more dramatic cooling in the first three months where veiling was densest. At the height of the 1991 Pinatubo event, a downturn of 1.3 °C was observed instrumentally.[74] The 1815 Tambora eruption—still smaller in most proxies than the sixth-century volcanism—is thought now to have lowered temperatures by upwards of 4 °C (see Chap. 35).[75]

Various volcanoes have been blamed for mid-sixth-century cooling. The first proposed, in 1980, was Mount Churchill, Alaska, whose eruption had been radiocarbon dated to around 700 ± 100.[76] This possibility was dismissed shortly thereafter for an eruption at Rabaul, Papua New Guinea, then radiocarbon dated to 1430–1390 BP and dated, by Stothers, to 540 ± 90.[77] Rabaul was soon rejected, too, in favor of a Northern Hemisphere eruption: in 1986, an Antarctic ice core had emerged showing a horizon only at around 505 and it was surmised that the clouding around 536 originated north of the equator, though by then the ice core signals for a big event in the mid-530s had been redated.[78] Following the 2004 detection of a large volcanic episode in Antarctic ice, Rabaul was reproposed as the source of the downturn; however, subsequent studies of the eruption site reassigned Rabaul's eruption to the seventh century (first to around 633–70, then around 667–99), taking it once more out of contention.[79] In his popular history, *Catastrophe*, Keys assigned the cooling to a super-eruption at Indonesia's Krakatau, which he thought severed Sumatra and Java.[80] This proposal gained little currency.

In any case, a single massive eruption could not account for more than a decade of cooling, as paleoclimatologists have now long acknowledged. Moreover, as the trees tell us, the cold was not constant. Recent assessments of polar ice affirm that multiple unique sources underlay the downturn, including a cluster of large eruptions; the first two, and the largest, occurred at 535/6 and 539/40.[81] The record of sulfates in Arctic and Antarctic ice firmly places the first eruption in the Northern Hemisphere, quite possibly at high latitudes, and the second in the tropics.[82] Additional downturn volcanism, smaller but still large, around 545/6 and 550/1, has attracted less attention.[83] The ice core records strongly suggest that the downturn only became global with the eruption at about 540. Indeed, while the eruption of around 536 left a big mark on Greenlandic ice, it is, so far, only faintly visible in Antarctica in the West Antarctic Ice Sheet core. The follow-up 540 eruption is very visible in both Antarctic and Greenlandic ice. Recent work on sulfur isotopes, using samples from the Greenlandic Tunu13 core, confirms that eruptions both around 536 and around 540 were stratospheric, that the former was high-latitude Northern Hemispheric, and that the latter was near equatorial.[84]

Tephra and palynological studies led, in 2009, to the dating of a major explosive event at Mexico's El Chichón to the early sixth century. This event, fixed at 550–650 in 1984 and 553–614 in 2000,[85] was proposed to have occurred precisely in 539, following the dendroclimatological data for severe cooling about 540—rather than reports of mystery clouding, which the authors suggest was sourced by a local tropospheric Mediterranean eruption.[86] A year later, it was argued, Ilopango, El Salvador, was the source of dark Mediterranean skies in 536. A reappraisal of physical evidence for Ilopango's Tierra Blanca Joven (TBJ) eruption, considered the largest Central American volcanic event of the last 84,000 years, moved the episode's date up from 260 ± 114 to 495 ± 55, and a fragment of a tree carbonized in the TBJ event was given a date consistent with 535, making Ilopango a very good fit.[87] However, the more recent finding that the second major eruption of the downturn (*c.* 540) was near the equator, unlike the first atmospheric-clouding event, has led one team of scholars to bump Ilopango to 539/40.[88] A separate study concluded that an eruption site at about 15°N best matched the distribution of the remnants of volcanism found in polar ice at 540.[89] Ilopango sits at 13.67°N and El Chichón at 17.21°N. Another possibility raised for the northern high-latitude eruption that initiated the downturn is Haruna, Japan.[90] The major Plinian eruption of this mountain, northwest of Tokyo, has been dated archaeologically to the mid-500s.[91] If Haruna erupted in about 536, detailed analysis of tephra lodged at the 535–6 mark of Greenland's NEEM core, still in part being worked on, suggests that it was not alone. This work finds that there were multiple eruptions around 535. Although it is uncertain how many of these events were stratospheric, the tephra implies several North American sources, casting doubt on Haruna's role.[92] North American or not, the ice core data concurs that a large eruption of 535/36 was Northern Hemispheric and mid-latitude.[93]

The veiling observed over the Mediterranean in 536 and the global cooling registered in tree rings could have different origins. Silence in other European texts,[94] and the absence of severe cold at 536 in the Constantinopolitan tree ring chronology (assuming those trees register cold events, which they very well may not), both suggest that the observed veiling may have been temporally and spatially limited.[95] In his 2005 analysis of the literary sources, Arjava argued that Mediterranean observations of veiling only testify to an affected zone north of 35° or 40°.[96] Earlier, however, it was argued that since observers north of 40° report twelve months of veiling and John of Ephesus (thought then to be have been somewhere between 30° and 37°N) reported eighteen months of veiling, the eruption should be located south of 30/37°N.[97] These estimates are a touch rough, but they could still agree with the tephra-based reasoning that the eruption at around 535 was North American and with the conclusion, pulled from ice cores, that the event was extratropical. They also fit with the abovementioned modeling, which finds the densest aerosol loading for the 535/6 eruption north of 30°.[98]

Nevertheless, it is possible that a smaller Mediterranean eruption caused the mystery cloud at the same time that some larger event initiated the downturn. Mediterranean volcanic activity is restricted largely to central and southern Italy (Etna, Stromboli, Vesuvius, and Vulcano) and the southern Aegean (Kos, Methana, Milos, Nisyros, Santorini, and Yali). Much ancient and medieval volcanism in the region remains obscure. Scholars have harnessed various written and archaeological sources as well as archaeomagnetic dating of lava flows and radiocarbon dating of tephra layers to construct eruption series for individual sites.[99] Many Mediterranean events, such as the 1631 CE Vesuvian eruption, the most lethal in that mountain's history with perhaps 8000 dead, were explosive, but did not affect climate.[100] Some, such as the 472 CE "pollena" eruption from that same "extinguisher of all green things," left traces in the archaeological, ice core, and tree ring record but still did not greatly shift climate.[101] Marcellinus Comes wrote that this eruption "showered the whole surface of Europe with fine particles of dust" and was celebrated annually on November 6 in Constantinople some 1200 km away. Another Byzantine tells us that the ash in the imperial city was four fingers deep.[102]

There is no witness of a large Mediterranean eruption or ash fallout in 535–50. In 536, Procopius reported rumbling at Vesuvius alongside a description of a typical volcanic event.[103] Between 472 and 536, that mountain had already vomited ash and lava in a regional event in July 512.[104] Procopius' account has led some volcanologists (seemingly unaware of the dendroclimatological and ice evidence for the downturn) to assign the mystery clouding to the Campanian site.[105] Yet there is also archaeomagnetic evidence for "a large explosive eruption" at Stromboli in 550 ± 50.[106] A local eruption at either site might account for the reported dimming of the sun and a greater, distant event detectable in the form of the first dip in global temperatures discerned in tree rings, speleothems, and polar ice. A new Alpine ice core extracted in 2013 along the Swiss–Italian border may soon shed light on this matter.[107]

Not all researchers, however, have thought a volcano responsible. Before the recent redating of many major eruptions—when it still appeared that there were no volcanic horizons in polar ice plausibly related to the 536–50 climatic downturn—some scholars proposed that a "medium-sized asteroid" struck "one of the world's oceans" or a comet disintegrated in the upper atmosphere ("an airburst") and ignited "one or more large-scale forest fires." Both asteroids and comets were thought capable of filling the atmosphere with debris, which could reflect enough sunlight to cause a decade-long "climatic recession" beginning in 536.[108]

Several authorities judged an extraterrestrial vector a "much less likely" explanation than a volcanic event even without evidence for an eruption,[109] and Baillie, the principal advocate of the impact theory, retracted his proposition in

2008.[110] Nevertheless, in 2004, it was mathematically determined that a comet of less than one kilometer in diameter could generate multiple, successive years of dust veiling, and it was suggested that the earth may have been struck by such a rock as it passed through the Taurid meteor complex, as it does every November–June, and which is thought to have broken up around 500 CE.[111] In 2008, iron oxide and silicate spherules, alongside other plausible ejecta indicators, were recovered in meltwater at the "lost" 536 mark of the GISP2 core, again suggesting an impact event. Further analyses found nickel and tin particles and a high concentration of calcium. The latter was interpreted as calcium carbonate (a primary component in seashells) following the discovery at the same horizon of an assemblage of tropical and subtropical marine-life microfossils—a first for Greenlandic ice cores. Based on the radiocarbon dating of the formation of the Gulf of Carpentaria crater (Australia), the crater's chemical similarities with this GISP2 horizon, and the size of extraterrestrial rock considered necessary to generate both the crater and the observed dust veil, a team of scholars proposed that an impactor 640 m in diameter landed in Australia, causing the 536 event.[112]

To account for these findings, these scholars argued that the downturn's first low had multiple origins: a major volcanic eruption coincided with a comet impact and/or a low-latitude oceanic "explosion."[113] The possibility of multiple origins of the first low around 536 cannot be discounted.[114] Other phenomena were also raised as potential causes when ice core evidence for volcanism was still lacking: an "interstellar cloud" of unknown origin and, for Mediterranean dimming specifically, a tropospheric "damp fog."[115] It is certainly clear that multiple events forced the downturn as a whole: at least several large explosive volcanic eruptions, the first (one but possibly two or more[116]) 535/6 in the Northern Hemisphere, possibly at Haruna but more certainly in northern North America, and the second a near equatorial "global" event about 539/40, perhaps Ilopango or El Chichón.

32.7 Collapse and Resilience

Much has been written on whether the 536–50 climatic downturn—however understood—caused cultural, demographic, or socioeconomic change. As with many pre-modern short-term climate events, its human impacts are difficult to discern where the written sources are "thick," enigmatic where they are thin, and nearly imperceptible where they are non-existent. Archaeology, the sole source of relevant data for most affected regions, is incapable of revealing the downturn's toll with precision. No matter how vast and severe, the human implications of climate anomalies are often hard to tease out of the material record.

There has been a tendency among historians to ignore or downplay the paleoclimatic evidence, to demote the anomaly to a minor atmospheric incident, and thereby understate its cultural, demographic, and economic significance. These scholars miss an opportunity to see the downturn for what it was and to highlight the resilience of contemporary societies to abrupt and severe climatic anomalies. Indeed, many prefer to write history as though sixth-century peoples (and pre-modern organic agrarian economies in general) were undisturbed by dramatic temperature fluctuations.[117] At the other end of the spectrum, many natural scientists, and some historians and archaeologists who prioritize climate proxies, have described the event as a watershed, an almost unparalleled phenomenon that shook sixth-century societies. These scholars tend to view sixth-century peoples as highly vulnerable to environmental change, socioeconomically weak and rigid, and consequently incapable of adapting to an anomaly of this scale.[118]

The 536–50 downturn was a significant and rare event. Yet claims that it spawned a new era—whether in the Americas, Asia, or Europe—are as groundless as suggestions that it did not affect contemporary peoples are short-sighted. Although no account directly connects the Mediterranean mystery clouding of 536 to famine, qualitative evidence for harvest quality in the 530s and 540s suggests that the downturn did drive some demographic and economic change. A comparative approach that considers the effects of lesser volcanic episodes on better-documented populations also suggests that the sixth-century eruption cluster would have negatively affected harvests in many regions. It is the cultural and socioeconomic effects imputed to these food shortages that remain questionable.

It has long been recognized that sudden drops in summer temperature of 0.5–1 °C or more can have disastrous consequences for food production in temperate regions by shortening the growing season, limiting arable land, and augmenting the risk of harvest failures.[119] But proxies must be employed carefully to understand the downturn's effects on crops, and gaps in the paleoclimate data must be acknowledged also. The impact of a spectacularly cold and/or dry year would have varied from region to region, harvest to harvest, and plant to plant. Regions already cold and dry perhaps suffered more than warm and wet ones. As noted, trees reveal only growing-season conditions, and their temperature signals do not offer the timing and precision needed to fully understand the impact of a year's weather on crops. Not only the severity but also the timing of a downturn's climatic shifts within the growing year are important (see Chap. 27).

Here, analogies with more recent eruptions are instructive. Multiproxy paleoclimatology indicates that large tropical eruptions of the last 500 years have caused cold-dry summers but wet-warm winters in the Northern Hemisphere for two or three years, unlike large high-latitude eruptions which forced cold-dry winters and summers.[120] The first and second lows of the downturn, therefore, may have affected crops differently. In the Mediterranean, where winter precipitation is fundamental, the tropical event of 539/40 may have been beneficial in some ways. Its climate forcing may also explain the aforementioned blossoming of Korean fruit trees in the winter of 540. That said, warm-wet winters would not have been a boon for food production in all regions, and a shorter growing season is detrimental for crops everywhere.

Moreover, if most sixth-century societies were able to absorb one bad year, very few were able to absorb successive harvest failures. Back-to-back years of extremely poor growing conditions were certain to take a toll. Sharp cooling of 1.5 to 4 °C in consecutive years should be expected to have generated significant subsistence crises—true famines, in other words.[121] It has been shown that at least eight volcanic events between 750 and 950 registered in polar ice correspond to harvest failures recorded in European sources.[122] Not one of these eruptions or food shortages created catastrophe, although each undoubtedly eroded human numbers through hunger and associated epidemic disease. The eruptions and cooling of 535–50 were significantly more severe, suggesting that they would have generated more widespread and ruinous harvest failures. Yet, such events are not easily detected in sixth-century sources. We surely cannot generalize about an intercontinental famine spanning 536–50.[123]

At least one region, Thrace, was already suffering dearth on the eve of the mystery cloud. Justinian referenced a grain shortage there in a *novella* (decree) directed to a local consular, dated June 15, 535.[124] The initial low of the downturn presumably worsened that dearth. In addition to the description of the mystery cloud, the letters of Cassiodorus give several indications of crop failures. In 537, he wrote of a general food shortage throughout the provinces, failed harvests in Liguria, and "starving people" in Lombardy, but a rich Istrian harvest (of grapes, olives, and grains). In 538, he reports growing-season frost and drought injuring grain, fruit, and grape crops, as well as general food scarcity, although his letters also mention "an exceptionally abundant" previous harvest that should be able to stave off present penury. In 538, he also observed another good grape crop in Istria but Friulians and Venetians suffering a dearth of millet, wheat, and wine crops.[125]

John the Lydian stated bluntly that the dimming of the sun destroyed crops, and John of Ephesus observed that it harmed the harvest and prevented fruits from ripening ("all the wine had the taste of reject grapes"), but neither speaks of widespread hunger.[126] Pseudo-Zachariah wrote simply of the 536–7 winter causing "distress" in Syria.[127] The provisioning, disruptions to agriculture, and destruction of arable associated with the initial phase of Justinian's Italian reconquest (535–40) caused multiple local Italian shortages and possibly worsened a general agricultural crisis.[128] John the Lydian and Pseudo-Zachariah may indicate that a food shortage existed beyond the theater of war. Other sources shine some light here. The *Liber Pontificalis* documents a hard shortage within besieged Rome in 537 but also a great subsistence crisis "throughout the entire world"—one so dear that, according to a report from a Milanese bishop, Ligurian mothers were driven to consume their own children.[129]

To the north, Irish annals document a "failure of bread" in 536 and 539 (the latter is possibly a doublet), and the Welsh *Annales Cambriae* speak of a "mortality in Britain and Ireland" in 537.[130] Severe food shortages are reported in China as well. In the eastern region between the Yangtze and Yellow Rivers, the cold summer of 537 is written to have caused widespread harvest failure and triggered a famine the following autumn. Unusual weather is associated with famine and human mortality for multiple years in China, in 536, 537, and 538. The population of a kingdom north of the Yellow River is reported to have declined 70–80%.[131] There are indications, as noted, that harvests were poor in Korea (then south and north of the Yalu River) and Japan too.

These texts convey short-term demographic shocks in several regions of Eurasia, but not a vast long-term crisis across continents. Europe and the Mediterranean certainly did not then "decline into the Dark Ages."[132] The dearth of evidence for a vast population crisis in 536–7, and the lack of any mention of poor harvests or mortality in the sources for some regions, may reflect the success of some peoples and the failure of others to cope with the poor harvests that the downturn caused. Alternatively, the lack of evidence for a pan-Eurasian crisis may reflect the unequal effects of volcanic dust clouding as well as geographical and seasonal variation in the downturn's climatic effects. The aforementioned simulations of downturn volcanism suggest that the densest aerosol loading from the two largest eruptions was by and large confined to the Northern Hemisphere. Clouding in 536 was severe north of 30°N and 540 clouding north of about 5°N. But the clouding of both events was markedly worse north of 50°N. The same study identified the Baltic region in particular as hard hit.[133] A multiproxy study that covers China's sixth-century climate also suggests, albeit with some uncertainty, that the downturn did not everywhere cool temperatures and that its effects varied regionally. Indeed, at least one area of East Asia (far northeastern China) seems to have experienced warming.[134]

Absence of evidence is not always evidence of absence. Yet, the downturn has been posited as the cause of massive population contraction in some regions altogether lacking written records. Some scholars have considered this anomaly a plausible explanation for the considerable demographic and socioeconomic change revealed by archaeology in late migration period Scandinavia and late classical Maya Central America. In Scandinavia, successive widespread harvest failures and famine are thought to account for declining sixth-century settlement numbers, abandonment of arable and pasture, and a noticeable increase in gold hoards. The chronology of these phenomena and the dating of the archaeology, however, require that such bold claims be softened. Most of the gold hoards are only roughly dated to the first half of the century, others to mid-century. One deposit can be affixed a narrower 525–50 date.[135] Neither the decline (or shifting) of settlement nor the contraction of cultivation can be assigned precisely to the mid-530s either. In fact, both phenomena clearly predate 500. For example, Göthberg's data on the number of (excavated) settlements in Uppland province (Sweden) spans millennia. It shows an unprecedented sixth-century "collapse" in the range of 75% of sites, but a gradual decline had set in from about 300 CE.[136] Likewise, the abandonment of tens of well-worn gravesites in Västmanland province (Sweden) can be assigned a rough sixth-century date, but such burial ground desertion was nothing new there.[137]

These uncertainties have not stopped some scholars from assigning vast consequences to the downturn in Scandinavian and Baltic countries.[138] These include the reorganization of power structures, property rights, trade networks, and burial customs, as well as a contraction in metallurgy and craft production: all phenomena only loosely discernable in the material record and vaguely dated to the sixth century.[139] More tenuous are associations between the downturn and mythical bouts of severe weather, for instance the dimming of the sun, moon, and stars, and the Fimbulwinter—a three-year-long, snowy, frost-laden winter that precedes Ragnarök, the destruction of the known world.[140] Yet, the paleoclimatology and climate modeling does indicate that the downturn greatly affected climate in this region.

An ocean away, Gill has argued that the downturn accounts for the Maya "hiatus" described above. He accordingly assigned a firm start date of 536 for this Mesoamerican interval, drawing on high-resolution dendroclimatology from elsewhere. Gill implicated El Chichón, then with a large eruption roughly dated to the fifth or sixth century, and tied 536 aridity and cold to unrest, conflict, and population collapse: "a genuine demographic disaster" of 70–73% in "large areas" of the Maya Lowlands.[141] How dramatic the effects of downturn volcanism were in this world region, however, remains to be seen. In the modeling mentioned already, Central America, unlike Scandinavia and the Baltic, is largely spared both the brunt force of the 536 event and also the worst of the larger 540 event.[142]

The downturn is commonly thought to have affected populations in and beyond these regions through harvest failures and famine. In Europe and Western Asia, mass poisoning and pandemic disease are also implicated.[143] One theory connects population contraction in late migration period Scandinavia to the widespread poisoning of common grains (cold-tolerant rye but also barley and wheat). It is hypothesized that the anomalous weather encouraged the growth and spread of the parasitic plant fungus *Claviceps purpurea*, causing ergotism.[144] This theory hinges partially on the extensive cultivation and consumption of rye, the grain most vulnerable to ergot, in pre-downturn Scandinavia. Another theory holds that the downturn drove neighboring Estonians to start cultivating rye.[145]

The downturn's connection to the well-known Justinianic Plague is more complex.[146] Many scholars have rightly grouped the demographic effects of the climate anomaly with those of the first wave of this pandemic.[147] Procopius reports the arrival of the fast-spreading lethal disease in the Nile Delta region in mid-July 541. Through him and other witnesses, we can piece together the pathogen's subsequent dissemination through Western Asia and Southern Europe between 541 and 543. Other regions of Asia, Africa, and Europe were certainly affected, too, before and after this 541–3 window. Ireland was likely hit in 544.[148] The sudden and dramatic mortality in the plague may have precluded famine during the 540s and partially explain the absence of evidence for dearth following the second eruption of 539/40.[149]

Some scholars have proposed that the climate anomaly actually caused or triggered the pandemic.[150] The proposed connections between the two events depend on the *Yersinia pestis* diagnosis of the pandemic and the path envisioned for the pathogen's dissemination. Keys has argued that a drought followed by extreme rainfall fostered a population explosion of sylvatic rodents in East Africa (where there is no high-resolution data for climate in 536–41 or the sixth century generally).[151] The rodents expanded their natural range and spread the pathogen eventually to commensal rats in the Mediterranean.[152] Other scholars have found the basic tenets of this theory plausible.[153]

Historians long favored a Central or East African origin for the Justinianic Plague (*Y. pestis* now possesses enzootic foci in rodents there).[154] Genetic studies have recently concluded, however, that the *Y. pestis* found in Justinianic Plague-era graves from Bavaria ultimately came from northwestern China.[155] An alternative theory, by historian Stathakopoulos, that the drought-triggered migration of 15,000 people from Iran to Syria introduced the pathogen to the Mediterranean region, better suits this recent finding.[156] So too does McCormick's proposal that the pathogen reached Pelusium at the eastern edge of the Nile Delta via the Red Sea and points further east.[157] It should be noted that although the *Y. pestis* strain isolated from late antique skeletons best matches plague strains found in northwestern China, it is not impossible that the Justinianic *Y. pestis* emerged from a region closer to the Mediterranean than East-Central Asia. Extinct reservoirs could have existed for this northwestern Chinese-like strain in, for example, Africa or West Asia. It has also been proposed, though *Y. pestis* is not an opportunistic infection, that the downturn heightened plague mortality through harvest failure, famine, and malnutrition,[158] and that the unusual weather encouraged the dissemination of pneumonic plague, bubonic plague's more mortal variant, which does well in colder climates, as it spreads most effectively in closed indoor environments.[159]

Of course, if the climate anomaly did lend itself to this pandemic, it can account only for the initial occurrence, not the subsequent thirteen to seventeen outbreaks which took place over the next two centuries.[160] Although climate anomalies are thought to underlay many European recurrences of the Black Death (via their effects on bubonic plague-carrying Asian rodent populations),[161] and are generally considered vital in the history of disease,[162] similar environmental triggers have not been established yet for reappearances in the Mediterranean world of the Justinianic Plague.[163] It is worth noting, however, that recent genetic research indicates that the *Y. pestis* introduced to Europe with the Black Death seems to have become endemic or enzootic in some European regions.[164] Were this also shown for the Justinianic Plague, the downturn could be firmly implicated in the erosion of West Asian and European populations through plague from the mid-sixth to mid-eighth centuries. In other words, if the downturn was instrumental in spreading the plague to the wider Mediterranean region after 541 and if, once there, the plague focalized in one or more reserviors, then the downturn undoubtedly had a major demographic impact.

Downturn-driven dearth and malnutrition may explain why the initial outbreak of 541–4 seems to have spread farther and persisted longer in Europe and Western Asia than later outbreaks. Malnutrition may have raised mortality slightly, and poor harvests possibly fostered wider and longer lines of trade, facilitating disease transmission. On the other hand, the downturn may have inhibited the dissemination of a pathogen hosted in part by commensal rodents which favor warm climates and depend partially on stored grains. Similarly, the exceptional summer cold may have lessened the burden of malaria, a temperature-sensitive parasitic disease transmitted by anopheles mosquitoes.[165]

In whatever way it was related to the Justinianic Plague, it is reasonable to think that the 536–50 climate anomaly caused some demographic contraction in many parts of the world. Not all scholars have affixed significant cultural and economic change to this depopulation. A number of historians see the 536–50 event not as a significant driver of change but as a short cold trough in a larger multicentury climate reorganization (or "deterioration"[166]) of late antiquity (that for some predates 536 but for others starts in 536), which fostered a large but gradual agricultural and demographic transformation of late antique Western Europe and the Mediterranean.[167] Some emphasize the downturn's unfortunate timing. From a Byzantine perspective, the cooling and aridity drove a "reduction of revenues and available resources in a time of high expenditure and rising insecurity."[168] This moderatism takes the position that socioeconomic and environmental explanations of change are not mutually exclusive. Such scholars find direct, mono-causal links between the downturn and long-term agrarian or population trends "quite unconvincing." Yet, they do not dismiss the anomaly outright. Rather than a watershed, it was an accelerator of change already underway.[169]

Similar approaches have emerged for other world regions.[170] Scholars of the northern and southern dynasties in China have argued that the anomaly contributed to—but did not cause—political instability, since poor harvests affected the collection of grain taxes and shrank state resources.[171] One recent study of the downturn in Central America held that it brought severe drought but argued that Maya cities were unevenly affected: some were prepared to absorb and respond to sudden climate "deterioration," others not. Calakmul, for instance, experienced profound growth, even "florescence," during the hiatus.[172] Differences in aridity and elevation also meant some settlements were more vulnerable than others. Already dry cities suffered more from arid episodes. Of course, water access and management mattered greatly as well in Maya cities, if they relied on tribute for access to reservoirs that could dry up in droughts.[173] A focus on hydrology has led to the suggestion that low-lying coastal sites were most resilient during the "hiatus" and "collapse."[174]

In short, the downturn's effects were complex and varied, more indicative of the dynamism of human–environment relationships than of system collapse.[175] The ability of contemporary populations to be resilient in the face of poor harvests should not be underestimated. Poor yields were not new anywhere in the 530s and contemporaries can be expected to have possessed a number of coping strategies to ward off dearth.[176] Scholars who propose that the downturn generated widespread famine in Europe and Western Asia may overestimate reliance on grains. Although the sudden onset of successive years of severe cooling would have affected adversely plant life of all sorts, not just sown crops, including grasslands, silvopasture, and possibly aquatic flora essential for animal and fish populations, traditional ecological knowledge and collective memory, however difficult to discern now, would have ensured some adaptive capacity across the globe.[177] Of course, neither harvest failures nor the ability to cope were everywhere equal, and some populations would have been more resilient than others, as crop varieties, cropping strategies, and systems of agrarian production and management varied tremendously. There may have been, as such, big variations in mortality over relatively small spaces.

32.8 Conclusion

The 536–50 downturn has no definitive history yet. Paleoclimatology now makes clear that a cluster of very large volcanic eruptions underlay the anomaly, including explosive events around 535/6 and 539/40, and lesser but still large eruptions in about 545/6 and 550/1. Each of these events shows up in tree rings in the Americas, Asia, and Europe. The first eruption was one of the largest of the last several millennia in the Northern Hemisphere. The second, a tropical eruption, was bigger. From 540, the downturn appears to have gone global. That said, more high-resolution paleoclimatology is needed, particularly data from the Southern Hemisphere. Proxies that reveal winter conditions and multiple climate parameters are also badly needed. Data on the impact of downturn volcanism on precipitation is sparse. Yet, while our understanding of the downturn's spatial and temporal contours will improve, its exceptionality and severity have been well established. The uniqueness of the event is locked in trees and other natural archives. Written descriptions of the Mediterranean mystery clouding are no longer the most telling evidence.

Historians must keep apace as more natural proxies of sixth-century temperature and precipitation come into play and existing proxies are perfected. Local, regional, and global histories continue to assign the event different degrees of importance, depending on the inter- or multidisciplinarity brought to bear, the priority given to different categories of evidence, as well as the resiliency envisioned of contemporary societies. To understand the origins, extent, severity, impact, and human responses we must bridge disciplines and weave together paleoclimatic, written, and archaeological data.

That temperatures fell dramatically in the mid-sixth century, and that multiple regions experienced especially dry conditions, does not mean catastrophe ensued. Resiliency and vulnerability to sudden and severe climate anomalies will have differed between and within contemporary cultures. Even in the worst-affected regions (perhaps Central America and Japan if the eruptions took place there), people would have been affected unequally according to the uneven distribution of, or entitlement to, resources. It has been proposed that the effects of the dearth in Sweden varied between classes, that elites with larger reserves of foodstuffs and ability to participate in long-distance trade had a better chance of survival as well as a "window of opportunity" to seize deserted lands and better themselves.[178] Of course, not all regions were equally affected to begin with: veiling density and distribution varied, so too the effect of cooling and drying on agro-ecosystems. By carefully interweaving the information afforded by natural archives with understandings of the ability of cultures to respond, we will begin to tease out how the 536–50 downturn registered with people on the ground. Neither unnoticed nor a demographic watershed, this anomaly was remarkably severe and unusual in recent millennia. It remains a major episode in environmental history warranting further investigation.

Notes

1. A handful of antiquarians and Byzantinists drew attention to accounts of a *c*. 536 Mediterranean mystery clouding before the 1980s (Stathakopoulos, 2003, 247–49), but none envisioned this atmospheric phenomenon was part of a European, Eurasian, hemispheric, or global climatic event before NASA scientists Stothers and Rampino: Stothers and Rampino, 1983a, 412, 1983b, 6357, 6362–63, 6367, 6369; Stothers, 1984; Rampino, 1988, 87–88. Early Byzantinist scholarship notably includes Koder, 1996, and Farquharson, 1996, 266–68, 76–77.
2. Masson-Delmotte et al., 2014; Steig et al., 2013, 373; PAGES 2K Consortium, 2013, Tab. 1, Fig. 2; Jones et al., 2009, 6, 7. Although there remain many large gaps in our knowledge, limited evidence indicates temperature was not unusual in the mid-sixth century near the South Pole. Recent simulations of the climate forcing of downturn volcanism also suggest that the Southern Hemisphere was relatively unaffected: Toohey et al., 2016, 406. It is notable that Tambora too appears not to have much disturbed extratropical climates south of the equator: Raible et al., 2016, 569, 572, 582. The climate forcing of that 1815 eruption was slightly less than that of the *c*. 540 event: Sigl et al., 2015, 547–48, Extended Data Tab. 4. Yet, as Raible et al., 2016, remark (576), a dearth of climate records in the Southern Hemisphere may account for Tambora's poor showing in the south. Of course, there are even fewer records for the sixth century.
3. Sigl et al., 2015, 547–48, Figs. 2 and 3, Extended Data Tabs. 4 and 5.
4. Büntgen et al., 2016. This LALIA falls within a longer period of less extreme cooling (known by many names, including Vandal Minimum, Late Roman Cold Period, Migration Period Pessimum, and Early Medieval Cold Anomaly) that commenced, depending on the proxy employed, in the fourth or fifth century and petered out in the seventh or eighth century. For example, Büntgen et al., 2011, 581; McCormick et al., 2012, 191–99.
5. Luterbacher et al., 2016, Fig. 1.
6. Toohey et al., 2016, 401, 405, 406, 410, Fig. 2.
7. Some historians have over-generalized the fragility of paleoclimate dating: try Moorhead, 2001, 143. The dendroclimatological data has proven robust. The ice core data is trickier. Yet the former cannot be problematized on account of the challenges the latter can present.

8. Bondesson and Bondesson, 2014, 63, for instance, claimed the cause of the downturn, which they consider both vast and severe, "remains unclear," and they seem to suggest the event was restricted to the mid-530s, even though its volcanic origin was reconfirmed in 2008 (and only since reinforced) and its decadal duration was made evident no later than 1994.
9. The notable exception is Arjava, 2005, 73–94. Many in the humanities continue to read the paleoscience through Arjava's paper, though much has changed since 2005. See Power, 2012, 190; Lee, 2013, 290.
10. Keys, 2000; Wickham, 2005, 549.
11. McCormick writes of a "tremendous volcanic winter" in 536 with widespread atmospheric effects that "must have had serious economic and human consequences" but which only "weakened and did not destroy" the Roman Empire revived under Justinian: McCormick, 2013, 72, 88.
12. Cassiodorus' first appearance: Rampino, 1988, 87.
13. Cameron, 1985, 14.
14. Procopius, 1916, IV.14, 328–29.
15. Cassiodorus, Variae 12.25, 518–20.
16. Lydian, 1897, 25. On the misdating: Arjava, 2005, 80.
17. Pseudo-Dionysius of Tel-Mahre, Chronicle, 65.
18. Michael the Syrian, 1901, 220–21.
19. Pseudo-Zachariah Rhetor, Chronicle 9.19, 370.
20. Pseudo-Zachariah Rhetor, Chronicle, 370 n. 305.
21. Arjava, 2005, 79.
22. Pseudo-Zachariah Rhetor, Chronicle 10.1, 399.
23. Marcellinus Comes, Chronicle, 39.
24. Arjava, 2005, 80–83; Stothers and Rampino, 1983b, 6362.
25. Notably: Stothers, 1984, 344–45; Rampino, 1988, 87: "the densest and most persistent dry fog in recorded history was observed during AD 536–537."
26. Lydian, 1897, 25; Arjava, 2005, 80.
27. By which John may have meant Ethiopia or southern Arabia. Sixth-century Byzantines sometimes confused the two: Sarris, 2002, 171; Schneider, 2015, 184–202.
28. It was suggested John borrowed his explanation from Campestris who lived centuries earlier. Arjava thinks this dubious: Arjava, 2005, 81.
29. Keys, 2000, 253; Abbott et al., 2014b, 413.
30. Weisburd, 1985, 91–94; Houston, 2000, 71, 73, 77. Whether there is textual evidence for exceptional cold and drought in West Asia and Europe in the 540s remains to be determined. Previous searches have centered on 536.
31. Aston, 1896, 34–35.
32. Shultz, 2012, 122–24. There appears to be nothing potentially related to the downturn in Paekche Annals of the Samguk Sagi.
33. Koguryo Annals of the Samguk Sagi, 168–69. There appears to be nothing potentially related to the downturn in the Paekche Annals of the Samguk Sagi.
34. LaMarche and Hirschboeck, 1984, 121–26 (cf. Parker, 1985); Briffa, 2000, 87–105; Gao et al., 2008; Cole-Dai, 2010, 824–39.
35. Churakova et al., 2014, 145–49.
36. Esper et al., 2013, 2, 2015.
37. On these issues: Esper et al., 2015, 62–70; García-Suárez et al., 2009, 183–98.

38. 535 registered as the second coldest June–January in an early TRW study of a Sierra Nevadan pine chronology spanning 1–1980 CE (536 placed first), TRW and cell wall thickness analysis also drew attention to a 532 cold plunge in the aforementioned Altai series, and TRW analysis of the associated Sakha series revealed a pre-downturn 533 low. These Russian lows may be connected to local volcanism and suggest that the downturn had an early start in Siberia.
39. Cook et al., 2015.
40. Büntgen et al., 2011.
41. For instance: Esper et al., 2013, 736, Fig. 3.
42. Cook et al., 2006, 689–99; Larsen et al., 2008.
43. Pearson et al., 2012.
44. Major low-latitude eruptions, like the *c.* 540 event, are known to reduce global mean precipitation: Iles et al., 2013. Fischer et al., 2007, finds drier conditions in Central and Eastern Europe after more recent large (tropical) eruptions. Also Luterbacher and Pfister, 2015.
45. Pearson et al., 2012, 3405, 3411–12. Vesuvius' 472 eruption also does not register in this series. Narrow rings are apparent, however, at the 475 mark (see below), perhaps indicating a post-472 eruption dry spell.
46. Esper et al., 2013, 736, Fig. 3.
47. See Fig. 2.6 and references there cited in Luterbacher et al., 2012, 103.
48. Tan et al., 2003, 1617; Zhang et al., 2008, 940, 941 (Fig. 1).
49. Holzhauser et al., 2005; Thompson et al., 1985, 973, 1994, 85, 87, 92. The second study indicates dryness recommencing *c.* 570, following a decade-long hiatus, and continuing until 610. Chu et al., 2011, 789–90; Van Bellen et al., 2015, 1, 9. The Patagonian dry period, which seems to predate but span the downturn, is visible as well in another southern South American proxy too: Moreno et al., 2014.
50. Kobashi et al., 2011.
51. See note 2 above.
52. Sixth-century sections of long high-resolution Central American proxies are wanting. The region is held to suffer heightened aridity following large eruptions—see Gill and Keating, 2002, 125–33.
53. Hodell et al., 1995, 393 (Fig. 3); Curtis et al., 1996, 41, 44–46; Hodell et al., 2001, 1368 (Fig. 2), 2005, 1421, 1424 (Figs. 10, 15). These studies focus on the more severe and prolonged droughts corresponding to the classical "collapse," not the hiatus, though the latter is visible in them. The very existence of severe and prolonged classical-era droughts, however, has been questioned. The Chichancanab data has been reassessed and it has been argued that the arid cycles identified in the aforementioned 2001 and 2005 papers are "methodological artifacts": Carleton et al., 2014, 151–61. Dry conditions evident in the Chichancanab data, though, appear in other independent proxies from the region: Wahl et al., 2014, 23.
54. Medina-Elizalde et al., 2010, 260 (Fig. 7).
55. Webster et al., 2007, 1, 12, 13–14.
56. Rosenmeier et al., 2002, 183, 185, 188–89.
57. Haug et al., 2003, 1733 (Fig. 2).
58. Lane et al., 2014, 93, 95.
59. Gao et al., 2008; Cole-Dai, 2010, 824–39.
60. Hammer et al., 1980, 235.

61. Herron, 1982.
62. Hammer, 1984, 51–65; Clausen et al., 1997, 26,707–23.
63. Zielinski, 1995, 20,939, 20,944; Clausen et al., 1997, 26,707–23.
64. For instance: Cole-Dai et al., 2000, 24,435, 24,438–39; Kurbatov et al., 2006. On the missing GISP2 section, Zielinski, 1995, 20,940, 20,949, 20,953.
65. Traufetter et al., 2004, 141; Severi et al., 2007, 367–74; Larsen et al., 2008.
66. Baillie, 2008. Recently supported by Sigl et al., 2015, 543.
67. Ferris et al., 2011; Plummer et al., 2012, 1931, 1933–36.
68. Sigl et al., 2013, 1159.
69. Motizuki et al., 2014, 785, 798.
70. Sigl et al., 2014, 693, 694, 695.
71. Sigl et al., 2015, 544, 545, 547–48; also Büntgen et al., 2016.
72. Aizen et al., 2016, Fig. 5a.
73. Stothers and Rampino, 1983b, 6357, 6362–63, 6369; Stothers, 1984, 344–45.
74. Simarski, 1992, 3–5; Kelly and Sear, 1984, 740–43; Bradley, 1988, 221–43; Schmincke, 2004, 259–72.
75. Luterbacher and Pfister, 2015, 246.
76. Hammer et al., 1980, 233, 235. This 'White River Ash' eruption was redated recently to 833–50/847 ± 1: Jensen et al., 2014, 875–78.
77. Stothers and Rampino, 1983a, 412, 1983b, 6362; Rampino, 1988, 88. Cf. Heming, 1974, 1259.
78. Stothers, 1999, 717.
79. Traufetter et al., 2004, 141, 145; McKee et al., 2011, 27–37, 2015, 1–7. Stother's 540 ± 90 date was shown as well to be a mistake.
80. Keys, 2000, 277–78, 86–91.
81. Sigl et al., 2014, 695, 2015, 547–48. The second eruption had been earlier put in the tropics: Ferris et al., 2011 (who dated it to *c*. 535) proposed a "low latitudes" site and Larsen et al., 2008 (who dated it to 533/4 ± 2) were confident the eruption took place near the equator. Larsen et al., 2008, assigned the first event (with a 529 ± 2 date) a "more northerly source."
82. Sigl et al., 2013, 2015.
83. Both seem to register only in Greenlandic ice: Sigl et al., 2015, 547 (Fig. 5).
84. Andrea Burke, personal correspondence, June 20, 2016.
85. Tilling et al., 1984, 747–49; Espíndola et al., 2000, 90, 93, 102.
86. Nooren et al., 2009, 97, 101, 106–07. It is not specified why the dendroclimatological data for widespread cooling *c*. 536 was overlooked. Recently, Nooren et al., 2017 has again assigned the eruption to El Chichón.
87. Dull et al., 2010. Dull had previously dated the eruption to 410–535 and, more precisely, *c*. 430, Dull et al., 2001, 25, 27; Dull, 2004, 238, 243. A wide mid-fourth- to mid-sixth-century window is advanced independently in Mehringer et al., 2005, 199, 203–04, and Kitamura, 2010, 28.
88. Sigl et al., 2015, Extended Data Tab. 4 puts the Ilopango event at 540.
89. Toohey et al., 2016, 410.
90. Suggested by Larsen et al., 2008, but assigned to 529 ± 2 before being bumped by Baillie to *c*. 535.
91. Suzuki and Nakada, 2007, 1545, 1565; Soda, 1996, 40.
92. Sigl et al., 2015, 547; Gill Plunkett personal communication June 20 and 22, 2016.
93. Toohey et al., 2016, 406.

94. Gregory of Tours, Marius of Avenches, John of Biclaro, Victor of Tunnuna, and Isidore of Seville mention nothing plausibly related to Mediterranean sun dimming 536–7.
95. Pearson et al., 2012, 3402–14. One might also question why Cassiodorus had to inform his deputy about the dust veil (see above). If it were a major event, would he not have known? See also Grattan and Pyatt, 1999, 173–74, 77–78; Arjava, 2005, 73–94. Not long before the important study of Larsen et al., 2008, which established evidence for a volcanic origin of 536 clouding at both poles, Larsen advised Arjava (p. 77 n. 24) "nothing of interest" was found in Greenlandic ice layers between 531 and 550.
96. Arjava, 2005, 81–83.
97. Rampino, 1988, 87–88.
98. The modeling employed written accounts of clouding duration to help constrain the height of the eruption column. However, ice core data was used to establish the eruption's latitude, which is the important factor for understanding the latitudinal spread of volcanic aerosols. Matt Toohey, personal correspondence, November 1 and 2, 2016.
99. For instance: cf. Tabs. 1 and 7 in Principe et al., 2004, 705, 716–17, 719.
100. Oppenheimer and Pyle, 2009, 444; Mrgić, 2004, 238. Others, notably Rosi and Santacroce, 1983, 250, consider the most mortal Vesuvius eruption that of 472.
101. Rosi and Santacroce, 1983, 250–51, 253–55; Pearson et al., 2012, 3406 (Fig. 4). On 472: Kostick and Ludlow, 2015, 8–13.
102. Marcellinus Comes, Chronicle, 25; John Malalas, Chronicle, 14.42, 205–06; Chronicle Paschale, 90–91. For discussion, Stothers and Rampino, 1983b, 6361–62; Kostick and Ludlow, 2015, 8–13. These scientists also link Hydatius' account (35) of poor weather in northern Portugal to this event (Chronicon, ed. T. Mommsen MGH AA XI p. 35), though Hydatius' text stops in 469 and this passage should be fixed a late 460s date.
103. Procopius, 1919, VI.4, 324–27.
104. Cassiodorus, 1886, 261–62. Discussion: Macfarlane, 2009, 109–11; Cioni et al., 2011, 789–810.
105. See Principe et al., 2004, 705–07, 710 who attribute a ^{14}C dated tephra layer to 450 ± 50 to 536 (not 472 or 512) and speak of "an explosive eruption" that "must have occurred" considering evidence for Mediterranean clouding. Stothers and Rampino note 536 was "probably not" Mediterranean in origin, but Vesuvius may have erupted after Procopius left Campania: 1983b, 6362, 6367.
106. Arrighi et al., 2004.
107. http://climatechange.umaine.edu/colle_gnifetti_2013_.
108. Clube and Napier, 1991, 49; Baillie, 1994, 216, 1999; Rigby et al., 2004, 123–26. Further discussion of the impact of extraterrestrial impactors: Napier, 2014, 391–92.
109. For instance: Stothers, 2002, 4; D'Arrigo et al., 2003, 257.
110. Baillie, 2008.
111. Rigby et al., 2004, 123–26.
112. Abbott et al., 2008.
113. Abbott et al., 2014a, 2014b.
114. Kostick and Ludlow, 2015, 15.

115. Baillie, 1994, 216; Arjava, 2005, 79, 80, 93.
116. See note 92 above.
117. Moorhead, 2001, 147–48, concentrates on Mediterranean mystery clouding, misdates Cassiodorus' letter to 533, ignores other accounts of sun veiling, and emphasizes the "remarkable ability" of human societies to "bounce back from disasters, including widespread failures of crops."
118. Tvauri, 2014, 35, is well versed in the paleoclimology of the downturn (30–32) and suggests "primitive" agrarian technology then in Baltic countries made contemporaries especially vulnerable to famines far worse than those of the historical period. He proposes that a "single incident of famine" could erode centuries of population growth.
119. Parry and Carter, 1985.
120. Fischer et al., 2007.
121. The food shortage spectrum: Garnsey, 1988, x, 6, 20–37, 271.
122. McCormick, 2007b, 878–89; cf. Newfield, 2013, 125–48. Later examples: Atwell, 2001, 32, 42–62.
123. The 1257–8 eruption, recently assigned to Samalas, Indonesia, and long known as the largest of the Common Era, did not generate widespread famine. Unlike downturn events, however, dendroclimatology indicates this event did not much affect climate. Stothers, 2000, 361–74; Timmreck et al., 2009; Mann et al., 2012, 202–05; Anchukaitis et al., 2012, 836–37; Esper et al., 2013, 736.
124. For discussion: Stathakopoulos, 2004, 265.
125. Cassiodorus, 1886, 519–20; 12.22 (513–14); 12.27 (521); 12.28 (523–24); 12.26 (520–21).
126. John the Lydian, 1897, 25; Pseudo-Dionysius of Tel-Mahre, Chronicle, 65; Michael the Syrian, Chronique, 220–21.
127. Pseudo-Zachariah Rhetor, Chronicle, 10.1 (399).
128. Procopius documents several tactical siege shortages then: Stathakopoulos, 2004, 270–77.
129. Davis, 2000, 56. Note the reconquest reached Liguria in 538 and this episcopal report was delivered in person in Rome over the winter of 537–38 meaning the dire situation in Liguria is to be assigned to 537. Milan suffered a multi-month-long siege during the war, but in 538–39, also after this report.
130. Charles-Edwards, 2006, 94–95; Williams, 1965, 4. Note the CELT (Corpus of Electronic Texts) transcription of the Annals of Ulster dates the bread failure to 538: www.ucc.ie/celt/published/T100001A/index.html.
131. Weisburd, 1985, 93. Weisburd implies Chang State's summer snow and autumnal famine occurred in 536 in the text, but the map caption (also p. 93) seems to date these events to 537.
132. Grove and Rackham, 2001, 143–44; Diaz and Trouet, 2014, 168.
133. Toohey et al., 2016, 401, 406, 408–09, 410, Fig. 2.
134. Ge et al., 2010, Figs. 2 and 3.
135. Axboe, 1999, 186–88, 2001, 119–35. Bondesson and Bondesson, 2012, 167–70, discuss a twenty-item deposit dating to the second quarter of the sixth century.
136. Discussed in Gräslund and Price, 2012, 433–34; also Price, 2015, 258–59. Continuity is seen at many settlements.
137. Löwenborg, 2012, 10–13.

138. Gräslund and Price, 2012, 431–36; Löwenborg, 2012, 5–7; Tvauri, 2014, 32–34, 35–39, and references therein. Detailed discussion of a sixth-century site where bread was found as a burial offering: Arrhenius, 2013, 1–14.
139. Löwenborg, 2012, 5, 8–10, 15–17, 19–23; Tvauri, 2014, 39–40, 42–43, 44–47, 48.
140. The Fimbulwinter was recorded first in the late Viking period and long thought by modern scholars to be rooted in the climatic transition away from a warm Scandinavia Bronze Age about 600–450 BCE: Pettersson, 1914, 24. More recently it was assigned to the downturn: Axboe, 1999, 187; Gräslund and Price, 2012, 436–40.
141. Gill, 2000, 228–33, 245, 287, 313, 318.
142. Toohey et al., 2016, 401, 406, 408–09, 410, Fig. 2.
143. For example: Koder, 1996, 277; Farquharson, 1996, 266; Houston, 2000, 73, 74; Gräslund and Price, 2012, 433, 438; Löwenborg, 2012, 7, 17–18, 22; Tvauri, 2014, 32, 35, 36, 46, 48.
144. Bondesson and Bondesson, 2014, 61–67.
145. Palynology indicates a sixth- or seventh-century date for the wide sowing of rye in Estonia: Tvauri, 2014, 30, 47–48, 49.
146. Justinianic Plague: Stathakopoulos, 2004, 110–54; Horden, 2005, 134–60; Little, 2007.
147. Cheyette, 2008, 155–56; Gräslund and Price, 2012, 434; Löwenborg, 2012, 7, 17, 19, 24; Tvauri, 2014, 35; Headrick, 2012, 39–40; Kostick and Ludlow, 2015, 16. Long ago, Farquharson emphasized that the downturn was part of "an extraordinary clustering of events," which included pandemic and epizootic disease: 1996, 267.
148. Maddicott, 1997, 10–11, 17.
149. Campbell has observed that the Black Death's arrival in England forestalled a sequence of exceptionally poor harvests from creating famine: Campbell, 2010, 301–04; Campbell, 2012, 140, 144–47, 159.
150. Stathakopoulos, 2003, 254 observes that Seibel lumped this Justinianic Plague and mystery clouding together as though they were causally associated in his 1857 work. Recent linkages include: Brown, 2001, 92–94; Stathakopoulos, 2003, 253–54, 2007, 100; McCormick, 2003, 20–21, n.33; Horden, 2005, 152–53; Sallares, 2007, 284–85; McCormick et al., 2012, 198–99; Gräslund and Price, 2012, 433–34; Lee, 2013, 290; Sigl et al., 2015, 548; Haldon et al., 2014, 123; Izdebski et al., 2015.
151. Though low-resolution paleoclimatology now illuminates a pronounced humid period setting in about 550 in Central Africa: Oslisly et al., 2013. In Western and Northern Africa, there is evidence for dry conditions. Low-resolution hydroclimate proxies in Chad and Algeria identify the sixth century as fitting into a two- or three-century dry period. In some proxies from Ghana and Senegal, this dryness is part of much longer-term aridity. In others, from Nigeria and Cameroon, dry conditions appear to set in abruptly in the sixth century. Reconstructions from Eastern Africa are more variable. The sixth century is the last of a long humid period in parts of Kenya. But proxies from other areas, like Tanzania, indicate dry conditions setting in abruptly in the mid-sixth century. Conversely, wetness sets in suddenly in Rwanda, Namibia, and northeast South Africa in the mid-sixth century: Nash et al., 2016, 6–8.
152. Keys, 2000, 16–23.

153. For example: Sallares, 2007, 284–85; Stathakopoulos, 2007, 100; also Lee, 2013, 290. Horden expressed skepticism, Brown thought the temperature sensitivity of plague-bearing rodent fleas problematic to Key's theory, and McCormick suggested that the connection was more complex than Keys allowed, though he too thought that the two events connected via the effect of climate change on rodent populations: Horden, 2005, 152–53; Brown, 2001, 92–94; M. McCormick, 2003, 20–21, n.33.
154. Biraben and Le Goff, 1975, 50, 58, 64; Sarris, 2002, 169, 170–72; Sallares, 2007, 251, 285–86 thought the plague popped up closer to home, possibly in Egypt.
155. Morelli et al., 2010, 1140–3; Harbeck et al., 2013; Wagner et al., 2014, 323; Feldman et al., 2016.
156. Stathakopoulos, 2003, 254.
157. McCormick, 2003, n.33; McCormick, 2007a, 303–04.
158. McCormick et al., 2012, 198–99.
159. It is not limited to cold climates or seasons, but pneumonic plague does generally require close contact for transmission. Sallares, 2007, 241–42, 286.
160. Unless the disease became endemic or enzootic following the initial introduction. Justinianic recurrences: Biraben and Le Goff, 1975, 58–60; Stathakopoulos, 2004, 113–24; Horden, 2005, 138–39, n.6.
161. Schmid et al., 2015, 3020–25; Kausrud et al., 2010, 112; Ben-Ari et al., 2011. Campbell has demonstrated the Black Death occurred, in Europe, within a distinct climatic anomaly: Campbell, 2010, 287, 300–05; Campbell, 2012, 144–47.
162. McMichael, 2015.
163. Though see Kausrud et al., 2010.
164. Bos et al., 2016; Seifert et al., 2016.
165. The same would apply to other mosquito-borne diseases. In Europe, both *vivax* and *malariae* varieties of malaria were well established south and north of the Alps by 550. Gowland and Western, 2012; Newfield, 2017.
166. See note 5 above.
167. For example: Stathakopoulos, 2004, 166–67, 268; Cheyette, 2008, 155–56; Devroey and Jaubert, 2011, 10; Izdebski et al., 2015.
168. Farquharson, 1996, 267.
169. Arrhenius, 2013, 13.
170. Widgren, 2012, 126, 131–33; Nunn, 2007, 9. In Satingpra, Thailand, a downturn drought is seen as spurring major irrigation works: Stargardt, 2014, 129–30.
171. Houston, 2000, 71, 74.
172. Dahlin and Chase, 2014, 127–55.
173. Lucero, 1999, 814–22.
174. Dunning et al., 2012, 3652–57.
175. Turner and Sabloff emphasize spatial and temporal variability in the effects of Maya droughts: Turner and Sabloff, 2012, 13,908–14.
176. A survey of late antique Mediterranean famines: Stathakopoulos, 2004, 23–30, 35–56.
177. Smit and Wandel, 2006, 282–92; Berkes, 1993, 1–10.
178. Löwenborg, 2012, 22–23.

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CHAPTER 33

The 1310s Event

Philip Slavin

33.1 Introduction

In the 1310s, northwestern Europe experienced two environmental crises, each on a catastrophic scale. First, between approximately July 1314 and July 1316, there were twenty-four months of extreme weather, characterised by almost incessant torrential rain in summer, autumn, and spring, and then frost during winter. The disastrous weather resulted in three back-to-back harvest failures and omnipresent food dearth. Because of both anthropogenic and demographic factors, the 'Great Famine' of the 1310s became probably the single harshest subsistence crisis in Europe of the last two millennia. Second, between around 1314 and 1321, Europe was devastated by a disastrous cattle pestilence, most likely caused by rinderpest. In order to appreciate the environmental and biological foundations of the two disasters, it is necessary to consider their wider ecological and climatic contexts.

33.2 The Wider Climatic Context: Transition from the MCA to the LIA

Despite much progress in the last two decades, the climatic reconstruction of the past remains far from straightforward, and there are still more questions than answers.[1] Nevertheless, scholars have reached a solid consensus regarding some long-term palaeoclimatic trends. It is now generally accepted that by the second half of the thirteenth century (*c.* 1250–70), some profound climatic changes were under way. After some 200 years dominated by warm climate (the Medieval Climate Anomaly, or MCA), when average annual temperatures

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approached those of around 2000 CE, the North Atlantic region entered a new climatic phase, in effect a transition from the MCA to the Little Ice Age (LIA) (see Chap. 22).

This transition, a part of a much broader global climatic shift, is a highly complex and still poorly understood phenomenon. Although its chronology is debated among both historians and palaeoclimatologists, it would be reasonable to place it at about 1270–1420. Around 1270, we witness a shift to a highly unstable climatic regime marked by high variability of year-to-year sea-surface and air temperature and great variance in year-to-year precipitation levels. This was caused by a general weakening of the North Atlantic Oscillation (NAO), especially since the 1320s, to the point that by the 1430s it became strongly negative. This shift created stormy conditions and cold spells, which became predominant for the duration of the LIA.[2] These conditions were a stark contrast to those of the MCA, dominated by a strong positive NAO, when strong winter westerlies brought mildly wet and relatively warm weather to northwestern Europe and arid conditions to the Mediterranean and North Africa (see Chap. 23).

In addition, there was a gradual reduction in solar irradiance, partially caused by major volcanic eruptions in 1257, 1268, 1275, and 1341/3.[3] In particular, solar irradiance was depressed between around 1280 and 1340, a period known as the 'Wolf Minimum'. During this period, levels of solar irradiance were significantly lower than average for the period 1000–1500 CE.[4] Piecemeal weakening of the NAO on the one hand and reduced levels of sunshine on the other meant gradual cooling. Indeed, Greenland witnessed a period of severe cold spells, peaking in 1303, 1320, and 1353, while Iceland saw sea-ice formation along its northern coast in the 1310s and 1330s.[5]

These macroclimatic shifts and climate instability are reflected in various types of climate proxies all over Northern Europe. Thus, between the 1270s and the 1380s, sea-surface temperatures fluctuated a great deal from year to year in the North Atlantic Ocean,[6] and in the waters of Atlantic France.[7] In England, summer precipitation levels varied significantly from year to year, reflecting the corresponding annual fluctuations in sea-surface conditions of the North Atlantic, as indicated in the Greenland ice-core record.[8] Thus, the summers of 1315 and 1316 were very wet, followed by a relatively dry summer in 1317, an excessively dry summer in 1318, and a fairly wet summer in 1319. The period 1315–18, overlapping with the Great Famine years, coincided with unusually warm North Atlantic sea-surface temperatures, which created atmospheric conditions encouraging unusually wet, cold, and stormy weather all over Northern Europe.[9]

There is further physical and biological evidence of the increasing cooling and storminess in Scotland and northern England during the second half of the thirteenth century and the first half of the fourteenth century. As recent archaeological and palaeobiological evidence from the Western Isles has revealed, commercial fisheries declined significantly because of changes in the migratory behaviour of herring and other deep-sea species.[10] Similarly, there are archaeological indications of sand-blowing and dune deflation events across both the west and the east coasts, which ruined the quality of soil and reduced the arable production capacity of Scotland and, evidently, northern England. In some regions, arable land was abandoned altogether.[11] The grazing season shrank by approximately one month, with adequate grass no longer growing in early May and late September.[12] The reduced growing season would have produced less annual biomass for grazing animals, and this fact would have made livestock husbandry more challenging and costly than before.

33.3 The Weather Anomaly of 1314–16

Such was the climatic context for the abnormal weather of 1314–16. Torrential rains seem to have spread all over northwestern and north-central Europe, from western Poland in the east to Ireland in the west, from northern Italy in the south to Norway in the north. However, the only place where a meticulous reconstruction of seasonal weather is possible is England. This is largely due to the uniquely rich English source material, consisting of chronicles and manorial accounts. Manorial accounts were financial and agricultural reports rendered on an annual basis by estate officials of local lords. Although these documents were concerned primarily with the financial income, expenditure, and agricultural production of those manors, there are occasional references to seasonal weather conditions, especially in the case of bad weather. The written and statistical sources can be complemented by evidence from the archives of nature, chiefly tree rings and speleothem bands (see Chap. 3).

Taken together, the following picture emerges. The downpour started in summer 1314, possibly around July. By harvest time, namely late August–early September, the torrent was strong enough to disturb harvesting. The flooding continued into autumn, persisting into October and possibly November.[13] We are unaware if the flooding stopped temporarily at some point in the late autumn or early winter, or if it turned right into snow, as some documents suggest.[14] The winter crops failed miserably, which indicates frost, hail, or ice storms. The torrent kept coming in the spring of 1315, pouring incessantly into the summertime, disturbing mowing and harvesting.[15] The rain was accompanied by severe gales and thunderstorms, which destroyed buildings and felled trees.[16] As a recent palaeoclimatic study of late medieval Norfolk concludes, April–July temperatures in 1314 and 1315 were remarkably low, standing at ~11.92 °C and 11.79 °C, respectively, or 1 °C lower than average for the period 1250–1330.[17]

The rain poured during the harvest period, making harvesting long and challenging. In some places, the harvest of 1315 continued until October. The winter and spring of 1316 were excessively rainy and stormy.[18] The pluvial weather continued into the summer, and the downpour was so strong that in some places spring fields lay submerged under water by the harvest time.[19] It seems that the rain stopped during the harvest, and the weather finally turned dry.[20] At the same time, it appears that the winter of 1317 was cold, and there are several references to snow and frost.[21] In any event, the short-term weather anomaly was certainly over by spring 1317.

33.4 Agricultural Production Destroyed

The weather anomaly had a destructive impact on both vegetation and food resources. First, there were three back-to-back crop harvest failures in 1315, 1316, and 1317. The annual composite *gross* yields (that is, the ratio between the present year's harvest and the amounts of crop sown in the previous year) stood, respectively, at about 25, 35, and 14% below the average late medieval figure. The *net* yields (the ratio between the present year's harvest *minus the harvest share used as seed-corn* and the amounts of crop sown in the previous year) were much lower, standing at about 38, 50, and 26% below average in 1315, 1316, and 1317, respectively.[22] In the case of the 1315 and 1316 harvests, legumes and winter grains (wheat, rye, the wheat-rye mixture known as 'maslin', and winter barley known as 'bere') performed much worse than the spring grains (barley, oats, and barley-oat mixtures). Weather conditions were particularly harsh in winter, when wheat, rye, and winter barley germinate and legumes are planted (usually in late January–early February). There are references to snowy conditions, but it is also possible that that at some point the flooding turned into hail or ice storms, stunting the growing winter grains and the recently planted legumes. Indeed, as some recent studies have demonstrated, hail storms and ice storms can be devastating for field crops, much more than snow.[23] In 1317, on the other hand, it was oats that fared worse than other crops, despite the fact that the weather seems to have normalised by spring 1317.

In actual figures, the composite *gross* per-seed yields (ratio between this year's harvest and the previous year's seed) were approximately 2.76 in 1315, 2.39 in 1316, and 3.16 in 1317 (compared with approximately 3.70 in non-famine years around 1300). The *net* per-seed yields (*gross* yields minus seed-corn) were approximately 1.68 in 1315, 1.32 in 1316, and 2.08 in 1317. After the deduction of one-tenth of the harvest paid in tithes, the figures are deflated to about 1.40 in 1315, 1.09 in 1316, and 1.76 in 1317. It is true that in theory the tithes should *not* be regarded as a loss, because tithe-owners would usually redistribute them for sale at local markets. But given the excessively high prices of the famine years, very few tenants had the means to purchase additional grain. In other words, an average English tenant was left with virtually nothing to eat.

While net crop yields stood at about 38, 50, and 26% below average, the calorific decline may have been even worse. As several English chronicles narrate, grains were devoid of their usual nutrients because of the lack of the summer sun. As a result, the poor-quality bread could not satisfy people.[24] Although any interpretation of this report might be speculative, we should bear in mind that excessive rain can damage maturing grains and reduce their calorific value in several ways. It can create mould, namely micro-fungi, which encourage biodegradation through mycotoxins.[25] It can also reduce the quality and size of kernel contents (germ and endosperm).[26] Perhaps most importantly, it causes unwanted sprouting of seeds, whereby enzymes break down the kernel starch and reduce the calorific value, nutrients, and quality of flour.[27] In any event, the reports of bad bread incapable of satisfying people undoubtedly indicate that the disastrous weather not only ruined harvests but also damaged harvested grains. Although impossible to quantify, it is likely that relative calorific loss was greater than relative volume loss. In other words, if crops yields stood at, say, 50% below average, the calorific loss may have reached as much as 60 or 70%.

When talking about arable produce, one often focuses too much on kernels and forgets about stalks. Straw was a major component of fodder for animals, and it was undoubtedly affected by the torrential rain as well. Although poor grain yields implied a high proportion of straw in unthreshed sheaves, the wet conditions of the famine years would not allow local producers to dry it quickly and efficiently in order to produce the best livestock feed. If unsheltered, inundated straw tends to become dirty, mouldy, rotten, and hence dangerously unfit for animal consumption.[28] Straw was an especially crucial fodder during wintertime, when grass grew poorly or not at all, and animals were stall-fed.

The disastrous weather also had a profound impact on grassland, a far more important source of animal feed than straw. It may be argued that pasturage fodder, deriving from both pasture grass and meadow-mown hay, was the backbone of the late medieval economy, which was so dependent on healthy working plough-horses and oxen to ensure a steady supply of food for humans.

Here, it is important to distinguish between permanent pasture and mowable grassland, which was converted to hay. While the torrential rain of 1314–16 destroyed much arable, it also produced grass in great abundance, to the point that the supply well exceeded demand, and the value of pasturage declined a great deal. At the same time, the incessant rain made mowing extremely difficult and costly. As a result, much grass remained unmown, destined to be consumed by water and rot. But even in those instances, when some meadow was mown, it could not be easily dried and converted into hay, on account of the torrential rain. In many cases, putrefying hay encouraged the activity of parasitic fungi, bacteria, worms, and gastropods. It appears that the consumption of putrid herbage was the single most important factor contributing to the outbreak of sheep and cattle murrains during the famine years. As we shall see below, one possible cause of sheep mortality was a liver fluke epizootic, while the bovine murrain of 1315–16 (not to be confused with the rinderpest panzootic of 1319–20) could have been brought about by either Barber's pole worm or by mycotoxic mould.

The torrential rain had an equally devastating effect on vineyards. There are numerous references to the destruction of the wine harvest in Normandy, the Paris region, and other parts of northern France. In some areas, the vintage declined by 50% in 1315 and 1316 and by some 80% in 1317. Similarly, the bad weather ruined vineyards of the Rhineland. In those instances, when grapes were harvested and processed, the quality of wine appears to have been deplorably sour.[29] Furthermore, making wine was impossible in parts of northern Italy, because of the rainy weather in the summer of 1315.[30] In England, viticulture was practised on a very limited scale, confined primarily to the southern counties. However, there can be little doubt that local vineyards were damaged at least as badly as on the Continent.

Other, minor sectors of agriculture deserve discussion, too. One such sector is fruit horticulture. The available evidence is scarce—only a few manorial accounts from south English estates. The paucity of evidence can be explained by the fact that horticulture contributed only a small fraction of total caloric intake, and fresh fruit and vegetables were traded on a small scale and in an informal manner.[31] Moreover, in many instances, the accounts seem to have under-recorded real produce yields. Still, the few accounts from southern England shed some light on the depression within the horticultural sector. As they indicate, in 1315 and 1316, very few apples were picked. At Shapwick (Somerset), 2.5 quarters (=840 lbs) of apples were harvested in 1315, compared to 16 quarters (5376 lbs) in 1314. At Westonzoyland (Somerset), the apple harvest amounted to 11 quarters in 1315, compared to 27 quarters in 1314. At East Meon Church (Hampshire), only one quarter was picked in 1315 and no apples were harvested in 1316—in contrast with 27 quarters in 1312.[32] Two main factors are essential for good fruit tree yields: sufficient solar irradiance and sufficient pollination by pollinating insects, primarily bees and butterflies. Cold and rainy springs hinder fruit tree blossoming and prevent insect pollination. Additionally, bees and butterflies (and other insects, with the exception of mosquitoes) cannot fly in the rain. To make things even worse, cold and rainy winters increase mortality rates of insects, because they are unable to secure food. Finally, the torrential rain of 1314–16 undoubtedly encouraged gastropods, that is slugs and snails, both notorious destroyers of leaves. Taken altogether, it is hardly surprising that those few accounts recording orchard production reported abysmally low figures.

The low levels of fruit harvest were closely related to the health of bees, often managed in garden beehives to produce honey and wax, both highly commercial products.[33] As with horticulture, beehive management is reported in few English manorial accounts, but those few documents clearly indicate that the rainy and freezing winters of the famine years greatly increased honeybee mortality. For instance, at Werrore and Cosham (Hampshire), five out of eight swarms died during the winter of 1315–16 'because of excessively rainy weather'.[34] Similarly, at Pilton (Somerset), thirteen out of seventeen swarms died in the course of the winter of 1314–15.[35] The same manors also reported depressed yields of honey and wax.

Salt production was yet another sector severely depressed by the inclement weather. In the late medieval period, salt making depended much on natural evaporation of brine (created by the formation of pools of seawater on the beaches during high tide in late spring).[36] Clearly, the flooding of 1314–16 would have prevented the evaporation of brine, and stoking fires around the salt ponds to quicken evaporation would have been extremely wasteful and inefficient.[37] Although there is no way to quantify the decline in salt production during the crisis, there are more than enough narrative references to the extent of the disaster. There was widespread deficiency of salt in England, and one fourteenth-century English chronicle states that the excessive flooding destroyed salt production in (northern) France.[38] Although England boasted several important salt-producing centres, especially in Cheshire and Lincolnshire, it still depended much on foreign salt, imported primarily from Bourgneuf Bay (on the frontiers of southern Brittany and Poitou) but also from Brittany, Normandy, and Lüneburg (Lower Saxony). Although the torrential rain poured over the Breton, Norman, and Saxon salterns, the Bourgneuf salterns were located outside of the climate anomaly zone and there is no evidence that salt production was disrupted there. However, the disruption of salt production within the climate anomaly zone drove an increased demand for, and dependence on, the Bourgneuf salt all over Northern Europe, which trebled and quadrupled salt prices in northern France and England.

33.5 From Shortage to Famine

Although the environment played a central role in initiating the shortage, it did not by itself create famine. The transformation of shortage into famine—or to use Amartya Sen's terminology, the transformation of 'food availability decline' (FAD) into 'food entitlement decline' (FED) (see Chap. 27)—depended on purely anthropogenic, and especially institutional, factors.[39] Once the harvest was collected and tithe paid, an average tenant would have been left with very little food supply, since the return from harvest barely exceeded the seed investment in the previous year. The consequences were especially harsh in those lands caught in a so-called Malthusian trap: namely, population was too large in relation to available resources. Thus, in England—where the population was somewhere between 4.75 and 5.25 million people on the eve of the famine, where over one half of the total population lived on less than ten acres of land, and where, according to one estimate, about 41% lived below the poverty line—an average tenant's parcel of land could not possibly provide sufficient food.[40] Grain-based products, primarily bread and ale, contributed about 70% of the caloric intake of an English commoner, which translates into about 1400 kcal per day.[41] Under those circumstances, well over half of the required kilocalories had to be secured from outside the tenancy strips, namely from local markets.

There was very little grain available for sale at local markets. This was not because of the abysmally low yields: after all, if crop harvests failed by, say, 50%, it implied that at least *some* grain should still have been available for sale, especially given that many wealthy producers would still end up with a surplus. The disruption of grain supply to local markets may be explained by the reluctance of the same producers to make their cereal stocks available for sale. As the manorial accounts indicate, in the course of the first fiscal year of famine

(September 1315 to September 1316) only about 30% of the 1315 grain harvest was released for sale by the spring of 1316, while the rest was hoarded in expectation of high prices. Here the issue of storage played an enormous role. Because of widespread poverty and crowding, peasants rarely had efficient storage facilities. To make things even worse, inclement weather ruined local granaries and barns. In contrast, better-off producers had both the storage space and means to make repairs as necessary. In addition to the storage issue, we also have to account for the rise in transportation costs. The abnormal weather turned the roads muddy and impassable, which meant that horse- and ox-drawn transportation became more time consuming and expensive. Shipping became even more costly and dangerous, not only because of the high tides and storms, but also because of the ongoing piracy in the North, Irish, and Celtic seas.[42]

Pirate attacks, often targeting food supplies, should be seen in a wider context of ongoing warfare. The most violent theatre of war was in the British Isles, where north English counties, southeastern Scotland, and the eastern parts of Ireland were devastated in the course of the ongoing Anglo-Scottish War (1296–1328). To this we should add the rebellion of Llewellyn Bren (28 January–18 March 1316) in south Wales. In the course of hostilities, all sides engaged in environmental destruction, including the desolation of arable fields, pasture, woodland, and wildlife resources, as well as plundering of granaries and barns, thus cutting local communities off from their access to food.[43] In addition, Louis X of France invaded Flanders in August 1315, but this short-lived invasion was doomed to fail because of the inclement weather, which destroyed French soldiers' provisions and discouraged them from fighting.[44] In Sweden, there was civil war between King Birger Magnusson and his magnates in 1317–18, which ultimately led to the king's downfall.[45]

It was due to those anthropogenic factors that transactions costs went up, driving abnormally high grain prices. In England, the selling price of one quarter of wheat (424 lbs) rose from 7 shillings in September to 24s in June. The average annual wheat prices were 15s and 16s a quarter in 1316 and 1317, respectively—that is, about three times higher than in an average 'non-famine' year around 1300.[46] Black market prices rose even higher: in one instance, a quarter of wheat was selling for an overwhelming 44s.[47] Grain prices rose in a similar manner in northern France, the German Empire, the Low Countries, and Central Europe.[48] As we have seen, salt prices in England and northern France trebled and quadrupled.[49] There is also evidence of a rise in apple prices in England, owing undoubtedly to the depression of orchard production during the crisis years.[50]

The disruption of grain supplies and excessively high market prices left the poorer elements totally helpless in the face of the crisis. This was especially true in those regions that suffered from overpopulation (most of England and northern France, the Low Countries, and presumably the western parts of the German Empire).[51] In other words, this seems to have been a classical Malthusian scenario, when there were too many hungry mouths and too few resources. The oversupply of agricultural labour meant low (and virtually stagnant) nominal wages and *excessively* low real wages (nominal wages deflated by the Consumer Price Index). At no other point were living standards in England so low; and although the scarcity of data does not allow any quantification, the same was probably true of other famine-stricken parts of Europe. This point is especially crucial in explaining hunger and malnutrition. As we have seen, the abysmally low crop yields implied that at least half of England's population needed to secure additional food from outside of their parcels, namely from local markets. The omnipresent poverty and the depressed real wages, however, meant that for many this was not a viable option.

33.6 Malnourishment and Mortality: Humans

The adverse combination of environmental and anthropogenic factors ultimately condemned both humans and domestic animals to malnourishment and mortality. At first, local communities attempted to take up the slack by switching their dietary patterns. In England, there is much evidence for an increase in livestock consumption, especially pigs, the quintessential peasant animal. However, as one English chronicler narrates, there were not enough legumes to fatten swine, and therefore ham, bacon, and lard could be produced only on a limited scale.[52] The shift from arable to pastoral husbandry would have been a highly expensive enterprise, unaffordable for the majority of famine-stricken peasants, who lacked both the necessary start-up capital and physical space for animal management. To make things even worse, there were (as we shall see in the next section) several outbreaks of livestock diseases in the 1310s, which made the task of securing healthy animals all the more challenging. According to the same chronicler, 'even flesh of animals began to be deficient, and eggs and other dairy products began to disappear too. One could hardly find capons or geese; sheep were lacking, because of their murrain.'[53] Another English chronicler stated that no one dared to eat the meat of animals that perished from murrain.[54]

It was in this context that the poorer elements of society had to resort to famine foods, consisting of otherwise inedible and repugnant comestibles. According to one source, people of Northumberland (north England) ate horses and dogs.[55] Another English chronicle reports the consumption of mice, dogs, and pigeon dung.[56] 'Pigeon dung', however, seems to have been a Biblical cliché, rather than the actual comestible.[57] One Dutch chronicler reported that hungry people devoured cattle carrion, just like dogs, and meadow grass, just like oxen.[58] Consumption of cattle that died from murrain is also reported in Würzburg.[59] Several English and Irish narratives tell in detail about instances of cannibalism, whereby both men and women ate their own and other peoples' babies, prison inmates ate each other, and hungry and exhausted Ulster soldiers dug up corpses in order to eat them.[60] Instances of eating children and corpses were also reported in Poland, Bohemia, Germany, and the Baltic lands.[61] The authenticity of these reports (and similar descriptions from later historical famines) has long been debated among historians. Some dismiss them as outright hearsay or curiosities; others remain undecided.[62] Given the recurrent reports of cannibalism in later famines, some based on first-hand witnesses, the possibility of human- and corpse-eating during the Great Famine—arguably the single harshest subsistence crisis in Europe in the last 2000 years—should not be dismissed lightly.

The omnipresent malnourishment and famine food consumption compromised the immune systems of the starving population and made them susceptible to various hunger-related diseases. Thus, some German chronicles speak about a 'general and universal pestilence'.[63] Other sources are more precise: several English chroniclers narrate that people succumbed to dysentery, caused by the consumption of corrupt foods.[64] An outbreak of a disease called *pestis gutturosa* ('throat pestilence'), interpreted by some as scarlet fever, was also reported.[65] Although scarlet fever indeed accompanied some famines, including the Irish Potato Famine (1845–52) and the Finnish Famine of 1866–68,[66] this identification is by no means definitive. It has been suggested that some may have died of ergotism caused by the consumption of fungus-infested rye.[67] There is no evidence, however, that there was an outbreak of ergotism, despite the fact that wet conditions encourage the growth of the fungal parasite. It is more likely that malnourishment and consumption of famine foods led to diarrhoea and dehydration, weakening the population and increasing its morbidity rates.[68] Although the contemporary sources do not reveal mortality patterns across gender and age, it is plausible that children and old people were most prone to these diseases, as modern famine studies show (see Chap. 28).[69] Recent palaeopathological studies based on skeletal evidence from a Black Death cemetery in London indicate that the Great Famine targeted frailer individuals. Likewise, food deprivation in breastfeeding mothers was likely to reduce their immunity and hinder the physical development of their children.[70]

Any estimate of human population decline during the famine remains somewhat speculative. This is largely due to the remarkable paucity of demographic studies on the early fourteenth century. Nevertheless, data from five English manors based on local court proceedings suggests that between 1315 and 1318 England's population declined by 10–15%.[71] It is likely that mortality rates in towns were even higher, given urban dependence on the surrounding agricultural hinterland. For instance, one London chronicler reported that the capital lost 20,000 people during the famine years—possibly an exaggeration, given that London's population on the eve of the famine was probably no more than 60,000 people.[72] At Ypres and Tournai (both in Belgium), about 10% of the population died.[73]

33.7 Malnourishment and Mortality: Animals

Humans were not the only victims of the crisis. The destruction of fodder resources by the torrential rain and freezing winters had a devastating impact on livestock, especially cattle and sheep. As we have seen, the crisis years destroyed much forage, including pasture, hay, and straw, which deprived domesticates of healthy fodder. Indeed, as some English chronicles state, animals succumbed by eating rotten grass and herbs.[74] To make matters even worse, the inclement weather had very negative implications for animals who were already exposed to colder temperatures and deprived of their most basic kinds of fodder, and therefore had to waste more energy to maintain body heat. These conditions likely decreased their resistance to pathogens within a very short period of time.[75] Malnutrition also delays physical growth in young animals, chiefly the development of muscles. Several months of deprivation in a young bullock or hogget (young sheep) will do enough damage to turn them into infertile and weak animals, prone to various diseases.

Such was the context for three outbreaks of animal mortality, each attacking different groups of livestock with different levels of intensity. First, from late 1313 or early 1314 until 1317, there was an outbreak of sheep murrain in England, Wales, and parts of Ireland, targeting primarily young animals. Second, sources record an excess bovine mortality in 1315–16 in England. This episode, however, was nothing compared to the devastating outbreak of bovine pestilence that decimated European stocks between about 1315 and 1321.

The murrain in British sheep broke out either in late autumn 1313 or around January 1314, long before the beginning of the torrential rain in the summer of that year. Although the outbreak is reported in many chronicles, the descriptions are rather laconic and at times vague. Thus, one chronicle specifies that there was 'a common rot (*communis putredo*) and sheep murrain, as well as mortality of other animals'.[76] Some historians have speculated that this 'rot' was an infestation of liver fluke (*Fasciola hepatica*), a parasitic flatworm infecting sheep livers.[77] There is one manorial account from Bourton-on-the-Hill (Gloucestershire) mentioning sheep mortality because of 'the rot in bile duct', which indeed fits the symptoms of liver fluke infestation.[78] Moreover, although 'rot' (*putredo*) was a generic term, it was also used to describe liver fluke in several late thirteenth-century English agricultural treatises.[79] Liver fluke activity is encouraged by rainy conditions, whereby the parasites migrate into the sheep's liver and bile duct via ingestion of rotten grass and then begin laying eggs. About twelve to fifteen weeks after ingestion, animals exhibit the first signs of the disease known as *fasciolosis*, whose common signs include liver malfunction and failure, jaundice, anaemia, gall bladder damage, weight loss, and diarrhoea.[80]

It seems, however, that liver fluke infestation was not the only cause of excessive sheep mortality during the famine years. A 1315–16 account from Stevenage (Hertfordshire) reports 'red disease' (*rubeus morbus*) devastating local flocks.[81] This term is far from straightforward. It might be identified with a now obsolete disease called 'Blood' in several early modern agricultural treatises. Once sheep contracted this disease, they would suddenly die in agony, and if not culled in time, their skin would become as red 'as blood'.[82] Although it cannot be established with certainty, it appears that Stone's identification of *rubeus morbus* with the 'Blood' disease is plausible. Some accounts also refer to *veroles*, most likely the sheep pox (*Variola ovina*) mentioned in one late thirteenth-century agricultural treatise.[83] Although the identification of this disease remains debatable, it is likely that *veroles/variola* is in fact *Variola ovina*, or sheep pox. Sheep pox is mentioned in one version of Walter of Henley's agricultural treatise as *pockes*.[84] Sheep pox is a highly contagious viral disease caused by a poxvirus. The clinical symptoms include lesions around the lips, in the axilla, and on the tail.[85]

To complicate matters even further, manorial accounts contain numerous indirect but unambiguous references to a concurrent outbreak of yet another disease: scab. Although the accounts do not refer to scab by its proper name, they indicate that traditional scab-treatment medicaments including lard, butter, oil, verdigris, quicksilver, and copperas were applied on ailing sheep.[86] Scab is an acute infectious form of dermatitis caused by the faeces and bites of sheep mites (*Psoroptes ovis*).[87] Sheep mites tend to mate and act aggressively during the cold and damp months of autumn and winter. Indeed, the weather conditions of 1314–16 provided ideal conditions for mite mating and aggressive behaviour. It should also be borne in mind that during those late autumn and winter months sheep were most likely concentrated in sheepcotes, in order to be protected from the inclement weather. This brought the animals into close contact and encouraged transmission of the mites. This outbreak of scab was one of several recurrent waves of the disease, which devastated Britain's ovine stocks between 1279 and around 1330.[88] However, the 1313–14 outbreak was harsher, with mortality rates standing at 20% that year (albeit not as harsh as the 1279–81 wave that killed almost half of English stocks). As such, it was yet another setback with harsh economic implications, particularly in the wool industry.

Bovine animals were yet another victim of the crisis. Several narrative sources report that cattle died from eating rotten herbs.[89] The accounting year of 1315–16 (running between two Michaelmases, that is, 29 September) stands out, with mortality rates reaching 9%, compared with only 3% in 1314–15 and 1316–17, a figure comparable to normal years.[90] Although most documents do not specify the nature of the disease, several accounts state that local animals died 'because of rot'.[91] It is possible, just as in the case of sheep, that the 'rot' was an infestation of gastrointestinal parasites. For instance, Barber's pole worm (*Haemonchus contortus*) is associated with rotten herbage and is known as the single most common type of stomach worm in cattle.[92] But it is equally possible that the 'rot' was caused by mycotic or mycotoxic mould infesting rotten herbage. The consumption of mouldy herbage can often lead to liver disease in cattle, causing periportal fibrosis (severe liver lesions) and biliary hyperplasia (enlargement of the bile duct), and leading eventually to death.[93]

This local animal mortality of 1315–16 was nothing compared to a much greater bovine crisis that devastated all of Europe around the same time, caused most likely by the rinderpest virus.[94] Unlike scab disease, which seems to have been confined to the British Isles, the cattle pestilence affected a vast stretch of Eurasia. Similar to the Black Death a generation later, the geographic origins of the pestilence remain obscure, but the disease seems to have originated in the Eurasian steppe. Outbreaks are reported in Mongolia between 1288 and 1331; in northern China in 1288, 1301, 1306, and 1335; in the Ilkhanate (comprising Persia, Azerbaijan, and parts of Asia Minor) during the reign of Gaykhatu Khan (1291–95); and in the Golden Horde (stretching from Lithuania into Siberia) during the reign of Tohtu Khan (1291–1312). The panzootic crossed the steppes into Rus' in 1298 and 1309, but it was not until about 1316 that it reached Central Europe, possibly through Lithuanian trade routes, and its presence was attested in Bohemia and eastern German lands. By 1318, the pestilence ravaged northern France, the Low Countries, and parts of northern Italy. In the same year, cattle mortality was reported in Denmark. Finally, by Easter 1319 the disease came to Essex, England. It swiftly spread throughout the British Isles, reaching Scotland shortly after September 1319, Wales by summer 1320, and Ireland in 1321.[95]

Although the bovine pestilence is attested in various European and non-European chronicles, again the language of the sources tends to be laconic and vague. Thus, one later Brabant chronicler, Edmond de Dynter (1375–1448), reported that the epizootics were of such catastrophic proportions that hardly one cow in ten survived.[96] It is only in England and east Wales that an accurate estimate of mortality rates is possible, thanks to detailed information found in manorial accounts. They indicate that about 62% of bovids perished. Unlike the scab outbreak, when both male and female animals died at a similar rate, this disease was particularly devastating to female animals, killing about three-fourths of all cows and heifers. This undoubtedly had to do with the fact that the immune system of lactating animals was compromised by malnourishment and the abnormally damp and cold weather. The morality rates of oxen, on the other hand, stood at about 50%, which may be explained by their better resistance to pathogens, because of stronger physiology and better diet, which included oats and legumes.

Although the exact nature of the disease has yet to be scientifically determined, several recent studies relying on descriptions of symptoms have suggested that it was rinderpest. Rinderpest is a viral disease with death rates approaching 100% in infected animals. The pathogen incubates from three to nine days and gets transmitted mostly through respiratory and sexual contact. Its dissemination is remarkably fast. The disease is characterised by haemorrhaging, fever, erosion of the lower intestine, debilitating diarrhoea, and nasal and ocular discharge. Animals succumb between six and twelve days. During symptoms and after death, infected animals contaminate fodder, pasture, and sources of water.[97]

33.8 Long-Term Impacts

Although the agricultural crisis was more or less over by 1318, and the bovine pestilence in 1321, the crisis had enduring environmental and economic repercussions. The recovery of bovine stocks proved a long and expensive process. As English evidence indicates, it was not until the late 1330s that herds reached their pre-crisis levels.[98] Oxen were the most important draught animal in England and many other parts of Northern Europe struck by the crisis; they had to be replenished first in order for the predominant arable sector to recover. In the meantime, to fill the vacuum, the draught-horse sector was temporarily expanded.[99] Thanks to these steps, there is no evidence of depression in the agrarian sector until the Black Death. The agrarian recovery allowed the human population to grow anew, as demonstrated by English evidence.[100] The dairy sector, however, remained depressed for some twenty years, because of the comparatively slow recovery of cow stocks. The contraction within the dairy sector meant the English population was deprived of their most important source of some vital nutrients, including protein, calcium, and vitamin $B_{12.}$

Obviously, early fourteenth-century Europeans had no knowledge of nutritional science and hence could not devise alternative strategies to compensate for nutritional loss by, say, expanding legume acreage. This fact had some far-reaching consequences on human health and susceptibility to pathogens. As skeletal evidence from one Black Death cemetery in London reveals, individuals born after 1319 (the year of the outbreak of bovine pestilence in England) clearly show more numerous signs of frailty and pathology, chiefly short stature, cribra orbitalia (lesions on orbital roofs), porotic hyperostosis (lesions on cranial vault bones), and linear enamel hypoplasia (horizontal lines on the enamel of an affected tooth). These pathologies are usually associated with insufficient intake of the aforementioned nutrients during physical development in childhood and adolescence. It is hardly surprising that the same frail individuals, born and maturing after 1319, were susceptible to the Black Death, now proven to have been caused by a biovar of the pathogen *Yersinia pestis*.[101]

A connection among these three biological disasters of the fourteenth century—the famine, cattle plague, and Black Death—is likely but by no means clear and straightforward. This remains a fascinating topic, which at present poses more questions than answers. It is only through meticulous interdisciplinary studies based on strong collaboration among historians, archaeologists, and scientists that we may one day reach definite conclusions.

33.9 Conclusion

The crisis of the 1310s was, by all means, an unusual natural event with far-reaching implications. It was a short-term weather anomaly within a wider climatic shift, which came as unusually wet and cold weather destroying virtually all sectors of agriculture at once. Biologically speaking, it wreaked much havoc in weakened and nutrient-deprived human and animal populations, susceptible to various pathogens and diseases. Economically speaking, it came when the living standards of northwestern European populations reached their lowest point in many centuries (if we assume that English evidence reflects conditions in other lands). The climatic and biological instability was a major setback for the impoverished human populations caught in a Malthusian trap, whose only exit would be a biological cataclysm that came some thirty years later: the Black Death.

Notes

1. Brázdil et al., 2005.
2. Dawson et al., 2007.
3. Oppenheimer, 2011, 263–67.
4. Muscheler et al., 2007.
5. Campbell, 2011, 186.
6. Dawson et al., 2007.
7. Mary et al., 2015.
8. Wilson et al., 2013.
9. Dawson et al., 2007, 431.
10. Cage and Austin, 2010.
11. Oram, 2015.
12. Oram and Adderley, 2008, 79.
13. Longleat House Muniments (henceforth, LH) 10666, membranes 9v, 33v (manors of Pilton and Wrington); LH 10030 (manor of Walton).
14. Westminster Abbey Muniments (henceforth, WAM) 8802 (manor of Kinsbourne, alias Harpendenbury).
15. The National Archives (Kew) (henceforth, TNA), SC 6/996/14, memr. 15r and 7r (manors of Haughley and Thorndon, both in Suffolk); Northamptonshire Record Office (henceforth, NorthantsRO), FM 248 (manor of Boroughbury, Northamptonshire); TNA, SC 6/1011/4 (manor of Byfleet, Surrey).
16. LH, 10666, membranes 9r and 39r (manors of Baltonborough and Pilton, both in Somerset).
17. Pribyl, 2011, 296.
18. Hampshire Record Office (henceforth, HantsRO), 11M59/B1/70, membr. 13v (manor of West Wycombe, Buckinghamshire); WAM, 8803 (Kinsbourne).
19. Bodleian Library (henceforth, BodL), Ch Ch DD27 (manor of Maids Moreton, Buckinghamshire).
20. WAM, 8766.
21. WAM, 25423 (Birbrook, Essex).
22. These figures are slightly different from those calculated by Bruce Campbell, who favoured the figures of 39% below average in 1315, 63% below average in 1316, and 10% below average in 1317. The discrepancy derives from the difference in manorial sample, methodology, and my inclusion of 'minor' crops (rye, wheat-rye mixture, winter barley, legumes, legume-oat mixtures, and oat-barley mixture).
23. Brázdil et al., 2003; Mauelshagen, 2011.
24. Riley, 1876, 93.
25. Didwania and Joshi, 2013.
26. Labuschagne et al., 2009a, 2009b; Beckles and Thitisaksakul, 2014, 58–71.
27. https://news.wsu.edu/2015/07/14/summer-rains-could-mean-sprout-damage-for-wheat-crops/#.Vk3oZnbhCM9 (last accessed 19 November 2015).
28. Suttie, 2000, 156–58.

29. Jordan, 1996, 34–35.
30. Lucas, 1930, 373.
31. Dyer, 2006.
32. HantsRO, 11M59/B1/59-72; LH, 11246, 11271, 11215, 11216, 10655, 10656, 10766, 10761, 10632 and 10633.
33. Dyer, 2006, 29.
34. BodL, DD Ch Ch Queens 251.
35. LH 10766, membr. 40v.
36. Hurst, 2004.
37. Jordan, 1996, 52.
38. Catto and Mooney, 1997, 272.
39. I have dealt with the institutional aspect of the crisis in much greater length elsewhere. See Slavin, 2014a, 9–49, 2014b, 528–50.
40. The estimates of England's population *c.* 1300 vary considerably. The population controversy is summarised in Broadberry et al., 2015, 3–22. The share of the population living below the poverty line is estimated in ibid., 317–18, 321.
41. Broadberry et al., 2015, 288–90 suggest an even higher figure of 80%, but agree that 2000 kcal was an average per diem figure.
42. Heebøll, 2013, 33–54.
43. McNamee, 1997, 72–122; Slavin, 2014b.
44. Lucas, 1930, 349–50.
45. Jordan, 1996, 178–79.
46. The non-famine prices are derived from Munro, 2006; Farmer, 1988, 794–95. The famine years' prices have been calculated by me.
47. Laumby, 1889, 411.
48. Lucas, 1930, 352–55, 373–75.
49. Farmer, 1988, 809–10.
50. Apple price series are extremely scarce. The most complete series comes from the manorial accounts of Sheen (Surrey): TNA, SC 6/1014/1-6.
51. Van Bavel, 2010, 278–79; Abel, 1955.
52. Riley, 1863, 92.
53. Riley, 1863, 92. The translation is mine.
54. Riley, 1876, 247–48.
55. Childs, 2005, 120–21.
56. Luard, 1866, 470.
57. 'Pigeon dung' is related to the Biblical famine in Samaria during the siege by Ben-Hadad, King of Aram, when one-fourth of the 'pigeon dung' (Biblical Hebrew: *hireyonim*, or *divioynim*) was sold for five pieces of silver (2 Kings 6:25). The term *hireyonim/divioynim*, however, seems to have been a long-standing textual corruption, while the original term is now commonly accepted to have been either wild onions or carob pods. See Marvin, 1998, 80–81.
58. Curschmann, 1970, 213.
59. Jordan, 1996, 87.
60. Lydon, 2008, 285.
61. Przezdziecki, 1876, 83; Jordan, 1996, 148–50.
62. Jordan, 1996, 149–50; Ó Gráda, 2015, 11–37.
63. Jordan, 1996, 142.
64. Riley, 1866, 94.
65. Rawcliffe, 2013, 361.

66. Clarkson and Crawford, 2001, 158; Pitkänen, 2002, 77.
67. Jordan, 1996, 116.
68. Jordan, 1996, 116.
69. Jordan, 1996, 116–18.
70. DeWitte and Slavin, 2013, 37–60.
71. Titow, 1961, 224; Razi, 1980, 31, 40; Poos, 1991, 106–07.
72. Raines, 1839, 96–97; thus, Derek Keene suggested the estimate of 80,000–100,000 people around 1300: Keene, 1989, 101.
73. Jordan, 1996, 145–47.
74. Riley, 1863, 147, 1876, 196.
75. Newfield, 2006, 64.
76. Bond, 1867, 333.
77. Kershaw, 1973, 37; Aberth, 2013, 157.
78. WAM 8262.
79. The most extensive description of liver fluke is found in the Latin version of the late thirteenth-century treatise *Walter of Henley* (BodL, MS Digby 147, fols. 6r-7r).
80. Mitchell, 2007, 195–204.
81. TNA, SC 6/871/5.
82. Stone, 2003, 20.
83. HantsRO, DC/J1/12, membr. 9v; Oschinsky, 1971, 380–81.
84. Oschinsky, 1971, 380–81.
85. Kitching, 2007, 302–06.
86. HantsRO, DC/J1/14, membr. 6v; Slavin et al., 2015, 123–25.
87. Bates and Aitken, 2007, 321–25.
88. Slavin et al., 2015, 114–17.
89. Riley, 1863, 147, 1876, 196.
90. These figures derive from Slavin, Manorial Accounts Database (as of November 2015).
91. TNA, SC 6/867/4; University of Chicago Library, Bacon Roll 446.
92. Stephenson, 1987, 87; Stone, 2003, 20.
93. Casteel et al., 1995.
94. Newfield, 2009, 188–89; Slavin, 2012, 1240, 1243.
95. Slavin, 2012, 1240.
96. De Ram, 1854, 497.
97. Obi, 1999, 6.
98. Slavin, 2012, 1249–51.
99. Slavin et al., 2015, 127–28.
100. Broadberry et al., 2015, 12–22.
101. DeWitte and Slavin, 2013, 55–58.

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CHAPTER 34

The 1780s: Global Climate Anomalies, Floods, Droughts, and Famines

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34.1 Introduction

In 1793, William Roxburgh, surgeon of the English East India Company in Samuelcottah (Madras presidency, India), reported to the President's Council on the failure of the South Asian Monsoon between 1789 and 1792, arguing that its severity in South Asia had been approached only by the droughts of 1685–87. His meteorological observations and collection of data on rainfall and cyclones

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were critical to the new science of climatology that was emerging in the colonies. Building on this archival evidence, and with corroborating evidence from St Helena, New South Wales, Mexico, and Montserrat, the environmental historian Richard Grove argued in *Nature* that the droughts of 1789–92 were part of an El Niño event with global ramifications.[1] Grove contended that the associated famine in Madras presidency, which claimed in the region of 600,000 lives, was part of a global disaster, resulting from extreme climatic conditions associated with this particular period of intense El Niño expression.[2]

How global was the event that Grove describes? How can we better analyse the climate anomalies of this period? This chapter draws on the contribution of Rob Allan and the regional expertise of Joëlle Gergis (Australia), A.E.J. Ogilvie and G.R. Demarée (Iceland), Sharon Nicholson and Stefan Norrgård (Africa), Alan Mikhail (Egypt), Takehiko Mikami (Japan), as well as James Hamilton and lead author Vinita Damodaran (South Asia). It offers an up-to-date reconstruction of global-scale climate anomalies during the 1780s before moving on to discuss the social impacts of these climate anomalies in Iceland, Egypt, India, Australia, Africa, and Japan.

34.2 Reconstructing Global Climate in the 1780s

The decade of the 1780s saw the first systematic instrumental observations of weather in several locations. By then, some of the earliest attempts to develop European instrumental meteorological networks had taken shape, including the Mannheim Societas Meteorologica Palatina (1781–92) (Germany), the Societé Royale de Médecine (France) (1776–89), the Baierische Ephemeriden (Germany) (1781–89), and the Academia Medico-Matritense (Spain) (1780–1825) networks (see Chap. 7).[3] Unfortunately, with the coming of the French Revolution and the Napoleonic Wars in the late eighteenth–early nineteenth centuries, these networks collapsed, and it was colonial meteorological networks that were to prove more robust, such as those initiated by William Roxburgh.

Early instrumental weather records during this decade can be found in the vicinity of Calcutta, India (1784–85) and at Baghdad and Basrah in Iraq (1782–84).[4] In India, what became the English East India Company's (EIC's)

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observatory at Madras—officially established in 1792—had evolved from the private observatory of William Petrie in the 1780s.[5] In Australia, the establishment of the British colony of New South Wales in Australia in 1788 began the record of instrumental weather observations in that country (see Fig. 34.1).[6] In Mauritius, Jean Nicolas Céré and Jean-Baptiste Lislet-Geoffroy began the first systematic meteorological observations of the Indian Ocean region during the 1770s–90s. In the marine sphere, scientific instruments such as thermometers and barometers were beginning to be used regularly on ships from all nations. Such records survive from the English East India Company ships trading with India and China from the 1780s, the First Fleet sailing from England to Australia with the first European colonists in 1788, and a number of major expeditions and circumnavigations, such as those of James Cook and Jean-François La Pérouse and George Vancouver.[7]

The international ACRE (Atmospheric Circulation Reconstructions over the Earth) initiative has undertaken various efforts to recover, image/scan, and digitise such early instrumental, terrestrial, and marine observations, and these have been linked into the evolving WMO International Data Rescue (IDARE) activities portal.[8] Both historical documentary and palaeoclimate analyses still provide essential material and evidence with which to investigate the global to regional climatic regimes and patterns of the 1780s. The weather of the 1780s specifically over Europe has been reconstructed by John Kington of the Climatic Research Unit in the form of historical weather maps.[9] Based on this evidence, we can identify both major climatic episodes and the human consequences as discussed in the following sections.

Fig. 34.1 Instrumental weather observations in the meteorological journal of William Dawes (14 September 1788 to 6 December 1791) from Sydney Cove, New South Wales, Australia

34.3 The Laki Fissure Eruption of 1783

During the year 1783, much of the Northern Hemisphere was affected by a phenomenon that many contemporaries described as the ‘great dry fog’. The origin of this fog was a major volcanic eruption in the county of Vestur-Skaftafellsýsla, in the southeast of Iceland. In the non-Icelandic literature, this eruption has often been referred to as the ‘Laki’ eruption. Strictly speaking, this is a misnomer, since the eruption did not occur on Mount Laki but on either side of it. In Icelandic, it is often called *Lakagígar*, the ‘Laki fissure’ eruption. The total length of the Lakagígar crater row from one end to the other is 27 km, divided by Mount Laki into two nearly equal parts. The eruption is also referred to in Iceland as *Skaftáreldar*, or ‘Skaftá fires’, from the nearby river Skaftá.

The first signs of the eruption were some weak tremors felt in May, and then strong earthquakes in southeast Iceland in early June. The eruption itself began on 8 June. This year also brought a marine volcanic eruption, on a much smaller scale, off Reykjanes in the west, as well as volcanic activity in Vatnajökull.[10] The effects of the eruption were felt and seen all over Iceland, mainly in association with the falls of tephra, and there are numerous contemporary descriptions.[11] The eruption lasted until February 1784, with a lava flow covering an area of 580 km^2, making it one of the most noteworthy and largest fissure eruptions in historical times.

The eruption had a catastrophic effect in Iceland, not because the eruption caused direct loss of life, but because of the indirect effects of volcanic gases and ashes distributed by wind. Poisonous substances in the volcanic dust adversely affected vegetation, killing numerous domestic animals, the backbone of the Icelandic economy. The grass, the basic sustenance of the grazing livestock, became fluorine poisoned, and within a year of the eruption 53% of the cattle, 80% of the sheep, and 77% of the horses died.[12] The Lakagígar eruption must be seen as the primary cause of the ensuing famine, which came to be known in Icelandic as *Móðuharðindin*, ‘The Famine of the Mist’, from the volcanic dust haze.[13] It is estimated that the total death toll of *Móðuharðindin* reached 19–22% of the Icelandic population, or approximately 10,000 people.[14]

The difficulties in Iceland set in motion by the Laki fissure eruption were further compounded by an epidemic of smallpox, and also the very severe weather that had already begun in 1782.[15] Furthermore, the sea ice that drifts on the East Greenland Current to the shores of Iceland was extensive in 1781, 1782, 1783, and 1784, which significantly lowered temperatures on land. In the past, the presence of sea ice had many negative effects in Iceland, preventing access to fishing grounds and the arrival of trading vessels.[16] In recent times, there has, for the most part, been little sea ice off Iceland’s coasts.

The consequences of the Lakagígar eruption were not confined to Iceland.[17] The fine ash and volcanic dust that rained down on most parts of Iceland were also reported in many regions of Northern Europe. Examples come from the

Faeroe Islands, Caithness in Scotland, Copenhagen, Friesland, Bergen (Norway), and northern Germany. The dry fog also appears to have been witnessed in areas as far apart as Labrador, Newfoundland, the Tunisian coast, Asia Minor, and possibly China.[18] The dry fog of the year 1783 lasted for approximately three months, starting around mid-June, with most of the final descriptions dating from September 1783.

European historical sources noted many harmful effects of the dry fog on the environment. Specifically, these negative effects seem to have been limited mainly to the banks of the North Sea and Baltic Sea regions. However, other sources reported its beneficial influence on the vegetation and harvest. These include accounts from regions in Germany, Austria, Hungary, Livonia (comprising nearly all of modern-day Latvia and Estonia), and Upper-Hungary (modern Slovakia).[19] Another factor to note was that the 1780s were one of the coldest decades in the Central England Temperature (CET) series. There was a notable sequence of three cold years, 1784–86, where the annual mean for each year was more than 1 °C below the series average.[20]

Benjamin Franklin has been credited as the first to suggest a relationship between volcanic eruptions and climate.[21] The evidence for this relationship is now unequivocal, but the discussion on its exact nature continues.[22] For Europe at least, there is evidence that explosive eruptions tend to lead to cold summers and warm winters. A sulphate aerosol dry fog could also lead to a cold summer, but this would depend on the exact composition of the aerosol. In the case of the 1783 event, such debates regarding aerosol composition are relevant with regard to both the cold winter of 1783–84 and the hot summer of 1783. Such questions regarding volcanic eruptions and climate remain highly relevant in the present context of global change and debates concerning the relative contributions of natural climate variability and greenhouse gas-induced warming.[23]

34.4 Protracted Episodes: El Niño 1782–84 and La Niña 1785–90

Aside from the effects of the Lakagígar eruption, 1783 was an extraordinary year for several reasons, including the occurrence of extreme weather conditions, other volcanic eruptions, earthquakes, and epidemics in many parts of Europe and elsewhere.[24] With regard to epidemics, the evidence suggests that the concentrations of noxious gases and the volcanic ash produced by Lakagígar were responsible for an increased mortality in England, France, Belgium, and the Netherlands.[25]

A 2011 study by Rosanne D'Arrigo and colleagues has suggested that the impacts attributed to the Lakagígar eruption may actually have resulted from the occurrence of a negative North Atlantic Oscillation (NAO) phase coupled with a 'protracted' El Niño in 1782–84 that occurred during the event.[26] According to Allan and D'Arrigo, protracted episodes in the El Niño Southern

Oscillation (ENSO) can be defined as 'periods of 24 months or more when the SOI [Southern Oscillation Index] and the Niño 3 and 4 CEP-EEP SST [Central Equatorial Pacific-Eastern Equatorial Pacific Sea Surface Temperature] indices were of persistently negative or positive sign, or of the opposite sign in a maximum of only two consecutive months during the period'.[27] A 2009 study by J. Gergis and A. Fowler refined the standard to those events 'defined as persisting for three years or more'.[28]

Such protracted episodes have not received anything like the degree of attention or research afforded to more 'traditional' El Niño and La Niña events and their impacts and teleconnections. This is partly due to the insufficient number of such episodes during the historical record for a reliable statistical sample: not even twenty episodes of either phase have been resolved since 1850. Nevertheless, extensions of dynamical weather reconstructions (re-analyses) back into the nineteenth century, plus the generation of more reliable historical documentary and palaeoenvironmental data and records before the instrumental period, are allowing for the resolution of more of these protracted episodes. Gergis and Fowler's 2009 study resolved two such episodes during the 1780s, an El Niño lasting from 1782–84 and a La Niña lasting from 1785–90. As noted above, the major El Niño and La Niña events of the 1780s are 'embedded' within these longer episodes, which effectively cover much of this decade.[29]

Michael Chenoweth's 2003 study suggests that the years 1784–85 experienced a La Niña event, as indicated by Luc Ortlieb in 2000, and that its impact was felt in several parts of the globe.[30] Geographer Georgina Endfield has provided evidence for droughts and frosts in Mexico in 1784 and 1785, potentially resulting from the 'disturbed' weather patterns caused by this event.[31] In the Caribbean, Chenoweth provides evidence for cooler Puerto Rico temperatures from coral proxies in the 1780–85 period, strengthened trade winds across Jamaica during the wet season in the 1780s, and incursions of cold air outbreaks from North America into the Caribbean during each of the winters in the 1781–84 and 1785–86 periods. Examining evidence from the New South Wales Colony, Gergis and Fowler's 2009 study indicates that 1788–89 was a very wet year influenced by La Niña conditions. This was, in turn, followed by a severe El Niño drought spanning 1791–94.[32]

Grove's 2007 study refers to the Great El Niño of 1789–93.[33] It is far more temporally extensive than 'usual' El Niño events and coincides with the strong 1791–94 'protracted' El Niño episode. Nevertheless, there is debate in the literature on this topic. Some of this criticism relates to Grove's interpretation of terms in old textual material relating to India; other criticism points to discrepancies with palaeoenvironmental evidence regarding the nature, severity, and extent of Indian famines during this period. Edward Cook and colleagues state that 'Much has been made of this drought's effect in India, with several references to severe famine there, but the MADA (Monsoon Asia Drought Atlas) does not suggest that it was any more severe over India than the other droughts … Although this could be due to limited tree-ring coverage in India itself, reconstructions over the entire Indian subcontinent have significant validation skill, and its more extreme occurrence in the southernmost part of India and near Sri Lanka is consistent with historical data from those regions. It is therefore possible that this drought was not uniformly severe over India and that other non-climatic factors may have contributed to the severity of the societal consequences.'[34]

A 2014 study by David Nash and George Adamson demonstrates that the monsoon onset over western India was early in the first half and slightly later in the second half of the 1780s.[35] Figure 34.2, by F. Shi and colleagues, shows evidence for drought during major periods of famine in Indian history, including the 1780s.[36] The question is whether the palaeoclimatic data currently available are of sufficient coverage and resolution in space and time to judge how extensive these droughts actually were across the region. The impact of these climate anomalies in some of these regions are considered in detail in the following sections (see Fig. 34.2).

34.5 Case Study 1: Famines in India, 1780–1812

This case study focuses on India, and aims primarily to contextualise Roxburgh's report, as utilised by Grove. By exploring archival material held at the British Library India Office, it builds a more nuanced, regional picture of the societal impact of this particular ENSO event across the subcontinent. Since both Gergis and Fowler and Allan and D'Arrigo have argued in favour of even more protracted ENSO episodes stretching from 1785–90 (La Niña) and from 1791–94 (El Niño), the period addressed is extended to include these years.

Of particular interest is that storms and typhoons in India became more noticeable in this period. Most often, tropical cyclones in the Bay of Bengal occur from April to June and again from September to November. The major storm event of the 1780s occurred on 20 May 1787, when a cyclone in the Bay of Bengal struck the Indian coast near Coringa in Andhra Pradesh resulting in some 20,000 deaths.[37]

Two East India Company (EIC) reports are of particular interest in this regard. Both were compiled in the mid- to late nineteenth century from contemporary accounts sent from various regions of the subcontinent to the East India House in London, and both concerned the prevalence of famine in India over the preceding century, since the expansion of EIC power, showing that concern over famine was obviously high at the time. First, in *A Century of Famines*, F.C. Danvers presented a chronology of famine in India. He observed, 'it is an appalling fact that during the past hundred years one part or another of India has been visited by famine on no less than thirty-four … occasions'.[38] His chronology for 1770–1812 is presented in summary form below, along with a map of areas affected by famine.

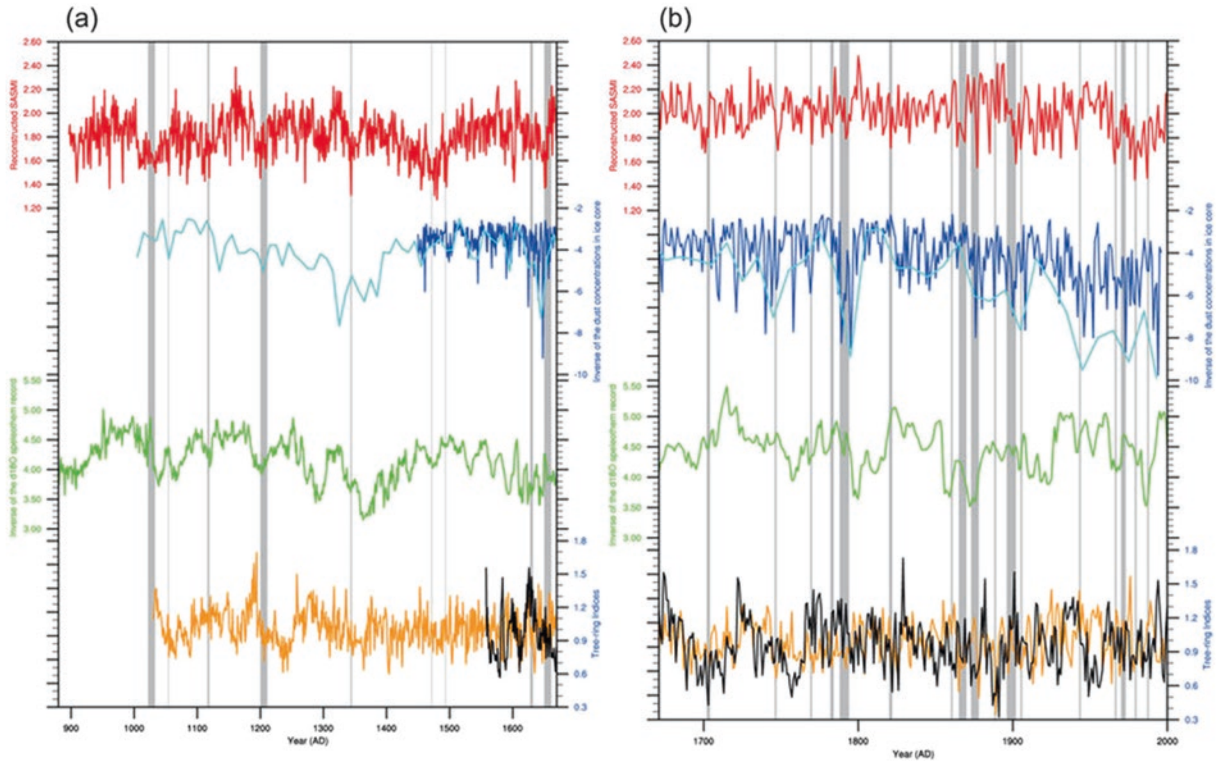

Fig. 34.2 Time series of the reconstructed South Asian Summer Monsoon Index (SASMI) (red line), the decadal (cyan line) and annual (blue line) inverse of dust concentrations in [an] ice-core record from Dasuopo, Tibet, the inverse of the $\delta^{18}O$ speleothem record (green line), and the tree-ring chronologies from Mae Hong Son (MHS) (black line) and Bidoup Nui Ba National Park (BDNP) (orange line) before 1670 CE (a) and after 1671 CE (b). The grey periods indicate the twenty-six famine events identified in India over the past millennium. (Reproduced without changes from F. Shi, J. Li, and R.J. Wilson, “A Tree-Ring Reconstruction of the South Asian Summer Monsoon Index over the Past Millennium,” *Scientific Reports* 4 (2014): 1–8 under a Creative Commons Attribution 4.0 International License

The great Bengal famine of 1770, an El Niño year, killed 10 million people. Its causes included the taxation policy of the East India Company.[39] It was followed by the famines of the 1780s that Danvers recorded in some detail. The decade was to prove particularly unsettled. There was general scarcity in 1781–83 in the Carnatic and the Settlement of Madras, caused primarily by Hyder Ali's incursions. Government action to provide food was considered to have helped alleviate the situation, and the scarcity was essentially over by early 1783. During 1782–84, the districts of Thurr and Parkur in Sind (then Western India; now Sindh, Pakistan) suffered the burning of crops and suspension of cultivation due to hostilities associated with the end of the Kulhora dynasty. These disasters combined with a two-year drought to produce famine.[40]

Again in 1783–84 Behar, Purneah, Bheerbhoom, and parts of Rajeshye, the Northwest Provinces, and the Punjab experienced famine. Although Danvers noted that information was limited, since much of the affected territory was not under British rule, 'there are reasons to believe that the upper parts of Hindustan had been visited with extraordinary drought during the previous years. In September and October 1783 there was an abnormal cessation of rain and extreme drought, and in the latter month a terrible famine was reported in all the countries beyond Lahore to Karumnasa (the western boundary of Behar) … the famine had already been severely felt in all districts toward Delhi. To the northward of Calcutta the crops upon the ground had been scorched, and nearly destroyed.' By early 1784, the famine was over.[41] Interestingly, Danvers observed that 'as usual, the long drought was succeeded by great floods'. The great Chalisa famine (literally, 'of the fortieth') of 1783–84 in South Asia is recorded as having killed nearly 11 million people. It is said to have followed the unusual El Niño, which caused drought events and affected many parts of northern India from Kashmir to Punjab in the north to Rajasthan in the west and Uttar Pradesh in the East. Famine in the previous year 1782–83 had extended over South India, including Madras under the English East India Company and Mysore under Haider Ali and Tipu.

The next Indian famine occurred in 1790–91, affecting the regions of Western India, Omerkot, Kach, Ahmedahad, Rewa Kanta, Broach, Surat, Kulladghi, Dharwar, Sawunt Warree, Kaira Belgaum, Rutnagheri, Pahlunpoor, Mahee, Kanta, and Baroda. Here Danvers emphasised the regionality of the famine ('in some of these districts famine was only partial and local') and the variety of causes, such as in Kach, where 'famine was caused by innumerable black ants which swarmed in almost all parts of the country and destroyed vegetation'. Again, the lack of full information is noted: 'very little is known concerning the famine in many districts named (above), beyond the fact that in 1790 tradition records the occurrence of a very severe famine. An almost total failure of rains was the immediate cause, apparently, of the calamity, and sufficient information exists to prove that it was one of the most remarkable on record. So great was the distress that many people fled to other districts in search of food, whilst others destroyed themselves, and some killed their children and lived on their flesh.'[42]

Danvers also reported famine in South India during 1790–92. ‘[I]n these years there was a very serious dearth in the northern districts of the Madras presidency, and the pressure was apparently felt for about two years … from November 1790 to November 1792. Many deaths from starvation occurred. At an early period the Government suspended the import and transit duties on all kinds of grain and provisions, and imported grain from Bengal. In the latter part of 1791 the export of rice from Tanjore was prohibited except to distressed districts. Rice was distributed gratuitously by government and relief was afforded by employing the poor on public works.’[43] Up to half the population perished in some districts of the Madras presidency, such as in the Northern Circars. In other areas, such as Bijapur, although no records were kept, both the famine and the year 1791 came to be known in folklore as the *Doji bara* (also *Doĝi Bar*), or the ‘skull famine’, on account, it was said, of the ‘bones of the victims which lay unburied whitening the roads and the fields’.[44] The famine also affected areas outside British rule, including Hyderabad, Southern Maratha Kingdom, Deccan, Gujar, and Marwar—then all ruled by Indian rulers.[45] As in the *Chalisa* famine of a decade earlier, many areas were depopulated by mortality or migration. According to Grove, a total of 11 million people may have also died during the years 1789–92 as a result of starvation or accompanying epidemics.[46]

Famines are also recorded in 1802–04 in Guzerat, Kach, Pahlunpoor, Rewa Kanta, Surat, Candeish, Ahmednagar, Poona, Sattara, Sholapur, Kolapur, Belgaum, Dharwar, Colaba, Ratnagherry, and the Nizam’s Dominions; in 1803–04 in Moradabad, Bareilly, Etawah, Furruckabad, Cawnpore, Allahabad; in 1804–07 in Tanjore, North and South Arcot, Nellore, Chingleput, the Ceded Districts, and Trichinopoly; and in 1812–14 in Madura. However, for this period, the tone of the various details of the famines suggests that those of 1790–91 and 1790–92 were the worst on record, both in extent and severity of societal impact.

Danvers’ report is pertinent not merely as a source on meteorology and famine chronology in India. He has much of interest to say that allows us to see in proper proportion the significance of rainfall variation within a larger causal framework, and how such variation is linked to famine (see Chap. 27). Danvers stated that ‘famines in India have arisen from several different causes … the most general cause has been the failure of rains. Distress has also, however, been caused by hostile invasions; by swarms of rats or locusts’ (or ants in the case of the 1790–91 famine in Kach, described above); ‘by storms and floods; and not infrequently by the immigration of starving people from distant distressed parts, into districts otherwise well provided with food supplies; and excessive exports of grain into famine stricken districts, or by combination of two or more of the above named circumstances’.[47] However, Danvers’ key but perhaps counter-intuitive observation (predicting Amartya Sen) is that most deaths in times of famine were not caused by actual shortage of food: ‘It is an important fact’, he states, ‘that famines in India are more generally famines of work than of actual absence of food throughout any large extent of the country.'[48] Danvers' point then is that the causal link between lack of rains and famine is more complex than might be assumed. The problem is not that local harvests are poor and therefore food is in short supply when rains are insufficient. It is more that lack of rain disrupts agricultural employment patterns and leaves poor workers without sufficient money to purchase food.

Danvers continued on this topic to describe how, 'from a study of the history of past famines it appears that these visitations are almost as liable to be caused by unseasonable rains, or by their unequal distribution, as by deficient amount of rainfall during the year'. He concludes by stating that 'there are altogether so many circumstances connected with rainfall and its influence on the crops that it is difficult to arrive at any definite conclusion as to the actual proportionate deficiency of rain that would constitute a famine drought'.[49]

A glance at Danvers' map of areas affected by famine (here reduced from its original coverage of a century to the period 1770–1812 only) shows the asymmetry of famine distribution. Even this half-century of frequent famines displays vast areas that remained completely immune. Danvers' map then, much like his report, points to a markedly complex relationship between deficient rains and significant social impact (see Fig. 34.3).

The second source, by George Campbell, gives details of the famine around Madras in 1782, which, it suggests, was primarily driven by warfare in the area: 'when the enemy was at their walls, and by his ravage, in every part of the adjacent country, had destroyed the cattle and reduced the inhabitants to the most pressing difficulty to obtain the common necessaries of life'. A note from Bengal in the 1783–84 famine is particularly interesting for the light it shines on the experience and cultural construction of drought, famine, and scarcity in the region and the period. A letter describes how the 'shocking experience' of the 1770 famine 'still fresh in the memories of most people' combined with the shipment of vast quantities of grain to Madras in the preceding seasons again left Bengal vulnerable to artificial shortages.[51]

Perhaps the most valuable section of this collection concerns the details of the famine and general upheaval caused by a series of storms in 1787. Several sources reported on this event: An article in *The Nautical Magazine* recorded that 'Captain Huddart describes one [storm] which destroyed ten thousand persons in the neighbourhood of Coringa, in May, 1787, and penetrated twenty miles over the country'.[52] William Roxburgh noted a major loss of his papers, including those on various plant species in his collection, as a result of this event.[53] 'I had made and noted down many observations on its uses, when in large practice in the General Hospital at Madras in 1776, 77 and 78, but lost them, with all my other papers, by the storm and inundation at and near Coringa in May 1787.'

The Madras typhoon of May 1787 was part of a series of very severe storms occurring throughout the year in Bengal. Reports of floods from the

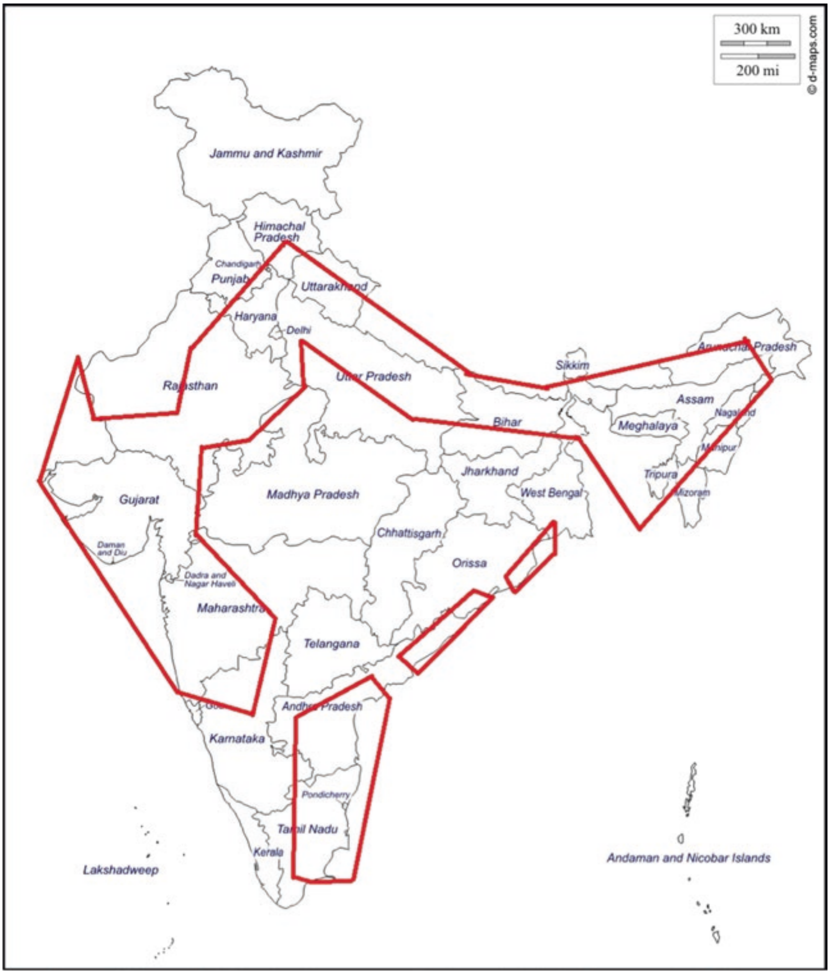

Fig. 34.3 Map of famine areas in India from 1770–1812, based on F.C. Danvers, *A Century of Famines*[50]

General Letter from India of 15 December 1787 describe a 'violent inundation' of which the author states that 'no memory can recollect any preceding instance of similar inundations … the distress occasioned by the inundation was aggravated by a storm which happened on the 2nd ultimo, [i.e., November] and which, wherever it prevailed, destroyed much of the existing crops'.[54] An important point here with regard to the meteorological record is that the second storm (along with others described below), which occurred in November, exacerbated the already difficult situation caused by the typhoon in May. This second disaster made the problems associated with the first much more difficult to recover from. The Governor General Lord Cornwallis was suspicious of false claims, warning that 'it will be the duty of the Board of Revenue to make the most scrupulous investigations, and to reject every ill-founded claim for deductions'. Again, an embargo on export was put in place, now for six months.[55] More disparities are seen in the aftermath of the flood and storms. Grain prices were very high in Moorshedabad and Dacca in particular, 'where sufferings of the poor inhabitants were the greater', but much more normal in Benares and Behar 'where the crops had been abundant'; thus exports from these regions to the affected areas were encouraged. In addition to the Madras event in 1787–88, other reports recorded early and abnormally heavy rains in Bengal and Behar. Through 'the latter part of March to the latter half of July, they had continued with such violence as almost to render cultivation impossible'. A government-imposed ban on grain exports was credited with resolving the situation by June of 1788.[56]

By 1 June 1788, the *General Letter* could state 'that the distresses which have been suffered by the scarcity of grain, in different parts of the country and particularly in Dacca, have been of late much relieved'. The proceedings of the Board of Revenue reveal the internal conflict over the continuation of collections through times of scarcity. As shown above, Cornwallis was resigned to the fact that remission would be necessary but aimed to scrupulously investigate any suspected false claims. W. Hindman, an acting collector, wrote on 20 July 1787 that since the 11th, 'rains have continued with a violence hitherto unknown, and, it grieves me to inform you, that by the advice I have received from the Mofussil [rural areas], I am apprehensive of a total depopulation of all the *pergunnahs* [subdistricts], if the weather does not soon moderate … about two thirds of the *ryots* [peasants] have retired for safety with their families to the hills and others are following daily, whole villages have been swept away'. He continued, 'it is impossible for language to convey the distressful situation of this province; where ever you go you see nothing but a sheet of water, with here or there the tops of houses and trees. Whole crops have been levelled and villages, cattle, grain, and implements of husbandry swept away. Many of the inhabitants have been drowned and whole *pergunnahs* deserted … the small islands before the city of Dacca are entirely overflowed, and only a few of the tops of the houses are to be seen, the oldest inhabitants remember nothing like it…. The overflowing banks of the Berhamputer [Brahmaputra], a circumstance never known before, has certainly occasioned this dreadful inundation.'[57] The collector of Chittagong reported that 'the deluge of rain which has recently fallen in these parts exceeds, I am given to understand, the memory of the oldest inhabitants'.[58]

Campbell's collection shows how very severe weather difficulties—again and again made worse by repeated storms, and very likely combined with administrative determination to continue tax collection to the greatest possible extent—left great want and dislocation amongst the poor. The collector of Nuddea wrote in September 1787 that ‘the rivers which run through this district have risen to so alarming a height that I should consider myself deficient in my duty did I omit to communicate the intelligence to you; the Jellingy in particular, which passes by this place has swelled to such a degree that there are few parts where its banks are not overflowed on both sides and to judge from my own observation and the opinion of people here, it must be at least two feet higher than it was in the rains of 1785, and then it was higher than the oldest inhabitants had ever remembered it’. At the end of that month ‘vast torrents’ were recorded in Midnapore, by which ‘those poor creatures that survived the calamity have lost everything in the world’.[59] Similar reports came from Burdwan, Sarun in the west to Sylhet and Rungapore in the east.[60] Numerous collectors wrote the Board of Revenue warning that the population could not support regular tax collections. In some cases, the Board permitted collectors to exercise discretion, but in other cases, remittance was refused.

Danvers’ and Campbell’s collections of famine reports appear to show a significant increase in climate-related societal difficulties during the 1780s–90s. Although the 1770 famine was extremely severe, no other famines are described for the remainder of the 1770s, whereas a total of six notable famines are described between 1780 and 1791 (including the Doji Bara and Chalisa famines), none in the remainder of the 1790s, two in the 1800s, and two in the 1810s. All of the 1780s famines were in part born of climatic irregularities, although as described above, through notably complex causal links. The most frequent climatic contribution was lack of rain, but disruptions to the expected timing of rain, excessive rain, and a notable season of extreme storms, floods, and intense winds in 1787 also contributed to famine when they occurred. Campbell’s collection of reports on the storms of 1787 add much detail to previous knowledge of the May typhoon and suggest that areas of Bengal were struck repeatedly by dramatic storms and floods of an extent not known in living memory. Such reports appear to support Allan’s and Gergis’ suggested identification of a more extended La Niña episode beginning in 1785.

Although statistical data are absent, Danvers’ qualitative assessment of the 1790–92 famines suggests they were the most severe of the period. However, it would be impossible from the information presented here to assess their impact in relation to the 1770 famine, which Campbell in 1868—with the benefit of hindsight—interestingly referred to as ‘the Great Famine of 1770’. Several types of evidence not found elsewhere indicate that at least in some regions the 1790–92 famine was remarkable in its impact, thus supporting Grove’s identification of intense ENSO activity at this time.[61] These include reports of direct governmental famine relief through the distribution of rice, the institution of employment programmes through public works, subjective judgements of its extreme severity, and descriptions of the failure of rains and of the resorting to suicide and eating of children.

34.6 Case Study 2: The Influence of Climate on the First European Settlement of Australia, 1788–93

Aside from some pioneering works of nineteenth-century scholars, Australian historical records remained until recently essentially unexploited for use in contemporary climate research.[62] From 2009–12, an initiative known as the South Eastern Australian Recent Climate History (SEARCH) project (www.climate-history.com.au) used historical documents together with meteorological and palaeoclimate data to reconstruct climate variability back to first European settlement in 1788 (see Chap. 21).[63] One of the aims of the research was to identify previously undescribed wet and dry phases in the pre-1900 period and examine any possible relationship with large-scale circulation modes like the ENSO phenomenon that influence the region.[64]

Extreme phases of the ENSO cycle frequently result in extreme weather conditions around a large part of the globe.[65] In the western Pacific, El Niño events increase the likelihood of severe drought, while La Niña conditions favour above-average rainfall and flooding.[66] Typically, the reverse is true in the eastern Pacific, where El Niño episodes bring heavy rainfall.[67]

Recent advances in the reconstruction of past ENSO conditions now incorporate data from the western Pacific, rather than traditional El Niño chronologies that only consider historical records from South America.[68] They now also reconstruct historical La Niña events for the first time. In contrast with Grove, Gergis and Fowler conclude that a very strong La Niña event (not El Niño) was centred on 1788 and continued to 1790. A characteristic 'phase flip' seems to have occurred in 1791, beginning a strong El Niño event that lasted until 1794.[69]

Evidence for the 1788–90 La Niña and the 1791–94 El Niño event sequence is found in the recently consolidated climate record for southeastern Australia (SEA).[70] While it is clear that ENSO influences rainfall variability in the broader SEA region, the signal recorded in coastal New South Wales is weak but still discernible for high-magnitude events.[71]

When Governor Arthur Philip arrived with the First Fleet in January 1788, Sydney was in the middle of a cold and wet summer. The colony's chief bureaucrat, David Collins, made meticulous records of weather conditions, the first of which reads: 'The weather during the latter end of January and the month of February was very cold, with rain, at times very heavy, and attended with much thunder and lightning, by which some sheep, lambs and pigs were destroyed.'[72]

More 'inclement, tempestuous weather' persisted throughout the winter of 1788, making life in the new colony difficult. Collins wrote: 'During the beginning of August much heavy rain fell, and not only prevented the carrying on of labour, but rendered the work of much time fruitless by its effects; the brick-kiln fell in more than once, and bricks to a large amount were destroyed; the roads about the settlement were rendered impassable; and some of the huts were so far injured as to require nearly as much time to repair them as to build them anew. It was not until the 14th of the month, when the weather cleared up, that the people were again able to work.'

By the second year of settlement, the foreign landscape and erratic weather were wreaking havoc on the establishment of agriculture in Sydney. In February 1789, the young colony was still experiencing wet conditions, making life increasingly desperate. Collins reported: 'the weather was extremely unfavourable; heavy rains, with gales of wind, prevailing nearly the whole time. The rain came down in torrents, filling up every trench and cavity which had been dug about the settlement, and causing much damage to the miserable mud tenements which were occupied by the convicts.'[73]

Unsettled conditions appear to have persisted into autumn 1790. As Sydney endured more flooding, soon they learned of the devastating loss of the cargo ship HMS *Sirius* on Norfolk Island on 19 March 1790.[74] When the HMS *Supply* brought news of the wreck of the *Sirius*, the mood of the colony sank deeper into despair. As Collins recalled: 'The weather had been very wet during this month; torrents of rain again laid every place under water; and many little habitations, which has withstood the inundations of the last month, now suffered considerably.'[75]

The loss of the *Sirius* brought Sydney Cove to the brink of famine, and drastic ration reductions were enforced. Collins wrote, 'it was unanimously determined, that martial law should be proclaimed; that all private stock (poultry excepted) should be considered as property of the state … the general melancholy which prevailed in the settlement when the above unwelcome intelligence was made public, need not be described; and when the *Supply* came to an anchor in the cove everyone looked up to her as to their only remaining hope … it was determined to reduce still lower what was already too low … very little labour could be expected from men who had nothing to eat'.[76] Cold and hungry, many feared that the weakened colony was in danger of collapse.

By September 1790, the weather started to improve. Soon, however, the colony faced a particularly dry summer. On 27 December 1790, Watkin Tench described the first European account of a summer heatwave in Sydney, likening the northwest wind to the 'blast of a heated oven'. Tench also described the impact of the dry conditions on the food supply: 'vegetables are scarce … owing to want of rain. I do not think that all the showers of the last four months put together, would make twenty-four hours rain. Our farms, what with this and a poor soil, are in wretched condition. My winter crop of potatoes, which I planted in days of despair (March and April last), turned out very badly when I dug them about two months back. Wheat returned so poorly last harvest.'[77]

Early in 1791, Governor Philip wrote: 'the dry weather still continued, and many runs of water which were considerable at this season the last year [1790], were now dried up … at Sydney, the run of water was now very small'.[78] David Collins commented on the heat stress on the local wildlife: 'Fresh water was indeed everywhere very scarce, most of the streams or runs about the cove being dried up. At Rose Hill [Parammatta], the heat on the tenth and eleventh of the month, on which days at Sydney the thermometer stood in the shade at 105°F [40.6 °C], was so excessive (being much increased by the fires in the adjoining woods), that immense numbers of the large fox bat were seen hanging at the boughs of trees, and dropping into the water … during the excessive heat many dropped dead while on the wing … In several parts of the harbour the ground was covered with different sorts of small birds, some dead, and others gasping for water.'[79] Governor Arthur Philip elaborated on the staggering scale of the scene: 'from the numbers that fell into the brook at Rose Hill [Parramatta], the water was tainted for several days, and it was supposed that more than twenty thousand of them [bats] were seen within the space of one mile'.[80]

In contemporary Sydney, autumn and winter rains are important for recharging reservoirs and rejuvenating parched land. The failure of these rains can have a devastating effect on agriculture, as it did in the late eighteenth century. In April 1791, Arthur Philip remarked that 'the dry weather continued … the quantity of rain which fell in the month of April [1791], was not sufficient to bring the dry ground into proper order for sowing the grain … this continuance of dry weather, not only hurt their crops of corn very much, but the gardens likewise suffered greatly; many being sown a second and a third time as the seed never vegetated, from want to moisture in the soil'.[81] As a result of the drought, Governor Philip tightened rations as the food supply of the struggling colony began to dwindle: 'Little more than twelve months back, hogs and poultry were in great abundance, and were increasing very rapidly … but as this time [April 1791] there was seldom any to sell.' Watkin Tench lamented, 'I scarcely pass a week in summer without seeing it rise to 100 degrees [Fahrenheit—i.e., 37.8 °C]; sometimes to 105 [40.6 °C].'[82]

David Collins described the dry conditions that persisted into June 1791: 'the ground was so dry, hard and literally burnt up, that it was almost impossible to break it with a hoe; and until this time there has been no hope or probability of the grain vegetating'.[83] On returning back from Norfolk Island John Hunter, ex-Captain of the doomed *Sirius*, described the scene at Sydney Cove: 'all the streams from which we were formerly supplied … were entirely dried up, so great had been the drought; a circumstance, which from the very intense heat of summer, I think it probable we shall be frequently subject to'.[84]

By November 1791, the worsening drought led to the first documented account of water restrictions imposed on Sydney. The small freshwater stream that ran into Sydney Cove proved an irregular source of water. To try and control the amount of water flowing out of the colony, 'holding tanks' were cut into the sandstone banks to provide storage for the water. Collins wrote: 'By the dry weather which prevailed the water had been so much affected, besides being lessened by the watering of some transports, that a prohibition was laid by the Governor on the watering of the remainder of Sydney … to remedy this evil, the Governor had employed the stone-mason's gang to cut tanks out of the rock, which would be reservoirs for the water large enough to supply the settlement for some time.'[85] These sandstone basins led to the freshwater creek flowing into Sydney Cove becoming known as the 'tank stream', and are likely to be the earliest example of water regulation in Australia's colonial history.

From August 1794 onwards, there are reports that conditions in the settlement gradually improved as the grip of drought loosened: 'Notwithstanding the weather was unfavourable during the whole of this month, the wheat every where looked well, particularly at the settlement near the Hawkesbury,' Collins remarked.[86] By January 1795, he commented on how agriculture was now beginning to thrive as heavy rains began to soak the floodplains of the Hawkesbury River. The first major drought experienced by Australia's European settlers had finally come to an end, but it would later come to be recognised as representing the quintessential ENSO cycle of drought and flooding rains that still defines life in twenty-first-century Australia.

34.7 Case Study 3: Regional Events and Impacts during the 1780s in Japan

In Japan, the 1780s were one of the most disastrous periods in historical times. The great 'Tenmei' Famine led to the deaths of around 100,000 people due to extremely poor summer rice harvests across northern and eastern Japan, particularly in 1783–84 and 1786. The primary cause of the famine and harvest failures was the exceptionally cool weather during the summers of 1783 and 1786. Under present conditions, generally hot summers are experienced in Japan under the influence of strong subtropical highs, which bring dry and sunny weather conditions. Cool summers occur under the influence of stagnant polar fronts and passing extra-tropical cyclones, which bring cloudy and rainy conditions.

Although instrumental meteorological data are not available for this period, several attempts have been made to estimate summer temperatures in the 1780s based on daily weather diaries in Japan.[87] These include the Ishikawa diaries, which are continuous family diaries kept in the western suburbs of Tokyo from 1721 to 1940.[88] Using these diaries, researchers have categorised weather patterns in Japan into several types, based on the number of days with rain in the months of July and August. The 'no rain across Japan' weather pattern had its lowest frequency (eight days) in 1783 and the second lowest (nine days) in 1786, in contrast with the highest (thirty-three days) in 1781 and 1789 and the second highest (thirty-two days) in 1785. This suggests that the weather and climate in the 1780s were unstable, with large year-to-year variability of weather patterns, and that 1783 and 1786 were extremely rainy and cool.

Since the number of rainy days is highly correlated with the mean temperature in a summer month, especially in July (the correlation coefficient is −0.70 based on the Japan Meteorological Agency data for 1876–1940), it is possible to reconstruct July temperatures in Tokyo for the period 1721–1940 based on the weather records in the Ishikawa diaries. The reconstructed temperature series show several cooler and warmer periods. From 1721 to 1790, temperatures are estimated to have been about 1–1.5 °C lower than at present, and July temperatures show large year-to-year variability with the lower values below 22 °C in 1728, 1736, 1738, 1755, 1758, 1783, 1784, and 1786. Temperatures in the 1780s were often very low with large interannual variations. In the summer of 1783, exceedingly cool and wet conditions brought an extremely poor rice harvest, and this unusual weather led to a severe famine in Japan. The nineteenth century brought warmer periods during the 1810s and early 1850s. By contrast, the 1830s, late 1860s, and late 1890s were relatively cool, and great famines occurred in the 1830s as they had in the 1780s (see Fig. 34.4).[89]

The weather and climate during the 1780s can be summarised as follows:

Summer 1781: Hot summer conditions across Japan with extremely dry conditions in southwestern Japan.
Summer 1782: Temperatures were basically as usual across Japan.

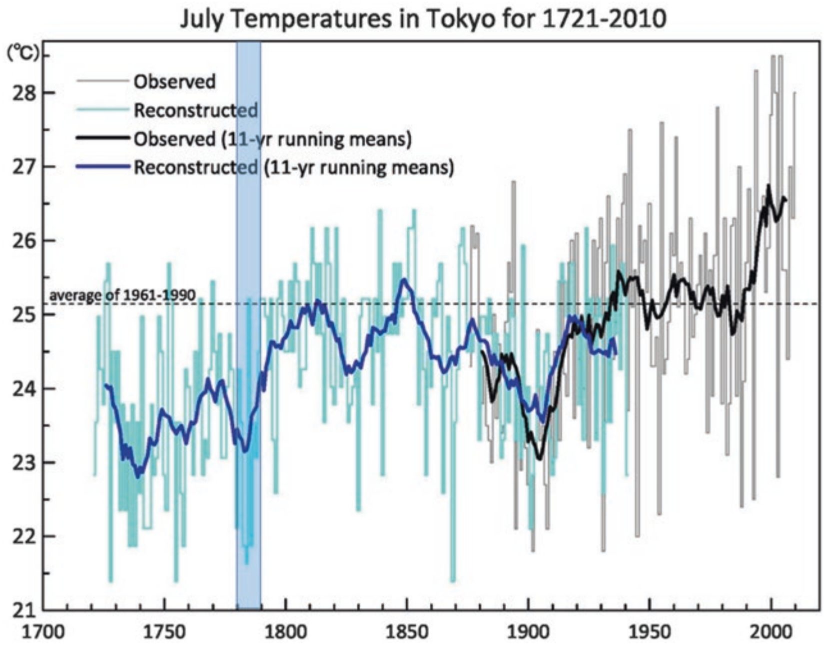

Fig. 34.4 Time series of reconstructed (blue lines) and observed (black/grey lines) July temperatures in Tokyo for 1721–2000. Thin lines indicate year-to-year variations and thick lines indicate eleven-year running means. The blue rectangular part indicates the period of the 1780s. Modern Tokyo has a very strong urban heat island effect and this is likely to have contributed to warming evident in the twentieth century. Figure modified and updated from Mikami (1996)

Summer 1783: Extremely cool and wet conditions across Japan with exceptional rainfall in northeastern Japan.
Summer 1784: Slightly warm in northern Japan and wet/cool weather in southern Japan.
Summer 1785: Hot summer conditions across Japan with dry weather patterns in western Japan.
Summer 1786: Extremely cool summer conditions across Japan, centred in the western area, with much rainfall.
Summer 1787: Rainfall amounts were as usual across Japan, with high temperatures.
Summer 1788: Usual temperatures across Japan; slightly wet in western Japan and less rainfall in northern Japan.
Summer 1789: Almost normal weather conditions across Japan with hot summer climate in northern Japan.
Summer 1790: Hot and dry weather conditions across Japan.

The government took several relief measures, such as promoting emergency rice stocks in local governments and reducing the price of rice. Nevertheless, mortality rose dramatically during the severe famines of the 1780s. Starving people in rural areas sought food in towns and cities, where destructive urban riots occurred.

34.8 Case Study 4: Africa (Including Egypt)

The explosion of the Laki volcanic fissure in Iceland between the summer of 1783 and the winter of 1784 had a direct impact on rural Egypt.[90] The Laki fissure eruption produced a heavy sulfuric acid aerosol burden in the Arctic, which led to 'substantial heating of the Arctic atmosphere and subsequent reduction of the equator–pole thermal gradient'.[91] The result was a weaker westerly jet stream of warm air, which contributed to a strong dynamical effect of lessening the African and Indian Ocean monsoon circulations.

The Indian Ocean monsoons feed the Nile. Moving over the Ethiopian highlands in early summer, these rains swell the upper reaches of the Nile system, eventually flowing into Egypt in June. The river rises in the south at Aswan in June and in Cairo by July, peaking in the capital in late August or early September. The Lakagígar eruption took place in June—just in time to interrupt the Indian Ocean summer monsoons. Climatological studies indicate that the Lakagígar eruption led to reduced Nile floods in 1783 and 1784. Estimates are that the Nile's flow decreased by as much as 18% in these years.[92]

The summer of 1783 brought the lowest flood and that of 1784 the third lowest of the entire period from 1737 to 1800.[93] The Nile was the literal lifeline of Egypt, its ultimate source of food, revenue, and power.[94] Thus, a reduction of nearly a fifth of its waters obviously had devastating consequences for the social, economic, and political structures built by the wealth the Nile produced.

The sources from this period make clear that the eruption's effects on Egypt precipitated a massive crisis in the countryside. Documenting the early autumn of 1783, the Egyptian chronicler 'Abd al-Raḥman al-Jabartī wrote of the Nile's dearth that year and the food shortages that followed. 'The Nile did not rise sufficiently, and it fell rapidly … The ground remained dry in the south as well as the north. Grain became scarce … The price of wheat was on the loose … and the poor suffered greatly from hunger.'[95] Almost a year later, another lack of summer floods exacted a similar toll on Egyptians, leading to great '*kaht ü galâ*' (scarcity and dearth).[96] The chronicler al-Jabartī wrote that the fall of 1784 was 'like the preceding one with distress, rising prices, an inadequate rise of the Nile, and continual internal strife'.[97]

Two consecutive years of poor floods ravaged the countryside, Egypt's economy, and its rural social structure. Land became so progressively unproductive that the taxes garnered from rural Egypt in 1785 were the second lowest total in over sixty years. 'The land turned to waste', 'peasants abandoned their villages because of a lack of irrigation', and 'many of the poor starved to death'.[98] Moreover, 'store-houses on the river stayed empty of grain for a whole year and the granaries also remained closed. People's daily bread and subsistence were cut off, and they perished regardless of whether they compromised or cheated.'[99] Travelling in Egypt in these years, the French philosopher and orientalist C.F. Volney corroborated al-Jabartī's description: 'the inundation of 1783 was not sufficient, great part of the lands therefore could not be sown for want of being watered, and another part was in the same predicament for want of feed. In 1784, the Nile again did not rise to the favourable height, and the dearth immediately became excessive.'[100] By the end of 1784, 'many men and animals had perished from hunger'.[101] As evidence of just how hungry people had become, Volney reported seeing two men 'sitting on the dead carcase of a camel, and disputing its putrid fragments with the dogs'.[102]

In Egypt (as in Iceland), drought and hunger in 1783 and 1784 made people more susceptible to plague and other diseases.[103] Volney guessed that in these years 'famine carried off, at Cairo, nearly as many as the plague'.[104] The plague began in the winter of 1783–84, with hundreds of dead bodies taken out of Cairo each day. It increased its deadly intensity in the summer and fall of 1784, probably because the previous years' food shortages had weakened rural people's immunities.[105] The combined famine, drought, and disease continued into 1785, and decimated rural populations through both death and flight. Citing 'received opinion', Volney estimated that Egypt lost one-sixth of its total population between 1783 and 1785.[106]

The environmental impacts of the Lakagígar eruption immediately contributed to the economic, political, and social transformation of rural Egypt. In the stress and confusion of drought, famine, depopulation, and disease, local powerbrokers throughout the countryside saw an opportunity for theft and a chance to tighten or extend their authority over territories and communities.

Banditry, plundering, and violence thus gripped Egypt in the middle of the 1780s.[107] 'During this period,' al-Jabartī wrote, 'lawlessness increased.'[108] Local elites and their henchmen looted cargo from ships on the Nile and from transport caravans on roads; exacted protection money from local communities; stole grain, animals, and cash; and destroyed crops.[109] This violence, theft, and turmoil further encouraged rural depopulation as countless people fled these dreadful circumstances. 'Extortions and acts of tyranny committed by the amirs [elites] followed one another, and their followers spread through the country to levy money from the villages and towns and invented illegal contributions … until they ruined the peasants, who became unable to bear the burden and abandoned their villages.'[110] So, the consequences of the ecological stress were a major component of the political and economic history of Egypt in the 1780s and 1790s.

Elsewhere on the continent of Africa, some meteorological information is available for nearly all of the 1780s. Historical sources—mainly from European observers—provide useful descriptions of meteorological conditions and human impacts, if not always the same level of context and detail found in the other parts of the world discussed in this chapter. For Morocco, Algeria, and Tunisia, enough information is available in the sources consulted that the absence of reference to famine or drought is a likely indicator of good rainfall. A fair amount of information is available from the central and eastern Sahel and Guinea Coast, but it is somewhat ambiguous. Relatively little information is available for eastern and southern Africa (see Chap. 20).

The 1780s appear to have been a relatively prosperous decade in parts of North Africa. Charles Bois stated that this decade was part of a long period of prosperity in Tunisia, with harvests being so good that wheat was being exported from the region.[111] The occurrence of plague in 1784 and 1785 could also imply good rainfall, since precipitation is correlated with plague occurrence in modern Africa.[112] In Morocco, however, famine and drought occurred in 1780, 1781, and 1782.[113] Algeria experienced bad harvests in 1784 and 1785, and a famine occurred near Oran, in western Algeria in 1786.

The most complete record from West Africa in the 1780s comes from the Cape Verde Islands, a region of summer rainfall similar to the Sahel. Good rainfall occurred in the years 1780–84, but drought and famine prevailed in much of the region from 1785–92.[114] Drought was particularly intense from 1785 to 1787. In Senegambia, the 1780s were primarily dry, and Charles Becker reports famine and/or food shortages in Senegal in 1782, 1784, 1786, 1787, and 1789.[115] Low rainfall and drought occurred in Gambia and Guinea-Bissau in 1786, followed by famine in southern Gambia. In Sierra Leone, John Matthews reported that the rainy season in 1785 was more severe and longer than usual.[116]

While droughts and anomalously wet years tend to affect the entire east–west extent of the Sahel, that may not have been the case in the 1780s. Chronologies for Chad, Agadez (central Niger), Nigeria, and the Niger Bend region indicate only a single reference to relatively dry conditions during that decade. Plague was common in the region between the Niger Bend and the Voltas (Burkina Faso and Ghana) from 1786 to 1796, suggesting relatively wet conditions.[117] This was supposedly a 'time of plenty' in the Sudan, although a drought occurred in Darfur in around 1786 and people were forced to eat tree branches. Lake Chad, which is influenced by both Sahelian and equatorial rainfall, rose to very high levels. As a consequence, it was possible to travel by boat from the lake to the Tibesti region. Some reports suggest extremely wet conditions in the northern Sahel and Sahara. In 1780, a great flood occurred in Agadez. Rainfall continued from early morning to early afternoon and destroyed the town. A strong stream flowed in 1789 in Murzuq but was later covered by advancing sands.[118]

For the more equatorial regions of the Guinea Coast and coastal Angola, information on the 1780s is abundant. Much of it is found in correspondence related to the slave trade and supplemented by travellers' journals.[119] A late onset of the rains and references to a scarcity of corn, including a famine in Dahomey, suggest that 1780 was relatively dry on the Guinea Coast. Dryness continued to cause trouble early in 1781. The rains also started late but were prolonged, which greatly affected Europeans. In 1782, the rains were reportedly the worst experienced in many years.[120] Heavy rainfall and rough seas were mentioned in March 1784, suggesting an early start to the rainy season.[121] References to much sickness and anticipation of better weather suggest intense rains in 1785; however, references to dried-up water tanks in early 1786 imply that the rains were inadequate. Wetter conditions commenced in 1787 and prevailed throughout most of the 1790s. Heavy rains caused the British fort at Sekondi, on Ghana's central coast, to fall down in 1787 and many houses to collapse again in 1788 and 1789. These heavy rains also affected the Danish fort at Christiansborg (Accra).[122]

The climate of coastal Angola is in some ways comparable to that of the Guinea Coast. Rainfall peaks in the boreal spring and the boreal summer is dry. Both regions are strongly influenced by temperatures in the nearby Atlantic. However, while rainfall peaks in June along the Guinea Coast, it peaks in March or April in coastal Angola. A chronology compiled in 1982 by Miller indicates abnormally dry conditions in eight years of the 1780s, with drought occurring in four of those years (1786–89). The drought conditions continued into the early 1790s. Ample rainfall is mentioned for Luanda only in 1785.[123]

There is little historical information for the 1780s in eastern equatorial Africa. However, lake-level reconstructions suggest that, as in Angola, conditions were relatively dry. Lakes Malawi, Chilwa, Tanganyika, and Rukwa were relatively low, and Nile minimum levels suggest that Victoria was similarly low.[124] During this decade, a famine occurred in the lakes region of East Africa that was so severe that large-scale migrations occurred.[125] At the same time, the levels of Lake Naivasha were falling, further suggesting dry conditions.[126]

Tree rings from the winter rainfall region of South Africa suggest that the 1780s was probably the wettest decade since the late sixteenth century.[127] Tree rings also indicate that wetter conditions occurred in Natal. An absence of drought references in the 1780s, despite references to drought in the 1770s and 1790s, suggest that rainfall was also adequate in Zambia, Zimbabwe, and Mozambique. Southern Namibia appears to have been relatively drought free in the 1780s.[128] The level of Lake Ngami (Botswana) was also high in the 1780s, consistent with other historical information. However, there are several references to protracted drought in the western Cape Province (South Africa) in 1783–85. The drought broke in 1786, allowing for a good harvest in 1787 and the following few years. Drought occurred in the central Cape Province in 1789 and 1790 and in the eastern Cape Province in 1783 and 1784.[129]

From this miscellaneous information, two patterns seem to emerge. In the eastern half of Africa, it appears that rainfall in the 1780s was relatively good in the winter rains region north of the Sahara along the Mediterranean coast and in the northern and southern subtropical latitudes, including the eastern Sahel. However, the eastern equatorial regions experienced a preponderance of drought. This pattern is a common one.[130] In the western half of Africa, the opposite appears to have occurred: relatively wet conditions in the equatorial latitudes of the Guinea Coast, but drought in Angola, the western Sahel, and extra-tropical regions further north. While that is also a common pattern, the east–west contrast overall is not. This suggests unusual forcing of conditions in the 1780s.

34.9 Conclusions

Climate events of the 1780s and early 1790s produced very unsettled conditions around the world. These events included very strong La Niña and El Niño events and a major volcanic eruption in Iceland—although D'Arrigo and colleagues have suggested that conditions may have actually resulted from the occurrence of a negative NAO phase coupled with a protracted El Niño in 1782–84. In contrast to Grove, Gergis and Fowler have concluded that a very strong La Niña event (not El Niño) was centred on 1788 and spanned to 1790. A characteristic 'phase flip' seems to have occurred in 1791, bringing a strong El Niño event that lasted until 1794.[131] It is important to note that extreme phases of the ENSO cycle frequently result in extreme weather conditions around a large part of the globe.[132] In the western Pacific, El Niño events often cause drought, while La Niña events bring heavy rain and major flooding to the region.[133] The reverse is true in the eastern Pacific with above average rainfall falling during El Niños, and dry conditions prevailing during La Niña episodes.[134] These patterns can be observed in the case studies that we have examined.

The case studies also reveal societal vulnerability to the cycle of floods and droughts, in terms of the loss of livelihoods, disease, and death for the populations involved. While some of the famines, for example in India, were exacerbated by factors such as colonial taxation policies and East India Company intransigence, most of the 1780s famines were at least in part—although as described above, through notably complex causal links—born of climatic irregularities. In India, the climatic element of the famines was lack of rain from 1789 onwards, although disruption to the expected timing of rains, some excessive rains, and a season of very extreme storms, floods, and intense winds in 1787 also contributed. While statistical data are absent, qualitative assessment of the 1790–92 famines suggests they were the most severe of the period, in line with the climate anomalies recorded by climatologists. In Australia, La Niña conditions and flooding in 1788 were followed by a prolonged period of drought from 1790–91, causing very unsettled conditions for the emerging colony. In Japan, the great 'Tenmei' Famine, which caused some 100,000 deaths, followed extremely poor rice harvests brought by cold summer weather in northern to eastern Japan during the 1780s, particularly 1783–84 and 1786. In Egypt, the impact of the Laki fissure eruption was immense, and drought and hunger in 1784–85 left people vulnerable to plague and other diseases. Elsewhere in Africa, it appears the 1780s brought lower rainfall and even droughts to the western Sahel but above normal rainfall to the eastern Sahel. The east–west contrast showed unusual forcing of conditions in the 1780s. Drought also prevailed throughout much of equatorial Africa. An exception was the equatorial latitudes of the Guinea Coast, where during the 1780s rainfall conditions were highly erratic and both droughts and abnormally wet years occurred. These case studies highlight both the unsettled conditions of the period and the enduring impact of ENSO on living conditions in many parts of the world.

It is clear that a better understanding of the ENSO cycle and its links with the Asian monsoon is critical to understanding the history of 'floods, famines, and empires' in different parts of the world.[135] Both instrumental and descriptive historical records gathered from the natural history collections of European empires are vital to ongoing interdisciplinary projects on the historical study of climate and society.

Notes

1. Roxburgh, W. MS *Report to the President's Council* 6 Feb, East India Company Boards Collections, ref.no. F/4/99 British Library India Office Collections, London cited in Grove, 1998.
2. Grove, 1998, 318.
3. Alcoforado et al., 2012.
4. Trail, 1799; Cotte et al., 1788. However, in some regions of the world that regularly experience active tectonic events, with earthquakes and volcanic eruptions, initial efforts to set up and/or maintain colonial observatories and their records around this time were dashed by the continual loss of instruments to breakages. The long distances and costs required to obtain new instruments eventually thwarted many of these endeavours. This was a particular problem in the East Indies (Zuidervaart and van Gent, 2004, 2013). Johan Maurits Mohr's expensive and well-equipped personal observatory that he had built in 1765, near Batavia on Java, was damaged by an earthquake in 1780 and then fell into ruin and was demolished in 1812. At its peak, it had been visited by the likes of Bougainville and Cook on their expeditions.

5. Ananthasubramaniam, 1991.
6. Gergis et al., 2009.
7. Mauritius Meteorological Service, 1974; Brohan et al., 2012; Gergis et al., 2010.
8. International Data Rescue Portal. http://ooxo.nl/opdrachten/I-DARE/content/dare-success-stories. Accessed 26 April 2016.
9. Kington, 2009.
10. Thordarson and Self, 1993.
11. Gunnlaugsson et al., 1984; Ogilvie, 1986; Demarée and Ogilvie, 2001.
12. Thórarinsson, 1969, 1979.
13. Bjarnar, 1965.
14. Gunnlaugsson et al., 1984.
15. Ogilvie, 1986.
16. Ogilvie, 2010.
17. Stothers, 1996; Demarée and Ogilvie, 2001.
18. Demarée and Ogilvie, 1998, 2001.
19. Demarée and Ogilvie, 2001.
20. "British Weather from 1700 to 1849." Accessed 26 April 2016. http://www.pascalbonenfant.com/18c/weather.html.
21. Franklin, 1785.
22. Gettelman et al., 2015; Santer et al., 2015.
23. Robock, 2000; Santer et al., 2013; Ridley et al., 2014.
24. Kington, 1980.
25. Grattan et al., 2005.
26. D'Arrigo et al., 2011. A potential 20CR reconstruction of the atmospheric circulation over North Atlantic–Europe region during and after the Laki fissure eruption, as was done recently for the later Tambora and Krakatoa eruptions, is planned: Tambora (https://vimeo.com/120228702 has volcanic aerosol estimates from Tom Crowley; https://vimeo.com/120787915 has volcanic aerosol estimates from Gao, Robock, and colleagues (much larger amounts but timing is late); https://vimeo.com/120792719 has no volcanic aerosols and will serve as a "control" of what can be obtained from the sparse pressure observations alone) and Krakatoa (https://vimeo.com/117533217).
27. Allan and D'Arrigo, 1999.
28. Gergis and Fowler, 2009. More recently, Allan et al., 2018 have refined the definition further, defining "a 'protracted' episode as occurring when the SOI and Niño 4 SST anomalies are of either sign for 2 years or more, with any sign change in that period being in a maximum of only two consecutive months, when using instrumental records, and 3 years or more when analysing palaeoclimatic ENSO reconstructions."
29. Gergis and Fowler, 2009.
30. Chenoweth and Thistlewood, 2003; Ortlieb, 2000.
31. Endfield, 2008.
32. Gergis and Fowler, 2009.
33. Grove, 2007.
34. Cook et al., 2010.
35. Nash and Adamson, 2014.
36. Shi et al., 2014.
37. Patnaik and Sivagnanam, 2007.
38. Danvers, 1877, 1.
39. Damodaran, 2015.

40. Danvers, 1877, 21.
41. Danvers, 1877, 21.
42. Danvers, 1877, 22.
43. Danvers, 1877, 22–23.
44. Elliot, 1863.
45. Hunter et al., 1907.
46. Grove, 2007.
47. Danvers, 1877, 1.
48. Danvers, 1877, 2.
49. Danvers, 1877, 2.
50. Danvers, 1877, 12.
51. Campbell and Hunter, 1868, 114–15.
52. *The Nautical Magazine*, 1832, 293.
53. Roxburgh, 1975, 34.
54. Campbell and Hunter, 1868, 142.
55. Campbell and Hunter, 1868, 141.
56. Danvers, 1877, 21.
57. Campbell and Hunter, 1868, 152.
58. Campbell and Hunter, 1868, 147–53.
59. Campbell and Hunter, 1868, 175–77.
60. Campbell and Hunter, 1868, 185.
61. Grove, 1998.
62. Jevons, 1859; Russell, 1877.
63. Gergis et al., 2009, 2010; Ashcroft et al., 2012, 2014a, 2014b; Fenby and Gergis, 2013; Gergis and Ashcroft, 2013; Gergis, 2018.
64. Risbey et al., 2009.
65. Diaz and Markgraf, 2000.
66. Risbey et al., 2009.
67. Allan et al., 1996.
68. Gergis and Fowler, 2009; Quinn, 2000; Quinn and Neal, 1995; Ortlieb, 2000.
69. Gergis and Fowler, 2009.
70. Gergis et al., 2010; Fenby and Gergis, 2013; Gergis and Ashcroft, 2013.
71. Gergis and Ashcroft. 2013.
72. Collins, 1798.
73. Collins, 1798.
74. Hunter, 1793.
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77. Tench, 1793.
78. Collins, 1798.
79. Collins, 1798.
80. Hunter, 1793.
81. Hunter, 1793.
82. Tench, 1793.
83. Collins, 1798.
84. Hunter, 1793.
85. Collins, 1798.
86. Collins, 1798.
87. Mikami, 1983, 1987.
88. Mikami, 1996, 2008; Zaiki et al., 2012.

89. Mikami, 1996, 2008; Zaiki et al., 2012.
90. Mikhail, 2015.
91. Thordarson and Self, 2003.
92. Oman et al., 2005, 2006.
93. Lyons, 1905.
94. Mikhail, 2011.
95. al-Jabartī, II, 1994, 123.
96. Başbakanlık Osmanlı Arşivi, Hatt-ı Hümayun 28/1354 (7 Zilkade 1198/22 September 1784).
97. al-Jabartī, II, 1994, 138.
98. al-Jabartī, II, 1994, 138.
99. al-Jabartī, II, 1994, 139–40.
100. Volney, I, 1798, 122
101. al-Jabartī, II, 1994, 155.
102. Volney, I, 1798, 123.
103. Mikhail, 2008.
104. Volney, I, 1798, 122.
105. Başbakanlık Osmanlı Arşivi, Hatt-ı Hümayun 29/1361 (13 Şa'ban 1198/1 July 1784); Başbakanlık Osmanlı Arşivi, Hatt-ı Hümayun 28/1354 (7 Zilkade 1198/22 September 1784).
106. Volney, I, 1798, 122.
107. For an earlier comparative example see: White, 2011.
108. al-Jabartī, II, 1994, 133.
109. al-Jabartī, II, 1994, 123, 133–34.
110. al-Jabartī, 1994, 138–39.
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113. Mercer, 1974.
114. Almeida, 1997; Patterson, 1988; Brooks, 2006.
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116. Matthews, 1788.
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118. Nicholson, 1980.
119. Nicholson, 1980; Norrgård, 2013, 2015.
120. Miles, 1782.
121. Watts, 1784; Morgue, 1784.
122. Norris et al., 1787.
123. Shanahan et al., 2009; Miller, 1982.
124. Nicholson, 1998a, 1998b, 2000.
125. Ogot, 1992.
126. Verschuren et al., 2000.
127. Tyson, 1986.
128. Nicholson, 1981.
129. Theal, 1888.
130. Nicholson, 2014.
131. Gergis and Fowler, 2009.
132. Diaz and Markgraf, 2000.
133. Allan et al. 1996; Risbey et al. 2009.
134. Allan et al., 1996.
135. Fagan, 2009.

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CHAPTER 35

A Year Without a Summer, 1816

Christian Pfister and Sam White

The April 1815 eruption of the Tambora volcano on the Indonesian island of Sumbawa turned 1816 into the most recent and most memorable "year without a summer." The Tambora eruption was among the largest in recent history. It brought dramatic climatic and human consequences, which were closely observed around the world. The bicentennial anniversary of the eruption and the "year without a summer" became the occasion for many new studies of this already well-researched event. Thus, Tambora and its aftermath provide a valuable case study in volcanic weather and its historical impacts.[1]

Tambora was the largest volcanic eruption since that of Samalas on Indonesia's Lombok Island in 1257, which produced another "year without summer" in 1258.[2] The explosion of Tambora began with a "Plinian eruption", shooting pumice, gases, and dust high out of its top; this was followed by a larger pyroclastic flow as the mountain collapsed in a river of lava, releasing more hot gases. Ships hundreds of miles away heard the explosions as though they were giant cannon shots. Sumbawa and neighbouring islands were buried under tens of centimetres of ash, and more than 70,000 people died either directly from effects of the eruption or from the ensuing famine and epidemics.[3] Overall, Tambora ejected some 100 km^3 of debris and ashes more than 40 km into the stratosphere, reducing the height of the mountain from 4300 to 2850 meters. The sulphur molecules in the stratosphere were gradually transformed into an aerosol of tiny droplets of sulphuric acid, which scattered back incoming solar radiation, warming the upper atmosphere but cooling the Earth's surface and altering global weather patterns.[4]

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The eruption occurred during a period of lower solar activity from 1790 to 1830 known as the Dalton Minimum, which meant that global temperatures may have been lowered already.[5] The volcanic cooling of the 1810s is especially evident in tree rings at high latitudes—particularly Canada—demonstrating the cold, dark summers and short growing seasons. Recent estimates based on tree ring density series suggest Northern Hemisphere temperatures in 1816 fell an estimated 0.5–1.3 °C below the twentieth-century average.[6]

More important from a human perspective, the eruption altered weather patterns around the world. As with other large tropical eruptions of recent centuries, the cooling created by Tambora weakened the Asian and African summer monsoons—the critical source of rainfall for crops that fed half the world's population. At the same time, the cooling may have weakened the subtropical Hadley Cell (see Chap. 2), displacing the Azores anticyclone southward. The effect of this shift was to enhance the flow of cool, wet maritime air into the southern parts of Central and Western Europe, contributing to extraordinary cold and rains throughout the summer.[7]

Moreover, Tambora had peculiar effects on jet streams high in the atmosphere over the North Atlantic. In some places, the jet stream dipped below its usual track, bringing Arctic air into the mid-latitudes. In between, the ridges formed so-called omega blocks, bringing high pressure that blocked cyclones.[8] Deep cold troughs developed over eastern North America and Western Europe, extending much farther south than normal, while ridges of warmer air pushed northwards over the region of east Greenland and Iceland, Eastern Europe, and the Hudson Bay region.[9]

This "volcanic weather" had far-reaching global effects on agriculture, economies, populations, and even culture. In a seminal 1977 study, economic and climate historian John Post called the aftermath of Tambora "the last great subsistence crisis in the Western world."[10] Agricultural modernisation had yet to reach most of Europe; markets and transportation were still constrained by the barriers of geography and limits of pre-industrial energy. Although at the dawn of the "modern" era (see Chap. 23), Europe still proved highly vulnerable to climate-driven disaster, and official institutions fell short in responding to the challenge. Furthermore, Europe had only just emerged from the long wars of the French Revolution and North America from the "War of 1812" (actually 1812–15).

The Alpine countries suffered from months-long sunless cold and rain. Observers in Switzerland recorded just a few isolated days of fine weather between May and September 1816, and eight successive weeks of rain from June to July. It snowed down to 800 metres elevation in every summer month. In July, fresh snow accumulated so deep at altitudes of 1300 metres that firewood was transported on sledges. Above 2000 metres, snow continued to fall all summer long, which even led to avalanches.[11] Alpine glaciers advanced rapidly. For example, observers described the Glacier des Bois in the northern Mont Blanc Massif advancing 30 centimetres every day.[12] By 1820, its tongue was only 55 metres from the nearest house in the hamlet of Les Bois.[13] The grain and potato crops in Switzerland (and elsewhere) failed, and the hay and vines never ripened. Grain prices soared, creating scenes of misery described by contemporary Swiss and foreigners.[14]

However, as Swiss researcher Daniel Krämer has demonstrated, vulnerability varied considerably by region and population. The small and closely studied Swiss case thus illustrates the roles of local geography, economics, and politics in climatic impacts. Hunger results from complex environmental and social interactions and can be difficult to measure (see Chap. 27). In this case, Krämer calculated the relative size of annual demographic cohorts, as an effect of births and deaths in a particular year, to serve as an indicator of nutritional stress. Annual cohort size can be derived from the Swiss federal census of 1860 at the district level, thus revealing geographic disparities. Based on this data, the worst affected populations in 1816 lived in vine-growing regions north of the Alps, whereas the valleys within and to the south of the Alps were shielded by the mountains from the northwesterly winds and killing frosts. However, in 1817, the hardest-hit populations came from proto-industrial regions and from landless classes who depended on selling their goods and labour to buy food.[15] The spinners and weavers in the densely populated northeastern districts bore the brunt of the crisis in 1817 (as reflected in the map for 1818—see Fig. 35.1).

Although the Alpine regions were especially hard hit by the extraordinary cold and rains, the "year without a summer" affected all of Central, Western, and, to some extent, Northern Europe. Low atmospheric pressure settled over the British Isles. The Englishman James Losh noticed that the weather in Newcastle-upon-Tyne, northeastern England, has been "uniformly cold and very frequently wet—the corn, though the crops seem very heavy, is so very far from being ripe that there seems too much reason for fearing that much of it will not ripen at all this year … Potatoes were both a scanty crop and of poor quality."[17] In this part of England and all of Scotland, warm-season temperatures were not sufficient to bring crops to full maturity. Farther south, in Ireland, crops suffered from lack of sunshine and excessive wetness that submerged low-lying areas.[18] Ducks were reported swimming across the fields sown with oats and potatoes. Weeds choked the cereal crops before they could ripen, or else they turned mouldy. Bread made from the affected flour was inedible. Draft horses grew sick from the season's oats. Potatoes—fast becoming the mainstay of Irish peasants—rotted in the saturated earth.[19] Ireland also suffered from its subordinate place within the British Empire. The disenfranchised Catholic majority largely lived as poor tenants of Protestant landowners, and the parliament in London paid little concern to suffering in Ireland. Without adequate relief, harvest failure turned into famine, and peasants fleeing hunger generated a severe epidemic of typhus.[20] Overshadowed by the more devastating events of the 1740s and 1840s in Ireland, the 1810s have been called a "forgotten famine."[21]

The Carpathian Basin (roughly Hungary and surrounding areas) also faced exceptional cold and persistent flooding. Thousands of houses were submerged

(a)

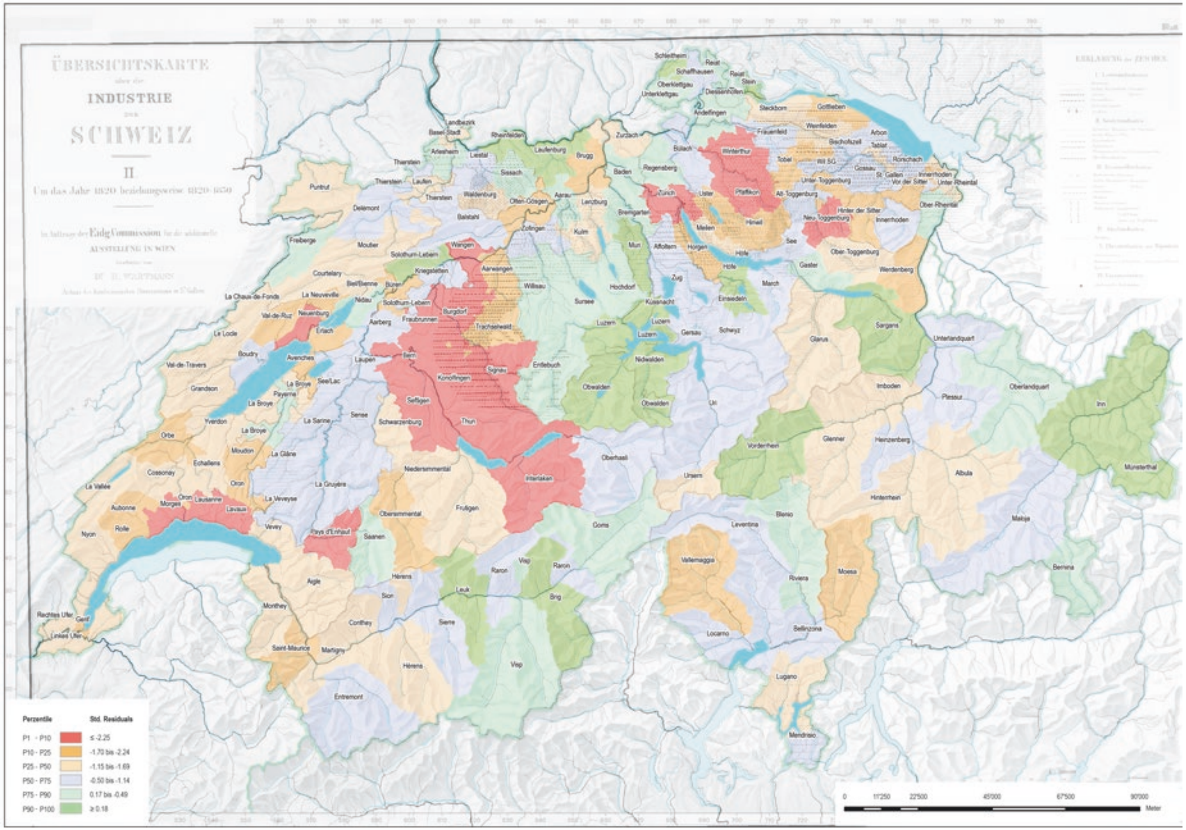

Fig. 35.1 Switzerland as a mosaic of climate- and weather-related impacts following the 1816 "year without a summer." The maps of figures (**a**) and (**b**) illustrate the relative frequency of baptisms in the different districts of the country during 1817 and 1818, respectively. Low values (in red) indicate a famine-related deficit of conceptions nine months before. The changing regional patterns illustrate differing patterns of vulnerability according to geography, local government responses, and economic conditions[16]

(b)

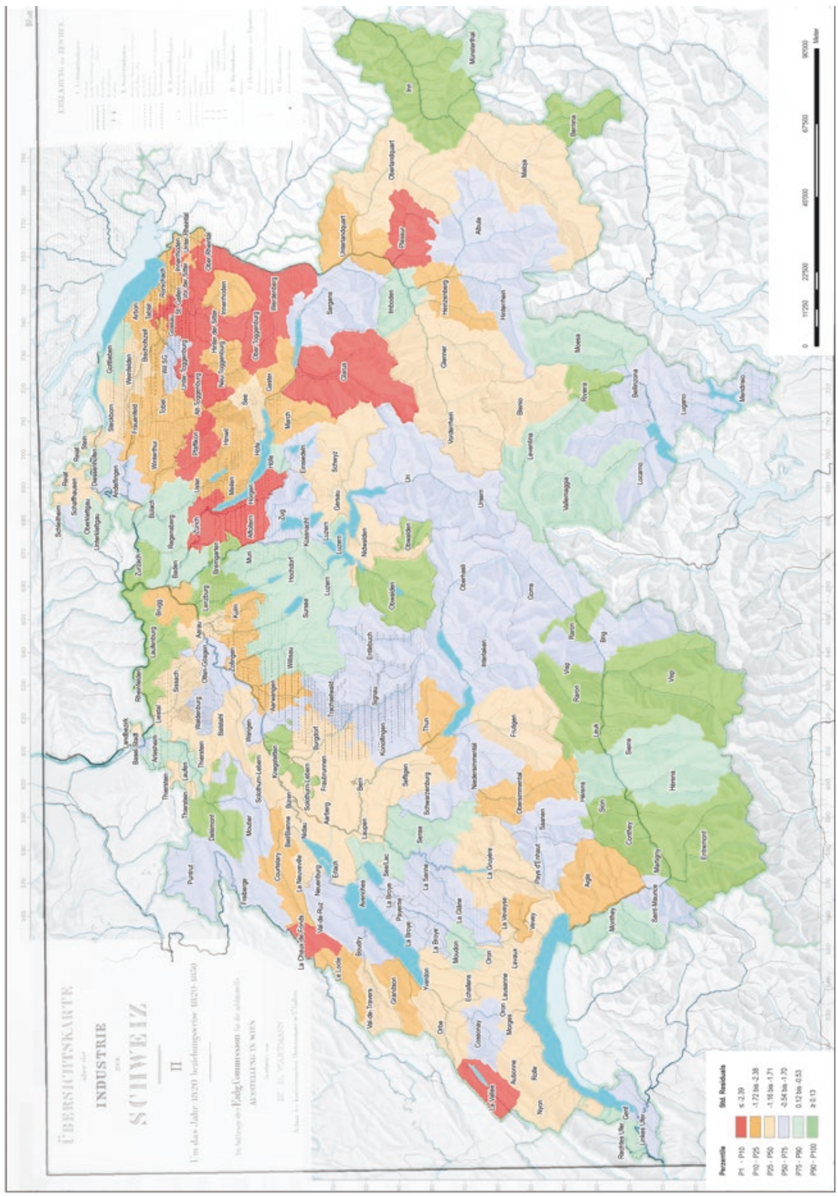

Fig. 35.1 (continued)

and collapsed under weeks of rain.[22] Even Spain and Portugal saw temperatures 2–3 °C below normal, cold enough to delay the ripening of grain and to ruin fruit crops.[23] In sum, the cold, wet summer weather affected harvests throughout Western and Central Europe. Grain prices spiked at twice or even three times their normal levels.

In eastern North America, the climatic effects were even more dramatic. Mean temperatures for July 1816 in New England are the lowest in US meteorological history.[24] Frosts were recorded in New England and Quebec throughout the month of May, and snows persisted into June. The killing frosts and perpetual cold destroyed the grain harvests, especially in the northern states of Maine and Vermont. Canada blocked its usual grain exports to avert hunger at home. Yet August was exceptionally dry: wells failed, and there was no grass for cattle. Cold waves at the end of the month penetrated as far south as North Carolina, where crop failures were widespread.[25] Former US president Thomas Jefferson wrote from Virginia, "we have had the most extraordinary year of drought and cold ever known in the history of America. The summer, too, has been as cold as a moderate winter."[26]

In contrast to the Arctic air penetrating far south on the US east coast, a wedge of warm air in the western Atlantic advanced extremely far north up to the coast of Greenland. William Scoresby, a frustrated whaler, wrote in his journal: "The fishery of the present season [1817] has been the most … unsuccessful of any occasion witnessed of many years … The ostensible reason of the scarcity of whales is the singular state of the ice which lies at a distance from the land greater than was ever known by any fisherman now prosecuting the business."[27] Arctic sea ice briefly retreated before the anomalous warmth, sparking a new phase in the search for the mythical open polar sea.[28]

The "year without a summer" in Europe and the USA has also provided an interesting early case study in climate-driven migration (see Chap. 31). For many in Europe facing rising prices and hunger, emigration to the USA seemed a way to escape from the misery. Yet, in that era before steamships, relatively few migrants—perhaps under 60,000 altogether—managed to cross the Atlantic that summer. Most came from Ireland, from where fares to Canada and the USA were least expensive. For most people in the other hotspots of the crisis, particularly southern Germany and Switzerland, the trip to reach harbours and buy passage was too expensive. An economic downturn in the USA after 1817 rendered migration harder still: "Even the relatively moderate number of emigrants was enough to end one popular scheme of getting to the USA on a low budget. Previously, emigrants travelling to the port of Philadelphia could sail without paying, provided they worked for a contracted amount of time for a local employer; their employer directly reimbursed the ship captain for the passenger's fare. However, when the Philadelphia regional job market was flooded by jobseekers in 1817 and 1818, captains could not find employers for their passengers, and thus lost interest."[29] On the other hand, migration within North America accelerated, as hundreds of thousands of settlers moved west, especially from New England into the new Midwestern states of Ohio and Indiana.[30]

Recent research on the "year without a summer" has begun to uncover its global impacts. Unusually heavy snowfalls in winter, and extremely heavy spring and summer rains, affected much of China, causing severe flooding, with 1816 by far the wettest year of the decade.[31] Snow fell in summer even in southeastern China and Taiwan, and destroyed much of the rice crop.[32] In June 1816, it snowed for three days and nights in southern Tibet, so that there was no autumn harvest.[33] In Yunnan (southwestern China), where mild climates and available land had recently drawn in millions of Chinese settlers, anomalous cold ruined the rice crop. Official efforts to stabilise crop prices and to distribute food and charity fell short, and the province suffered a disastrous famine.[34] By contrast, the summer was rather hot and dry in Japan.[35]

Some of the worst effects occurred in India, then under the control of the British East India Company. Most precipitation in South Asia comes from the summer monsoon, when the contrast between intense heat over the land and the cooler seas draws in moist air and rains from over the Indian Ocean (see Chap. 2). Volcanic eruptions, by reducing incoming solar radiation, tend to disrupt the monsoon cycle; and the effect was particularly devastating in 1816–17.[36] The monsoon rains failed to arrive until the end of August; and then in September, when the monsoon usually declines, the severe drought suddenly gave way to torrential rains. Harvests were ruined. Cholera, a water-borne virus then endemic to Bengal, broke out with unusual strength, causing thousands of victims. Recent research has since confirmed contemporary speculations that the "new" cholera was related to the unusual weather. In the following decades, cholera would break out in global pandemics, carried around the world by faster travel and rising trade, and flourishing in the unsanitary conditions of early industrial cities.[37]

The "year without a summer" has been equally famous for its influence on science and culture. The coldness of the summers 1812–16 and the resulting rapid glacier advance motivated the newly founded Swiss Society of Natural Sciences to launch in 1818 the first known research project on past climate change—a project that would prove instrumental in promoting the theory of the ice ages.[38] Vacationing in the vicinity of Geneva, Mary Shelley passed the gloomy summer by writing *Frankenstein*, the archetype of the literary genre of horror stories. The book opens with a hopeless quest to find an open polar sea, and its early chapters make indirect reference to the dark weather of 1816.[39] Under the same gloomy skies, surrounded by the suffering of the Swiss population, the English aristocrat and poet Lord Byron wrote the following lines in his famous poem "Darkness":

> I had a dream, which was not all a dream.
> The bright sun was extinguish'd, and the stars
> Did wander darkling in the eternal space,
> Rayless, and pathless, and the icy earth
> Swung blind and blackening in the moonless air;
> Morn came and went—and came, and brought no day,
> And men forgot their passions in the dread
> Of this their desolation; and all hearts
> Were chill'd into a selfish prayer for light.

Literary references such as these serve as a reminder that climate has been more than a mere background to human history, and more than an occasional factor in harvests or transportation. Climate, weather, and their variations have reached deep into human culture and psychology—a topic of academic research that has only just begun.[40]

Notes

1. E.g., Harington, 1992; Oppenheimer, 2003; Klingaman and Klingaman, 2013; Wood, 2014; Behringer, 2015; Luterbacher and Pfister, 2015.
2. Lavigne et al., 2013. For a chronology of major eruptions over the past 2000 years, see Sigl et al., 2015.
3. Sigurdsson and Carey, 1992.
4. Wood, 2014.
5. Wanner et al., 2008.
6. Chenoweth, 2001; Gennaretti et al., 2014; Anet et al., 2014; Cole-Dai et al., 2009; Stoffel et al., 2015.
7. Wegmann et al., 2014.
8. Klingaman and Klingaman, 2013, 110.
9. Wilson, 1992, 545.
10. Post, 1977.
11. Pfister, 1992.
12. Shelley, 1987, 116.
13. Grove, 1988, 144.
14. See especially accounts in Wood, 2014.
15. Krämer, 2015.
16. Krämer, 2013.
17. Wheeler, 2016, 110–11.
18. Kington, 1992.
19. Wood, 2014, 176.
20. Klingaman and Klingaman, 2013, 204–08; Wood, 2014, 171–98.
21. Wood, 2014.
22. Andrea Kiss, personal communication. On the historical climatology of the Carpathian Basin, see Kiss et al., 2011.
23. Trigo et al., 2009.
24. Post, 1977; see also Wood, 2014, Chap. 9.
25. Post, 1977, 13.
26. Jefferson, 1899, 64, quoted in Klingaman and Klingaman, 2013, 160.
27. Scoresby, 2003, 45–46, quoted in Wood, 2014, 125.
28. See Wood, 2014.
29. Luterbacher and Pfister, 2015, 246–47; Grabbe, Stuttgart, 2001.
30. Mussey, 1949; Klingaman and Klingaman, 2013.
31. Wilson, 1992, 548.
32. Klingaman and Klingaman, 2013.
33. Zhang et al., 1992, 428–36.
34. Cao et al., 2012; Wood, 2014; Gao et al., 2017.
35. Mikami and Tsukamura, 1992, 462–65.
36. Schneider et al., 2009.

37. Wood, 2014, 85–90.
38. Bodenmann et al., 2011.
39. Wood, 2014, 52–55, et passim.
40. Early examples include: Boia, 2005; Vasak, 2007; Behringer et al., 2005. On climate changes and literature, see Trexler and Johns-Putra, 2011.

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PART V

The History of Climate Ideas and Climate Science

CHAPTER 36

Climate as a Scientific Paradigm—Early History of Climatology to 1800

Franz Mauelshagen

36.1 Introduction

Over the last decade or so, the history of climatology has developed rapidly, driven more than anything else by the need for a history of the science of global warming and the greenhouse effect. Naturally, much of the recent research focuses on the nineteenth and twentieth centuries, while the early days of climatology remain somewhat obscure. A review of the existing literature on this theme reveals that studies in the history of climate ideas and climate science before 1800 have focused on meteorology, explaining the history of climatology as a by-product of technological progress in meteorological measurement and data collection (i.e., instruments, their standardization, and homogenization—see Chaps. 7 and 9).[1]

As a consequence, the history of climatology got absorbed into the overarching disciplinary framework of meteorology and its history.[2] This approach has taken for granted that "climate" has always been a meteorological category. But it was not. Climates (Greek: κλίματα) were an invention of classical geography for use in cartography. They had little, if anything, to do with meteorology or the atmosphere. Only later was climate defined as the average weather in a certain place or, more abstractly, the "statistics of weather." Jim Fleming and Vladimir Janković aptly stated that this definition "is an anomaly" in the

This chapter is based on original research on the early history of climatology, which I began in spring 2012. A fellowship at the Rachel Carson Center for Environment and Society (Munich) in 2014 gave me the opportunity to intensify my research and present first results at various occasions. Parts of this chapter are based on a German publication, see Mauelshagen, 2016.

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history of climate ideas, because it “is possible only in connection to an instrumental, quantitative, and weather-biased understanding of the atmosphere.”[3] This understanding emerged from a new approach to weather observation, from the seventeenth century onward, as well as from a redefinition of climate. However, it only became practical once the knowledge infrastructures of national weather services could provide extensive datasets to feed climate statistics, which did not occur until the mid-nineteenth century (see Chap. 25).

Therefore, the focus of this chapter is on “climate” as a shifting paradigm. We shall see in the first two sections of this chapter that the traditional geographic definition of “climate” remained remarkably stable, with very little modification in either geographic or cosmographic handbooks, or on world maps. The other two sections will sketch the paradigmatic shift that followed in the second half of the eighteenth century and turned “climate” into a physical category that represented the sum of all factors determining the average temperature of a place. This novelty gave rise to the invention of climatology as a new scientific discipline.

36.2 The Geographic Tradition of Climates

The ancient Greek term κλίμα means inclination or slope, referring not only to the sun’s rays but also to the entire cosmos as observed from a certain spot on the globe. The concept is completely missing from the work of Aristotle and Hippocrates, who nevertheless have often been referred to as inventors of ancient climatology.[4] Greek geographers coined the term no earlier than the late third century BCE; however, the moment of invention cannot be specified, because so little of early Greek geographic literature has survived. Our main source of information is Strabo’s remarks on some of his precursors. Some attribute the earliest use of κλίμα as a technical term to Eratosthenes, who also seems to have been the first person to write a book entitled “Geography”; others attribute the invention of the concept to Hipparchus, who may have taken the word κλίμα from Eudoxos’ astronomical treatises.[5]

What seems clear enough is that κλίμα was a term borrowed from astronomy and mathematics and embedded in a rather elaborate form of geocentric cosmology. This cosmology recognized the Earth as a globe, attributed a spherical shape to the cosmos, and involved a certain degree of understanding of the Earth’s ecliptic.[6] Based on this cosmology, geographers used climates to define the latitudinal location of places on the globe and on maps. Most common became a system of seven κλίματα that encompassed the *ecumene*, the inhabited part of the world.[7]

Altogether, “climate” was not a meteorological category in antique geography. Speaking of the “climate” of a place was equivalent to giving its latitudinal coordinates on the globe rather than explaining heat or cold, rainfall or humidity in a certain place. The five meteorological “zones,” probably invented by Parmenides and referred to in Aristotle’s *Meteorology*, were something different. These zones—the “torrid zone,” “temperate zones,” and “frigid zones”—were

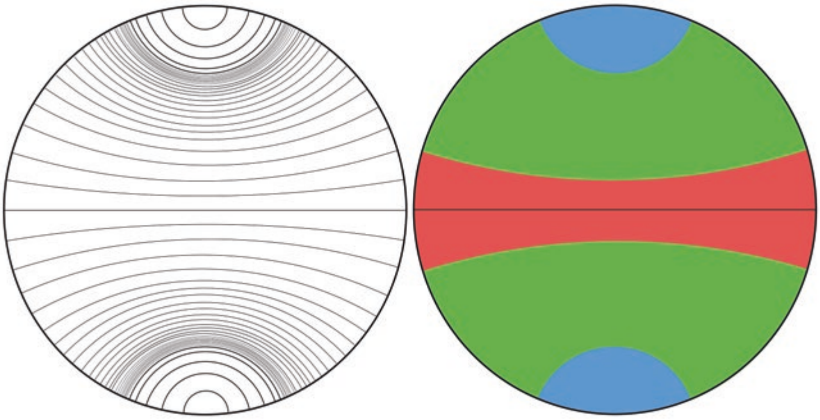

Fig. 36.1 *Left:* Traditional cartographic division of climates showing half-hour differences of the longest day during summer solstice to the polar circle and monthly climates from the polar circle. Note that the width of each climatic belt enclosed with two parallels decreases from the equator to the poles. *Right:* Classical division of the globe into five meteorological zones, separated by the Tropic of Cancer (23.5°N) and the Tropic of Capricorn (23.5°S) and the polar circles

defined by their relative heat, as their names indicate. However, meteorological zones and climatic belts did not form a symbiosis, despite the way they were often overlaid on world maps until well into the eighteenth century (see Fig. 36.1). Distinguishing climates in antique geography had nothing to do with meteorological zones. They were distinct technical terms as well as distinct ways of drawing parallels on world maps. That distinction is confused when Aristotle's meteorological zones are addressed anachronistically as "climatic zones."[8]

Ptolemy became the main source for medieval and Renaissance cosmographers and their practice of drawing climatic parallels on their new and constantly changing maps of the world. He was also the main source for a dual system that combined mathematical calculations of climatic parallels based on the longest daylight (during summer solstice) with geographical designations of seven parallels defining the supposedly inhabited part of the world, each given names of memorable places—including famous cities (the *epísemoi póleis*)—located roughly in the middle of each respective climatic belt. The mathematical climates were based on regular fractions (normally differences of half an hour, sometimes a quarter of an hour) of the twelve hours of sunshine difference that occurred from the equator to the poles on both hemispheres (see Table 36.1). Although Ptolemy's *Almagest* contained the oldest description of an astrolabe, which allowed for much greater precision in determining the latitude of a place, the catalogue of cities he added to his *Geography* is proof that the κλίματα had not yet lost their practical usefulness for him.[9]

Both Ptolemaic styles of representing climatic parallels on world maps survived. The system of seven climates was also adopted in Arabian and Persian

Table 36.1 Ptolemy's full system of climes (thirty-three parallels between the equator and the polar circle, six more parallels from the polar circle to the pole, Northern Hemisphere only) and the reduced system of seven climates (indicated in the rubric "clima" by Roman numerals)

Parallel	*Clima*	*Latitude*	*Daylight*	*Location*
1.		0°	12 hours	(Equator)
2.		4°4′ N	12:15	Taprobana (Sri Lanka)
3.		8°25′ N	12:30	Avilates (Saylac, Somalia)
4.		12°00′ N	12:45	Bay of Adulis (Eritrea)
5.	I	16°27′ N	13:00	*Meroe* island
6.		20°14′ N	13:15	Napaton (Nubia)
7.	II	23°51′ N	13:30	*Syene* (Aswan)
8.		27°12′ N	13:45	Thebes
9.	III	30°22′ N	14:00	*Lower Egypt*
10.		33°18′ N	14:15	Phoenicia
11.	IV	36°00′ N	14:30	*Rhodes*
12.		38°35′ N	14:45	Smyrna
13.	V	40°56′ N	15:00	*Hellespont*
14.		43°04′ N	15:15	Massalia (Marseilles)
15.	VI	45°01′ N	15:30	The Middle of the *Euxine Sea*
16.		46°51′ N	15:45	Istros (Danube)
17.	VII	48°32′ N	16:00	The Mouths of *Borysthenes* (Dnepr)
18.		50°04′ N	16:15	Maeotian Lake (Sea of Azov)
19.		51°06′ N	16:30	The southern shore of Britannia
20.		52°50′ N	16:45	Mouths of the Rhine
21.		54°1′	17:00	Mouths of the Tanais river (Don)
22.		55° N	17:15	Brigantion in Britannia
23.		56° N	17:30	The middle of Great Britain
24.		57° N	17:45	Katouraktonion in Britannia
25.		58° N	18:00	The southern part of Britannia Minor
26.		59° N	18:30	The middle part of Britannia Minor
27.		61° N	19:00	The northern part of Britannia Minor
28.		62° N	19:30	Ebudes island
29.		63° N	20 hours	Thule
30.		64°30′ N	21 hours	Unknown Scythians
31.		65°30′ N	22 hours	
32.		66° N	23 hours	
33.		66°8′40″ N	24 hours	Polar Circle
		69°30′ N	2 months	
		78°20′ N	4 months	
39.		90° N	6 months	(North Pole)

Last column: Locations through which parallels pass as given by Ptolemy. After Neugebauer, 1975, 43–45

astronomy and astrology. In that context, the seven climates were connected with the seven planets of the solar system. Thus, they became part of astrological systems of prediction. Definitions of "climate" deviated little from Ptolemy in early modern cosmographic and geographic writing, from Sebastian Münster (1488–1552) well into the eighteenth century. Authors like Bartholomäus Keckermann (*c.* 1572–1608), Paul Merula (1558–1607), David Christiani

(1610–1688), Philip Clüver (1580–1622), and Bernhard Varenius (1622–1650/1) used slightly different classifications of climates.[10] But adding minor nuances did not change the essence of the old geographic definition and the two systems of mathematical climates and the seven climates.

Christiani's account of the "climate doctrine" (*climatum doctrina*), as he called it, provides a good example. He first explained the difference between zones and climates; then the number of climates and their distinctions; and next how one knows "under which climate" a given place is located (or in his words, the *modus cognoscendi*), followed by a discussion of why it is useful to know the climate (*usus climatum*). Christiani concluded with a query section, in which he raised the interesting question of the diversity of peoples who lived under the same climatic belt, or "clime."[11] His suggested textbook answer was that it could only be explained by a combination of causes such as custom, the quality of the air, and the soil. It was obvious to him that "climate" alone—in other words, latitudinal location on the globe—could not account for human diversity.

Bernhard Varenius' *Geographia Universalis* (first published 1650), a work celebrated particularly for its unprecedented achievements in the field of physics and translated by Isaac Newton into English, provides further evidence of shifting conceptions of "climate."[12] Again, like his precursors and all his contemporary colleagues, Varenius followed the classical mathematical definition of "climate":

> A Climate is the Space included by two Parallels, between the Pole and the Equator, into which when the Sun comes, there is the Difference of half an Hour, as to the Length of the Day; in which we may observe the beginning of Climate in the Parallel nearest the Equator, and the middle when the Day becomes a Quarter longer, and the end in the Parallel from the Equator, which is the beginning of the next Climate.[13]

In the applied part of his work, which he called *Special Geography*, climate featured among the "Celestial properties of places" that needed to be considered in all chorographies (descriptions of provinces, regions, cities) or topographies (descriptions of places). In Varenius' taxonomy for both the physical and the applied parts of his geography, climate was obviously distinct from meteorology. That summarizes the state of the art until well into the eighteenth century. It is important to note that in the seventeenth century, meteorology was already splitting from astrology, which used to determine weather predictions. While only a snapshot in the history of geography, Varenius' *Geographia Universalis* shows why that separation was so important. Freed from the influence of astrology, meteorology had come down to earth, literally and figuratively. Thus, Varenius dealt with it in a chapter entitled "Of the Atmosphere," in the *Absolute Part* of his geography, meaning that part which (in Newton's translation) "respects the Body of the Earth itself," while any celestial influences belonged to the *relative* part of geography.[14]

36.3 Mapping Climates

The easiest way to illustrate continuity and change in the concept of climate is through cartography or, more precisely, through a selection of world maps from the fifteenth to eighteenth centuries. The earliest examples were published in some of the first printed editions of Ptolemy's *Geography*. Johannes Schnitzler's map of 1482 and the even more famous cordiform map by de Agostini, published in 1511, both represented the seven climates of the *ecumene*.[15] Although the latter was clearly post-Columbian in that it showed fragments of the Caribbean islands and the Americas, knowledge of the New World did not yet affect the idea of the inhabited world in a way that would require an extension of the seven traditional climates. In de Agostini's map, they were given their traditional names. Projected onto the Southern Hemisphere (here de Agostini was content with the number of four), the names were kept and only slightly modified by adding the prefix "anti-" so that Meroë became Anti-Meroë, and so on.

Moving forward into the seventeenth century, the *Atlas Maior* by Willem Janszoon Blaeu and Joan Blaeu counts among the most influential geographic and cartographic works of the early modern era—not least because it came out in the Latin, French, Dutch, and German languages, also in abbreviated editions, and was reprinted several times.[16] The world map, *Nova Totius Terrarum Orbis Geographica Ac Hydrographica Tabula*, was reproduced time and again and remained always the same (see Fig. 36.2).[17] Its inscriptions were Latin, while explanations were given in the language of each respective edition. For both the Northern and Southern Hemispheres, nine climates were represented but no labels were given to them. Leaving that part of the terminology open allowed for variety, perhaps with regard to different national geographic styles. The German edition, for example, explained the astronomical twenty-four half-hour climates (or mathematical climates) and introduced new names for two new climates in addition to the traditional seven, so that a total of nine now defined the *ecumene*.[18] That trend was already discernible in the sixteenth century. Expanding European knowledge about the inhabited world, particularly in the Northern Hemisphere, pushed the invention of additional climates, first from seven to eight and then to nine, as shown, for example, on the St. Gall Globe.[19] The Latin and French editions of the *Atlas Maior* proposed a completely different and new idea, which was to replace the half-hour differences that defined climatic parallels by constant latitudinal distances of 10° and then to give the resulting "climates" new names.[20] However, that proposal collapsed the distinction between climates and latitudes, which is probably the reason why it was not generally accepted.

In the eighteenth century, world maps favored the astronomically and mathematically most precise representation of half-hour climates, while the idea of subdividing the *ecumene* into a certain number of climates lost ground. Empirical knowledge about indigenous peoples around the world, which had accumulated since the beginnings of the colonial endeavor, had changed the

Fig. 36.2 *Nova Totius Terrarum Orbis Geographica Ac Hydrographica Tabula*, 1635. From: Blaeu, *Theatre du Monde*, t.1 (and various other editions, see notes). Climates are shown in the green area in between the right border of the map and the allegorical personifications of the seasons. (Credit: National Library of Norway)

Fig. 36.3 Buy de Mornas, *Climats d'Heures et de Mois*, Paris 1762, 38.5 × 54.0 cm, from Louis Charles Desnos, *Atlas Méthodique et Elémentaire de Géographie et d'Histoire*, Paris 1762

understanding of the human habitat and made the old idea of the *ecumene* obsolete. In the field of geography, the quarrel between the ancients and the moderns had clearly been decided in favor of the moderns. That is why most textbooks only mentioned the classical subdivision of the *ecumene* merely as an outmoded tradition. Visual representations showed monthly climates starting from the polar circles, as can be seen in the works of Desnos and de Mornas (see Fig. 36.3) or Jean-Baptiste Louis Clouet.[21]

Altogether, there was little change in the understanding of climates, from the first editions of Ptolemy's *Geography* until well into the second half of the eighteenth century. Mathematical calculations of half-hour climates improved; the old tradition of the *poleis episemoi* was first adapted to the expansion of geographic knowledge, which followed the expansion of European colonialism, and then it was dismissed. However, none of these modifications changed the fact that "climate" remained a specialized concept within cosmography and cartography. Moreover, the entire corpus of geographic writing in early modern Europe (from cosmographic tracts to atlases and textbooks) provides no evidence for a paradigmatic shift that would equal "climate" with the average weather in a certain place. Well into the eighteenth century, most classically trained geographers still did not use "climate" as a meteorological category.

36.4 Paradigm Shift

A paradigmatic shift occurred toward the turn of the century. Alexander von Humboldt's isothermal maps, which laid the theoretical foundations for what he called "comparative climatology," illustrate it best.[22] Humboldt's isotherms undermined the idea of homogenous average temperatures along latitudinal parallels, which had persisted into the eighteenth century, and inspired thinking about heat distribution in more complex terms of physical causality with regard to ocean–land interaction, maritime circulation systems and their interaction with the atmosphere, the influence of altitude and high mountains, and so forth.

This new understanding of causality replaced what once used to be the dominant theory to explain heat composition in a certain place: astrometeorology. The latter was still alive when Jean Bodin developed his ethnography based on a combination of Aristotle's meteorology of zones (torrid, temperate, frigid) with humoral-pathological medicine. In this combination, astrometeorology, which had a long tradition from Aristotle and Ptolemy to Arabic astrology and the Renaissance, explained heat distribution *on the Earth*, to which bodies of living beings responded. "Climate" was only marginally involved in this system of thought, through astrological practice that used the traditional subdivision of the *ecumene* into seven climates to create a connection with the seven planets based on numerological symbolism. However, that connection quickly lost plausibility once the traditional seven climates needed to be extended as a result of the expansion of geographic and ethnographic knowledge.

Explaining heat distribution on the Earth and within its meteorological zones in traditional terms of astrometeorology worked best in the former geocentric system: one that underrated the influence of the sun, hugely exaggerated the influence of planets in our planetary system, and to a great extent relied on symbolism (mainly for predictions) rather than physics. From a modern point of view, astrometeorological theories of heat distribution were deficient in so many ways—for example, lack of understanding of our (heliocentric) solar system, solar physics, and atmospheric chemistry—that this alone suffices to indicate how deeply the emergence of modern climatology was involved with scientific innovation across a variety of disciplines: geography, astronomy, mathematics, physics, chemistry, and so on—not only in meteorology.[23] Clearly, explaining the emergence of climatology requires an account of changes in many fields of early modern science.

In antiquity, the idea of inclination was generally assigned to astronomy and referred as much to the changing visibility of fixed stars, which occurs as one moves from the equator to the poles, as it referred to the changing inclination of solar rays due to the apparent path of the sun around the Earth (i.e., the ecliptic) in a geocentric world view. Furthermore, the dominant theory on the solar impact on the Earth's heat budget (as we call it nowadays) assumed that heat and cold correlated with the distance of the sun from the Earth.

In astronomy, the Copernican revolution forced these perceptions to change. However, the idea that the sun could be the main source of the global heat budget, and that the duration of sunshine and the inclination of solar rays at a given place and time during the annual cycle were key factors, took a while to emerge from the new heliocentric cosmology. Edmund Halley refined the theory of the relationship between sunlight and heat in a now famous article of 1693 by calculating the distribution of incoming solar radiation at the equinox, and at the summer and winter solstices (see Table 36.2).[24] Halley only referred

Table 36.2 Halley's calculations of the distribution of incoming solar radiation as a function of latitude at the equinox (left, under the signes of ♈ = Aries, and ♎ Libra), and summer (middle, ♋ = Cancer) and winter solstices (right, ♑ = Capricorn)

Latitude	*Sun in* ♈♎	*Sun in* ♋	*Sun in* ♑
0	20,000	18,341	18,341
10	19,696	20,290	15,834
20	18,794	21,737	13,166
30	17,321	22,651	10,124
40	15,321	23,048	6944
50	12,855	22,991	3798
60	10,000	22,773	1075
70	6840	23,543	000
80	3473	24,673	000
90	0000	25,055	000

Source: Halley, 1693, p. 884

to latitude, not to climatic parallels. Of course, latitudes were more appropriate to use for his calculations because the distance between them was constant, while climatic parallels were not. Nevertheless, one might have expected him to elaborate on the implications of his conclusions for geographical climates, and he might well have done so—despite being an astronomer, not a geographer; yet, at the time of his writing, the scope of ideas about climate was simply not developed enough to integrate solar physics.

Against this background, it can only be called misleading to address antique, medieval, or Renaissance ethnographies based on a combination of astrometeorology and humoral pathology as "climate theories," as is (too) often done.[25] This suggests that "climate" was the underlying idea of causality. But that is anachronistic. The rise of "climate" as a combined system of celestial (astronomic) and terrestrial (geographic) causes only *followed* the decline of classical astrometeorology and *replaced* it as a theory of heat distribution and humidity on the Earth. It is precisely for this reason that the history of climatology must not be confused with the long tradition of Aristotle's meteorological zones. The chronology of its emergence as a scientific discipline is best indicated by the paradigmatic shift that occurred in the concept of climate.

However, it is by no means trivial to determine when exactly the climate concept underwent that paradigmatic shift, while the contours of a new understanding of climate arose in the second half of the eighteenth century. Hence, the focus will be on this period. Some authors have claimed that its origins are evident in the climatic conceptions of the Baron de Montesquieu (1689–1755), who became one of the most popular authors of the Enlightenment—widely noticed for his theory of climatic influence on national character.[26] For example, half a century ago Robert Shackleton argued that Montesquieu had indeed been the first author of distinction to have used the word "climate" in the sense of the "weather."[27]

However, Montesquieu's texts do not clearly evince a meteorological understanding of climate. It is difficult to find any explanation of the climate concept in his works, let alone a coherent definition. His suggestion, that climates could be distinguished according to degrees of human sensibility just as they could be distinguished by degrees of latitude, is an exception in this regard.[28] But it is precisely here that Montesquieu assumed a traditional geographical climate concept. However, he also goes on to link meteorological factors with the climate as a matter of course.

The same mixture occurs in Espiard de la Borde's *Essais sur le génie et le caractere des nations*, first published in 1743.[29] In reaction to the first edition of *De l'esprit des lois* and its tremendous success, he published a second, slightly modified version of his previous oeuvre, now under the more promising title of *Esprit des nations* (1752). Here he explained with regard to climate:

> The climate is the most universal, most intimate physical Cause. Omitting, on this Head, the Authorities of great Men, as Theophrastus, Cicero, Hippocrates, and Galen, I shall begin with the common definition of a Climate, which is a

> Space on the Globe between two supposed Lines parallel to the Equator, and at such a Distance from each other, that there is half an Hour Difference in their longest Day. I divide the Earth into twenty-four Climates.[30]

There is some irony in the fact that none of the authorities listed by Espiard could be held accountable for the definition of climate, which he probably quoted without much thinking from one of the available geographic textbooks of his time. We see that he had little understanding of what he was quoting, as he seamlessly continued referring to an equally traditional classification of peoples (*peuples*) into three meteorological zones, similar to that found, for example, in Jean Bodin's *Six livres de la république* or *Methodus ad Facilem Historiarum Cognitionem*.[31] Like Bodin—who did not subject the climate concept to this classification—and like Montesquieu, Espiard divided these zones evenly into belts of 30° each, although it had long been commonplace in the geographical and cartographical tradition to distinguish between them with the help of the tropics (at ~24°) and the polar circles (at ~66°). And in the case of Montesquieu, it remained unclear just how the meteorological zones were connected to classifications of climate. Are we to understand them as overlapping? Is climate theory subsumed into the zones? Was there a causal relationship between the two? These questions were left unanswered by both Montesquieu and Espiard.

As the chronological survey of geographic traditions in the two previous sections was meant to demonstrate, even if only with a few selected examples, geographical and cartographical works before and around 1750 do *not* suggest a symbiosis of meteorological zones and climates based on physical causes. Their sudden blending was more likely a product of ignorance rather than intention based on knowledge. Neither Montesquieu nor Espiard was familiar with the tradition of the climate concept in classical geography and cartography. And why should they have valued that tradition? "Climate" had already been a niche concept, before it sank even deeper into its niche in the eighteenth century, losing all the practical relevance it used to have for the drawing of maps. But maybe precisely for that reason, the term was ready to experience a paradigmatic shift. Perhaps the lack of coherence in both Montesquieu's and Espiard's understanding of climate is an indication that terminology was already on the move. However, it would be premature to speak of a consummate neologism, or even a complete meteorological theory of climate, at that point.

Thus, both Montesquieu and Espiard linked two meanings that had little to do with each other and had been distinguished previously, for example in the *Dictionnaire de l'Académie Française*. The first six editions, published between 1694 and 1835, emphasized the geographic term (*terme de géographie*), that is, the traditional cartographic definition of climate.[32] Yet as early as 1718, the *Dictionnaire de l'Académie* also referred to the term's ordinary meaning (*sens ordinaire*) as "region, country, mainly with regard to the temperature of the air."[33] Following along the same lines, volume three of Diderot's and d'Alembert's *Encyclopédie*, published only a year after Espiard's *Esprit des nations*, in 1753, also had two articles on climate. The first one, written by Jean le Rond d'Alembert (1717–1783) himself, stayed with the geographic textbooks and revealed nothing new under the sun.[34] But the medical article that followed, written by the doctor, pharmacist, and chemist Gabriel-François Venel (1723–1775), stepped in a different direction:

> *Climate* (*in the medical sense*) Physicians do consider the climates only with regard to their temperature or the degree of heat peculiar to them: "climate", in this sense, is even exactly synonymous to "temperature"; as a result, that word is taken in a sense much less broad than that of "region", "country", or "area"; in that way doctors express the sum of all common or general physical causes, which can act on the health of the inhabitants of each country; know the nature of the air, that of the water, the soil, and the food.[35]

This was new, for it gave "temperature" as an intermediate term to combine "climate" with "physical causes." In Venel's view, these causes only spelled out what was already implied by the older, supposedly broader definition of "climate." While his reference to the air, water, soil, and food of a region resembles conventional Hippocratic wisdom, Hippocrates in fact never made "climate" the epitome of those environmental causes that affected human health. Bodin had also been missing an intermediary category to make that connection. His theory of national characters was based on humoral pathology, which related "temperament" to traditional "zones" and gave the "temperate zone" an advantage over the extremes of the "torrid" and the "frigid" zones. After all, the Latin adjective *temperatus* describes the "right" composition of heat and cold, both in the body and character of a human being and at a certain place on the globe, which were supposed to correlate with each other. Thus, "temperate" was basically a normative category. To go from "temperament" and the "temperate zone" to "temperature" as a measurable physical category was not a matter of continuity or the mere continuation of a certain line of thought. Rather, it marks a caesura in intellectual history.

Venel's *Encyclopédie* article presaged this paradigmatic shift during the eighteenth century: the relatively empty, purely descriptive geographical category was to be replaced by a complex causal concept explaining heat composition. Climate became the sum total of all physical causes that influence the temperature of a place on the surface of the Earth. This concept caught on quickly without the geographical tradition disappearing right away. Due to this development, the new paradigm also left the niche that was probably its birthplace, medical theory. A quarter of a century after Venel, the geographer and biologist Eberhard August Wilhelm von Zimmermann (1743–1815) made this very clear. In the introduction to his *Geographical History of Humans and the General Distribution of Quadrupeds*, he discussed the idea of attributing to climate a key role in the geographical distribution of plants. Here, he felt compelled to provide the reader with a terminological clarification:

> It is only that by the name of climate we must not understand the geographical, but the physical climate; because the latter would be the relationship between the location of a country [on the globe], the atmosphere, and the soil. It is not only determined by geographical latitude, but quite often also by the warmth and coldness of a country coming from additional causes as well as, finally, by the level of humidity. This physical climate, which often does not coincide with the geographical climate, is what in the following book will be referred to.[36]

The medical sense of "climate" of the *Encyclopédie* had now been renamed "physical climate," and just like the medical climate before it, it would be distinct from the old geographical concept. That distinction proved to be very fruitful and went through several terminological modifications over the course of a few decades, leading to Humboldt's distinction between solar and real climate, which was the theoretical foundation for his isothermal maps.

Altogether, "climate" came to signify the sum of all factors influencing heat distribution (or temperature) and humidity in a certain place on the surface of the Earth. Compared to its meaning in classical geography, this shift involved a significant increase in complexity. It also entailed a transition from a descriptive to a causal concept, and from a static to a dynamic one. Moreover, as soon as "climate" had been converted into a dynamic physical category, it opened the possibility that climates could change over time. Indeed, as we shall see next, the chronology of the idea of climate change parallels this revolutionary shift in the meaning of "climate" during the second half of the eighteenth century.

36.5 Climate Change and History

During the same period in which climate shifted from a traditional geographic (or cartographic) category to a physical one, the idea of anthropogenic climate change was born out of older colonial discourses on weather modification. As early as the seventeenth century, some settlers had engaged in meteorological observations and believed they had evidence of temperature and precipitation changes, at least in some places, attributing them to their own efforts as cultivators of "savage land."[37] In other words, settlers and colonial officials started believing that climatic conditions could be modified by human action. But only in the second half of the eighteenth century did writers explicitly discuss "climate" change.[38]

The earliest occurrence of the expression "change of climate" that we know of is in a treatise published by Hugh Williamson in the *Transactions of the American Philosophical Society*: "An Attempt to account for the CHANGE of CLIMATE, which has been observed in the Middle Colonies in North-America," read before the society on August 17, 1770.[39] The expression "change of climate" itself was a symptom that the old doctrine of climate had been overturned. In the eyes of geographers, from the times of Strabo until well into the eighteenth century, a "change of climate" would mean a change of place, usually by migration.[40] But the idea of a dynamic change in time of a climate, mathematically defined as the geographic space in between two latitudinal parallels distanced by the half-hour difference of the longest day, would have made no sense. Prior to Williamson, European colonizers around the world had sought to modify weather conditions, particularly in tropical colonies, through deforestation and desiccation, and the effects of such measures, whether real or imagined, had been discussed for more than a century. What had changed when Williamson held his lecture was that the old doctrine of climate had lost its practical relevance and the new concept of "climate" emerged ready to represent new content and ideas.

Once the idea of climatic change had been born, historians projected it into the past. The debate about climate change in historical time paralleled the initial debate about changing climates in the colonies almost from the beginning, and in fact reconnected with it at various points. To give just one example, in a letter to Samuel Mather, dated July 7, 1776, Benjamin Franklin discussed the theory of an early Viking discovery of North America "long before the Time of Columbus." Based on an account he had been given by Pehr Kalm (1716–1779), one of Carl Linnaeus' disciples who had visited North America twenty-five years before, Franklin speculated:

> if one may judge by the Description of the Winter [given in Kalm's account based on Swedish documents] the Country they [the Vikings] visited should be southward of New England, supposing no Change since that time of the Climate. But if it be true as Krantz and I think other Historians tell us, that old Greenland once inhabited and populous, is now render'd uninhabitable by Ice, it should seem that the almost perpetual northern Winter has gained ground to the Southward, and if so, perhaps more northern Countries might anciently have had Vines than can bear them in these Days.[41]

Cranz had written his *History of Greenland* when he was a missionary of the Moravian Brethren in Greenland. It is evidence of early ideas about changing climates in the northernmost Northern Hemisphere.[42]

Edward Gibbon was among the first historians to consider climate change as a historical force. In his *History of the Decline and Fall of the Roman Empire*, published in a series of volumes between 1776 and 1788, he attributed to climate change a significant role in pushing "Barbarian migrations" toward the Roman borders.[43] In his discussion of the ancient Germanic lands, Gibbon found earlier statements by David Hume (1711–1776), the Abbé du Bos (1670–1742), and Simon Pelloutier's *History of the Celtes* which confirmed "that Europe was much colder formerly than it is at present." His review of the evidence had some remarkable observations on the value of written record:

> The general complaints of intense frost and eternal winter, are perhaps little to be regarded, since we have no method of reducing to the accurate standard of the thermometer, the feelings, or the expressions, of an orator born in the happier regions of Greece or Asia.[44]

Gibbon found that reports on the freezing of rivers and the distribution of flora and fauna were “of a less equivocal nature,” thus recognizing, quite remarkably, the difference between direct qualitative observations and indirect phenological descriptions that is still meaningful for climate historians (see Chap. 3).[45] However, his comparison of the ancient climate of “Germany” (as he called it) with the climate of eighteenth-century Canada provoked some disagreement. While Johann Gottfried Herder (1744–1803) was, for the most part, an ardent follower of Gibbon’s ideas about the role of climate in antiquity, others, such as François Aragot (1786–1853) and Fredrik Schouw (1789–1852), both important characters in the emerging field of modern climatology, remained skeptical and found the phenological evidence of the written record rather ambiguous. Generally, the idea of climate change as a historical force lost ground again in the nineteenth century.

But before that happened, Georges-Louis Leclerc de Buffon (1707–1788) envisaged anthropogenic climate modification as a force of such potential that it might even change the course of Earth history:

> Let us suppose the world in peace, and take a nearer prospect of the influence of man’s power over that of Nature. Nothing appears to be more difficult, not to say impossible, than to oppose the successive cooling of the earth, and to warm the temperature of a climate; yet this feat man can and has performed. Paris and Quebeck are nearly under the same degree of latitude; Paris, therefore, would be as cold as Quebeck, if France and the adjacent countries were as thinly inhabited, and as much covered with wood and water as the territories in the neighbourhood of Canada. The draining, clearing, and peopling a country, will give it a warmth which will continue for some thousand years; and this fact will prevent the only reasonable objection which can be made against my opinion, that the earth is gradually cooling.[46]

This passage explains what Buffon meant when he characterized the seventh and most recent epoch of natural history as the epoch “When the Power of Man assisted the Operations of Nature.” Of course, his idea was founded on the false assumption that the warmer temperatures of Paris relative to Quebec were a civilizational achievement, while in reality, the generally milder Parisian winters are effected by the Gulf Stream and France’s maritime climate. Buffon’s vision of anthropogenic global warming is nevertheless remarkable, for it deserves credit as one of the precursors of the idea of an Anthropocene—a new geological era in which humanity “has become a global geophysical force, equal to some of the ‘great forces of nature’ in terms of Earth System functioning.”[47] Within merely three decades after publication of Montesquieu’s *De l’esprit des lois*, debate over the influence of climate on humans was joined by a debate over climate change and the influence of human activities on the climate, not only on a local but also on a global and geological scale.

36.6 Conclusions

The emergence of climatology as a modern scientific discipline required major transformations of knowledge in various fields of scientific inquiry (see Chap. 38). However, the history of the climate paradigm is key to it, because it makes discernible what is overlooked in purely "Baconian" narratives that emphasize the empirical collection of meteorological information. Climate was not a meteorological category from the start. Rather, for most of the time since its invention in antique geography, it remained a niche concept. Only later, in the nineteenth century, was "climate" understood as the average weather. But that development was preceded by a new *idea* of climate resulting from a paradigmatic shift, which turned it into a physical theory. It is therefore that a "Platonic" narrative emphasizing new ideas in the areas of physics and mathematics must complement the dominant Baconian narrative. The emergence of modern climatology combines both types of scientific innovation, that is, in the areas of physics and mathematics as well as in that of data collection. But the paradigmatic shift from a traditional understanding of climate to a physical category occurred first and, therefore, deserves priority in the chronology of the making of a modern discipline. Focusing on that shift makes clear that climatology emerged as a new theory of heat distribution and humidity (in a certain place) on the globe, *replacing* astrometeorology.

Though there are earlier signs of a new understanding of climate, the contours of "climate" as a physical category emerged in the second half of the eighteenth century and laid the foundations for modern climatology as a scientific discipline. Amazingly enough, until recently, this paradigmatic shift went almost unnoticed in narratives of the early history of climatology. It seems as if memory of the old geographic term and its meaning was erased, which made the caesura invisible. Instead, nineteenth-century narratives of the history of climatology invented a long tradition tracing the origins of climatology back to antiquity, which meant dissolving it into the history of meteorology.

Notes

1. For example, Feldman, 1983, Section III: Climatology. Feldman was nevertheless right in pointing to the danger of anachronism in applying the term "climatology" within the meteorological context prior to 1800, as "it and its cognates are not to be found in the eighteenth century but made their appearance in the first years of the nineteenth." See Feldman, 1990, 145.
2. This framework has been set by a number of important studies. I am only giving a short list of some of the most relevant books and edited books here: Frisinger, 1977; Feldman, 1983; Fleming, 1990, 1996. Several relatively recent monographs have focused on eighteenth-century Britain: Golinski, 2007; Janković, 2001.
3. Fleming and Janković, 2011, 2.

4. Neither the Greek texts of Hippocrates, *Aër* (Greek text and translation in Hippocrates, 1923–31, vol. 1), nor Aristotle's *Meteorology* nor his *Politics* (i.e., VII, 7; 1327b) refer to climate, while modern translations do most of the time. Tracing the origins of climatology back to Hippocrates and Aristotle is a tradition invented in the nineteenth century that continues today. For instance, Herder, 2002 (first published 1784–91), vol. 1, 241, considered Hippocrates to be "the main author on climate" ("Für mich der Hauptschriftsteller über das Klima"). Hellmann, 1922 provided a history and bibliography of "climatological textbooks" so focused on the Hippocratic tradition that it ignored the geographic tradition entirely.
5. The work of these, as well as many other, founding fathers of Greek geography has only survived in fragments. Honigmann, 1929 argued in favor of Eratosthenes, while Dicks, 1955 made a strong point for Hipparchus. He extended his argument by a reading of Strabo II. (Cf. Dicks, 1956.) For a critical discussion of Honigmann see also Gisinger, 1933, who provides valuable references reflecting the early use of the word κλίμα. Roller, 2010 adds little to the debate.
6. See Abel, 1974, 994. Only Aristarchus of Samos proposed a heliocentric conception of the cosmos.
7. See Honigmann, 1929 and the critique by Dicks, 1955.
8. Sanderson, 1999 is a typical example for this confusion, but there are many more. Just look at the Wikipedia article on "Climate," https://en.wikipedia.org/wiki/Clime (last accessed July 15, 2016).
9. Ptolemaios, 2006, vol. 2, 774–907.
10. Merula, 1636, 353–60 (Caput XXIII: De Climatibus); Keckermann, 1611; Clüver, 1667, 18–24 (Caput VI: De Parallelis & Climatibus). For Christiani and Varenius see the following footnotes. I am not referring to first editions of these works, since those were not accessible to me.
11. Christiani, 1645, 338–58 (Caput XXV: De Climatibus in Terrae). The term *climatum doctrina* (341) is as close as it gets to "climatology" in the seventeenth and eighteenth centuries.
12. See Warntz, 1989. Newton's translation laid the foundations for Varenius' broad reception in England and North America. See also Warntz, 1981. For the stemma of the early editions of Varenius' *Geographia Generalis* see Schuchard, 2007, xviii. On the (constantly extended) English editions of 1733, 1736, 1743, and 1765 see the chapters written by Schuchard (227–37) and Mayhew (239–57) in the same book. Humboldt credited Varenius for his "excellent work" and for having given "a physical description of the earth" "in the true sense of the words." See Humboldt, 1901, 48–49 (original German edition: Humboldt, 1845).
13. Varenius, 1734, vol. II, 559.
14. Varenius, 1734, 2–3. Soon after the first Latin edition had come out, the *Geographia Universalis* was translated into English, Dutch, French, and Russian.
15. See Shirley, 1987, No. 10 and No. 32. On de Agostini's map see also Kish, 1965, 13–15.
16. See the introduction in Blaeu, 2005.
17. Shirley, 1987, 264.
18. Blaeu and Blaeu, 1645, vol. 1 (no page numbers).
19. Schmid, 2010.
20. See Blaeu and Blaeu, 1641, vol. 1.
21. Buy de Mornas, 1761 and Clouet, 1787.

22. See Humboldt, 1817, 1831, and Bernhardt, 2003.
23. Some of the important changes in geographical and meteorological knowledge were related to subjects such as the habitability of the tropics and the surprisingly harsh weather in North American colonies. See also White, 2015, for more references.
24. Halley, 1693.
25. See, for example, Metzler, 2009, 381; also Tooley, 1953; Gates, 1967; Wands, 1986; Altmann, 2005 and many others. All these authors either failed to recognize the difference between the climate(s) and Aristotelian meteorological zones, or they did not note the specific meaning attributed to "climates" in some versions of astrology. The latter is precisely the reason why, for example, Shakespeare (in *Julius Caesar*) "associates the idea of climate with the ebbing and flowing of personal fates and fortunes, rather than with natural and inanimate meteorological forces," as Hulme, 2016 noticed correctly but without explaining the astrological context. Ignoring historical context explains why Hulme's account of climate "as an ordering concept" in Shakespeare's England is largely based on a projection of the modern understanding of climate back into the sixteenth and early seventeenth centuries.
26. Shackleton, 1955, 1961, 302–10. Some researchers belonging to the circle of editors of the *Oeuvres Complètes* have spared no effort to tear apart Shackleton's genesis of climate theory in Montesquieu's intellectual biography; see Montesquieu, 1998, vol. 4, 902–16, and Casabianca, 2013.
27. However, according to Shackleton, Espiard had already used the word "in its modern meteorological sense" and had therefore beaten Montesquieu to it. Shackleton speaks of a "neological coincidence." Shackleton, 1961, 309.
28. "Comme on distingue les climats par les degrés de latitude, on pourrait, pour ainsi dire, les distinguer par les degrés de sensibilité." Montesquieu, 1998, vol. 4, 357. The identical sentence appears in the unpublished manuscript *Essai sur les causes qui peuvent affecter les esprits et les caractères*, edited in Montesquieu, 1998, vol. 9. The commentators correctly remark that this is the old geographical understanding of "climate."
29. Espiard de la Borde, 1743.
30. Quoted from the English translation: Espiard, 1753, 4; for the French original see d'Espiard, 1752, vol. 1, 5: "Le climat est la cause physique, la plus universelle, la plus intime. Sans s'arrêter à recueillir les autorités des grands hommes, comme Theophraste, Ciceron, Hippocrate & Galen, sur cet article, on entrera d'abord en matière, en définissant le Climat, *un espace de terre renfermé entre deux cercles parallèles à l'Equateur, et tellement éloignés l'un de l'autre, qu'il y ait une différence de demi-heure dans la durée de leur grand jour d'Eté*. La Terre est divisée en vingt-quatre Climats." There was no definition at all in the *Essais* of 1743. The fact that Espiard changed this in the 1752 edition may have been a reaction to criticism.
31. There is an excellent new edition of the Latin text of the *Methodus* with an Italian translation and exquisite comments by Sara Miglietti, see Bodin, 2013.
32. The *Dictionnaire de l'Académie Française* can be accessed comfortably and searched electronically through the webpage of the ARTFL project under "Dictionnaire d'autrefois" (here search for "climat"), http://artflsrv02.uchicago.edu/cgi-bin/dicos/pubdico1look.pl?strippedhw=climat (last accessed September 29, 2015).

33. "Région, Pays, principalement eu égard à la temperature de l'air." Régnier, 1718, vol. 1, 275; see also Montesquieu, 1998, vol. 4, 909.
34. Diderot and d'Alembert, 1751–1765, vol. 3, 532.
35. Diderot and d'Alembert, 1751–1765, vol. 3, 534: "*Climat*, (*Med.*) Les Medecins ne considerent les *climats* que par la température ou le degré de chaleur qui leur est propre : *climat*, dans ce sens, est même exactement synonyme à *température* ; ce mot est pris par conséquent dans un sens beaucoup moins vaste que celui de *région, pays,* ou *contrée,* par lequel les Medecins expriment la somme de toutes les causes physiques générales ou communes, qui peuvent agir sur la santé des habitans de chaque pays ; savoir la nature de l'air, celle de l'eau, du sol, des alimens, *&c.*"
36. Zimmermann, 1778, vol. 1, 11–12 (translation by the author).
37. Vogel, 2011.
38. Gerbi, 1973; Glacken, 1967; Fleming, 1998; Fressoz and Locher, 2015.
39. Williamson, 1769; among others, Thomas Jefferson believed he was a witness of anthropogenic climate change in Virginia, see Jefferson, 1832, 85, 175.
40. That is precisely what the expression "change of climate" (or in French: "changement du climat") meant in the rare cases where it was used prior to Williamson. Just check the entry *climat* in the 1694 first edition of the *Dictionnaire de l'Académie Française:* "*changer de climat. passer dans un autre climat.*" http://artflsrv02.uchicago.edu/cgi-bin/philologic/contextualize.pl?p.2.dicofullpublic.1804014 (last accessed July 22, 2016).
41. Letter of Benjamin Franklin to Samuel Mather, London, July 7, 1773. The text of this letter can be accessed and read on the *Founders Online* webpage, http://founders.archives.gov/documents/Franklin/01-20-02-0156 (last accessed July 22, 2016).
42. Cranz, 1765.
43. For example, Büntgen et al., 2011.
44. Gibbon, 1813, 346.
45. Gibbon, 1813, 346.
46. Buffon, 1778, 240. Here quoted from the English translation: Buffon, 1812, 336.
47. Steffen et al., 2011, 741. The "Anthropocene" was first proposed by Crutzen and Stoermer, 2000. For more references see Sect. 5 in Chap. 6. Buffon has been discussed as a precursor, e.g., in Mauelshagen, 2017 and Heringman, 2016. Hamilton and Grinevald, 2015 rejected any anticipation prior to the invention of Earth system science.

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CHAPTER 37

Climate and Empire in the Nineteenth Century

Ruth A. Morgan

During the long nineteenth century, European and North American imperialism throughout Asia, Africa, Australasia, and Oceania connected peoples and places on an unprecedented scale (see Chap. 31), contributing to the globalising processes that historian Christopher Bayly describes as 'the birth of the modern world'.[1] Encounters with unfamiliar environments and cultures shaped and informed the production of knowledge in both metropolitan and colonial contexts. Climate loomed large in these colonial exchanges as imperialists confronted arid, tropical, and variable climatic conditions. To make sense of their colonial experiences and observations, Europeans and North Americans applied their own philosophies of climate.

During the seventeenth and eighteenth centuries, Western climate discourses had begun to bifurcate, such that by the nineteenth century, climate was largely understood both as an agent or force, and as an index or set of statistics.[2] The roots of the former discourse lay in a historical climate determinism, while the latter had emerged more recently as the product of empirical weather observation and the development of meteorology and climatology (see Chap. 36).[3] In the colonial context at least, climatology did not come at the expense of the agential interpretation, which flourished in the face of new geographies of risk and opportunity. Both approaches thrived where the paucity of instrumental data beckoned measurement, observation, and interpretation. Moreover, the study of colonial climate itself became an instrument of imperial rule and resistance.[4]

This chapter examines key areas of research by historians of climate and climatology in the nineteenth-century context of empire and colonialism. This research ranges from the reconstruction of past climates, the study of medical

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climatology, and the social and political consequences of climate events, to understandings of climate change and climate modification, the practice of colonial climatology, and the emergence of a 'global' climate. Although these areas have tended to be studied separately, common themes emerge when they are brought together, including climate and environmental determinism; scientific cultures and practices; geographies of knowledge and risk; the application of science for economic development; and spatial and temporal ideas of scale.

37.1 Recording the Colonial Climate

The expansion of European and North American empires during the eighteenth and nineteenth centuries helped to facilitate the rise of Western science, which in turn reinforced the imperial enterprise. Among the sciences aligned with empire—such as botany, geography, and geology—was the emerging science of meteorology. Jan Golinski and Vladimir Janković have shown how an increasingly quantitative approach to weather observation surpassed local folk traditions in Britain by the early nineteenth century.[5] In the colonies, meanwhile, both practices thrived, which encouraged the recording of colonial climates in both qualitative and empirical terms.[6] The former required observers to describe the quotidian and the extraordinary, while the latter noted variables such as temperature, pressure, rainfall, wind speed, and wind direction. Such a quantitative approach to weather recording fostered imperial understandings of climate in statistical terms, as an index by which to assist the achievement of imperial objectives.

European and North American empires established observatories to foster the systematic collection of meteorological statistics in their colonial territories. The English East India Company, for example, established observatories in Madras, Calcutta, St Helena, Bombay, and Singapore during the early to mid-nineteenth century (see Chaps. 7 and 34).[7] Later, such observatories became hubs for the collection of climate data recorded around the colonies (often by volunteers and native peoples) and from other colonial outposts. Stocked with European instruments and staffed by military (if not scientific) observers, these observatories were to be sites of colonial science and imperial authority. Katharine Anderson has shown, however, that the lack of a uniform pattern of observation, the absence of the standardisation of instruments, and the poor training of observers severely undermined the usefulness of colonial climate data.[8]

Nevertheless, these networks of climate knowledge became increasingly important to scientific communities in both the colonies and the metropole. In the colonies, the collection of meteorological data over time and space allowed for colonial meteorologists to attempt to interpret local climate patterns. Facilitated by the advent of the telegraph, their interpretations were critical to the development of weather forecasting, a predictive science vital to the agricultural and maritime endeavours of empire.[9] Richard Grove has shown how the exchange of meteorological data between India and the Australian colonies in the 1880s allowed South Australian meteorologist Charles Todd to identify the coincidence of drought conditions in both regions.[10] Meteorologist Jacob Bjerknes would later describe these patterns as a consequence of an atmospheric-oceanic phenomenon, the El Niño Southern Oscillation (ENSO).

The imperial collection of meteorological data provided the statistics necessary to contribute to the emerging field of climatology. Alexander von Humboldt's definition of climate was 'crucial' to the field's development, as Matthias Heymann observes.[11] In *Kosmos* (1845), Humboldt suggested that 'climate … indicates every change in the atmosphere which sensibly affects our organs', from temperature and humidity to 'electrical tension' and 'gaseous exhalations'.[12] Humboldt's approach to climate as both the atmospheric phenomena specific to a particular location and the atmospheric phenomena across different locations was especially suited to the wide networks of meteorological observation that European and North American empires were developing in the nineteenth century.[13] Humboldt himself recognised this scientific potential, and in 1836 he urged the British Royal Society to establish geomagnetic observatories in British colonies to aid the study of terrestrial magnetism.[14] His work informed the 'classical climatology' that later emerged in the continental empires of Central Europe (see Chap. 38). Austrian Julius Hann, head of the Central Office for Meteorology and Geomagnetism in Vienna, led the development of climatology as a quantitative and systematic science during the late nineteenth century. The aspiration for a climatology that would depict 'the interaction of all atmospheric phenomena over a patch of the earth's surface' encouraged Hann to average long-term time series of meteorological data for a particular location—the basis for the Köppen system of global climate classification.[15] Although the International Meteorological Organisation was established in 1873 as a means to advance such global climate research (see Chaps. 7 and 25), the politics of empire continued to shape climatological and meteorological research well into the twentieth century.[16]

37.2 Pathologising the Colonial Climate

In addition to meteorological records, the human body was deemed to be an important instrument by which to measure colonial climates. Colonial discourse on the merits of exploration, colonisation, and emigration was rooted in Hippocratic thought, which emphasised the dependence of human health on local geographical conditions. By the nineteenth century, the question of how European and North American bodies would fare in foreign climes, particularly the tropics, was becoming a source of considerable consternation. In contrast to the veneration of the tropics that Humboldt and Darwin espoused, the region between the Tropics of Cancer and Capricorn was increasingly conceptualised as a threat to the health of colonising peoples.[17] Historians have shown how these fears were deployed to justify European and North American imperial ambitions; to support arguments for slavery (see Chap. 31); and to account for the challenges that imperial powers encountered in colonial contexts.

The climate of prospective territories provided a rationale for European and North American imperial ambitions. If climate determined racial character and capacity, as contemporaries believed, then the civilised peoples of temperate nations were fit to subjugate those of the uncivilised tropics. This view aligned temperate climates with civilisation and the heat of the tropics with lack of industry, laziness, and despotism. Such moral discourse, most commonly associated with eighteenth-century thinkers such as Abbé Jean-Baptiste Du Bos and Montesquieu, had significant implications for questions of emigration and the mobility of imperial agents (see Chap. 31).[18]

During the eighteenth century, Western scientific thought reassured imperialists that whites could adapt or acclimatise to colonial climates. Dress, housing, behaviour, and creolisation were each important elements to the successful management of European health in the colonies.[19] By the early nineteenth century, however, the notion of acclimatisation was coming under scrutiny. Western medical geography increasingly attributed high rates of disease and morbidity among Europeans in the tropics to the heat and humidity of these climes, especially when these risks were exacerbated by the excesses of the colonists.[20] Under this schema, tropical climes posed the greatest threats to European constitutions and therefore to European rule.[21]

Experience only heightened these fears. For Spain, the climate of its Caribbean territories was thought to be a safeguard against military incursion. A proposed British military intervention in Caracas in 1808, for instance, was met with concern from one colonel, who argued, 'My fears on that subject are the climate, the climate, the climate.'[22] In Sierra Leone, an average of about half of the British troops garrisoned there between 1819 and 1838 died annually.[23] Meanwhile, in India, although the British had triumphed in the First Burma War (1824–6), climate and disease exacted a heavy toll on both sides of the campaign.[24] These experiences confirmed the shift in perceptions of tropical climes and their implications for the defence of European empires. The emerging field of medical topography identified environment—and particularly climate—as the most important determinant of both physical and moral health, and its practitioners sought to identify the healthiest areas for Europeans abroad.[25]

In the colonies, this approach emphasised segregation over acclimatisation. Adherents recommended that Europeans preserve their health by retreating to spaces more akin to their homelands. Consequently, hill stations, spas, and sanitary enclaves were set up as refuges in which Europeans could restore or preserve their health, away from the ills of the wider tropical landscape.[26] As Eric Jennings has shown, the French empire established climatic resorts or *climatiques* in Guadeloupe, Réunion Island, Madagascar, and Tunisia for the moral and physical benefit of Europeans.[27] In South Asia, too, hill stations provided sanctuaries for Britons to recuperate from the tropical heat of the plains. As European enclaves, these areas became key sites of political and military power that helped maintain imperial rule during the second half of the nineteenth century.[28]

The concern that European bodies would not thrive in warmer, tropical climes had grave implications for imperial projects founded on natural resource extraction. This climate determinism helped to justify arguments for the enslavement of non-Europeans in the era prior to abolition (see Chap. 31).[29] If Europeans were weakened by the climate, they would lack the energy to undertake the labours of agricultural production. It was vital then, slaveholders argued, that peoples born in and so accustomed to those climes, should undertake these labours.[30] A physician in British Guiana was quoted in 1835 as reporting, 'I entertain a more favourable opinion of the constitution of the Coolies, in reference to their adaptation to this climate, than of any class of immigrants whom I have seen in this colony.'[31] Supporting this racist notion of a climatic aptitude for enslavement was the view that slavery was the 'natural' form of the despotic government of tropical places.[32]

The rise of germ theory encouraged the decline of this form of climate determinism. Nevertheless, the tropics continued to be a source of concern for the expanding European and North American empires. The discovery of germs and vaccines buoyed imperial ambitions for the tropics but exacerbated anxieties over diseases already associated with those particular places. The emergence of tropical medicine in the late nineteenth century alleviated such climate anxieties, but it continued to emphasise the role of environmental and social factors in disease transmission.[33] As Warwick Anderson has shown, the new science of tropical medicine became a civilising tool for population management and control in the American Philippines that helped to perpetuate the idea of the tropical 'other' into the twentieth century.[34]

37.3 Changing Colonial Climates

Contemporaries also deployed quantitative and qualitative accounts of colonial climates to determine the extent to which the colonial enterprise affected local climates. In some cases, colonial climate change was a welcome prospect, while in others it was a source of anxiety. From the tropics to the temperate outposts of empire, the chief method believed to effect colonial climate change was the planting and removal of trees for medical and agricultural purposes. Therefore, imperial visions of environmental conservation and restoration had a climatic aspect.

The association of deforestation with climatic change, principally diminishing rainfall, became increasingly influential in France and England during the eighteenth century (see Chap. 36). These desiccation theories grew apace with imperial expansion, which brought Europeans into contact with unfamiliar peoples and places. Colonial climate change had grave implications for empire's civilising mission. The imperial anxieties arising from desiccationist discourse encouraged what Richard Grove has called 'seeds of modern conservationism', whereby colonial expansion led Europeans to re-evaluate the ecological and human impact of their activities.[35] In Venezuela, for example, Alexander von Humboldt attributed the shrinkage of Lake Valencia to the clearing of vegetation and diversion of water for plantation irrigation. His critique reflected his disdain for Spanish colonialism and its impacts on local peoples and environments.[36] By the mid-nineteenth century, such colonial conservationism had led to the development of forest protection and scientific forestry.

According to the logic of desiccationist theory, afforestation was a means to improve colonial climates. The East India Company, for instance, undertook a programme of tree planting in St Helena during the late eighteenth century to counter what it perceived to be a changing climate.[37] Starting in the 1850s, German-born botanist Baron Ferdinand von Mueller promoted the planting of particular tree species, such as the Tasmanian blue gum (*Eucalyptus globulus*), to overcome the miasma of swamps. These trees, it was believed, had desiccationist qualities that would clean the air in British India and the Australian colonies, as James Beattie has shown.[38] The belief in the capacity of afforestation to improve a local climate was especially evident in the French colonies of the Maghreb. There, as Diana Davis has argued, a narrative of environmental decline demanded French colonial authorities restore the region to its 'natural' condition of fertility. Following the conquest of Algeria in 1830, this narrative depicted a region suffering from deforestation, overgrazing, and desertification at the hands of indigenous peoples; the narrative served to rationalise French rule in the region, underpinning colonial laws and policies of dispossession.[39] This declensionist rhetoric was also deployed in French Algeria to *conserve* forests as a vital means to prevent the encroachment of the Sahara into the more salubrious areas where European settlers lived.[40] Although fears of the climatic consequences of deforestation persisted well into the twentieth century, the associated issues of soil erosion and sand drift came to compete with these anxieties by the interwar era.[41]

37.4 The Archive of Colonial Climates

The documentary archive of empire has proven a valuable source of climate information for historians and others seeking to reconstruct and recover past climates over wide spatial and temporal scales. Researchers can trace the climate monitoring of European and North American empires and their agents through a range of documentary sources, such as government records and gazettes, the accounts and diaries of missionaries and early settlers, newspaper articles, ships' logs, military records, physicians' journals, and weather records from colonial observatories and observers. This quantitative and qualitative information has been vital to international and regional endeavours to extend the global climate record; to reconstruct past climates for former colonies; and to understand human–climate interactions in colonial contexts.

Since the late 1980s, climate researchers have sought out this imperial data as part of the wider effort to collect global weather observations to study global change. These works include the Comprehensive Ocean-Atmosphere Data Set (COADS, now ICOADS), which is focused on amassing the instrumental data generated after the 1853 Brussels Maritime Conference that standardised shipboard meteorological and oceanographic observations (see Chap. 25).[42] More recently, researchers have sought to extend the climate record further. For example, ships' logbook records from the Spanish, British, Dutch, and French empires, as well as the English East India Company, have provided valuable data for the period 1750–1850 for the Climatological Database for the World's Oceans (CLIWOC), the Recovery of Logbooks and International Marine (RECLAIM) data project, and the Atmospheric Circulation Reconstructions over the Earth (ACRE) project.[43] The logbooks reveal information such as wind speed, force, and direction as well as other general weather descriptions for the ship's location. By virtue of ships' voyages, these datasets largely cover the Atlantic and Indian oceans, and focus mostly on the Northern Hemisphere (see Chap. 6).

Regionally focused initiatives have developed to overcome the relative paucity of meteorological data in Southeast Asia, South America, and southern Africa (see Chaps. 18–20). As David Nash and George Adamson note, few countries in these regions have continuous records extending back much further than the late nineteenth century.[44] For example, ACRE has since led to regionally focused initiatives in Southeast Asia, the Indian Ocean, Africa, and Antarctica.[45] The records of the English East India Company observatories established in Madras (1792) and Singapore (1841), as well as observations undertaken at the Buitenzorg Botanic Garden and Batavia, have shed light on the colonial climates of British India and the Dutch East Indies as well as the Southern Oscillation.[46]

In addition to instrumental observations, other documentary sources of climatic data have offered climate historians insight into the colonial past. Although the use of such documentary sources has been commonplace in analyses of European and North American climates, historians and geographers are increasingly turning these techniques to the study of climates in southern Africa, South and Southeast Asia, the Caribbean, and Mexico.[47] English-, French-, and Sesotho-language missionary accounts have revealed precipitation and temperature variability in Lesotho, the Kalahari, Natal, and Zululand, while private diaries have allowed a climate reconstruction of early nineteenth-century Bombay.[48] Similarly, ships' logs as well as missionary and plantation papers provided the basis for the reconstruction of rainfall variability and hurricane activity in the southern Caribbean.[49] Such work has also shed light on the nature of extreme weather events. For example, Jesuit records from the Spanish Philippines provide insight into typhoons in the archipelago; French, English, and Norwegian missionary accounts reveal the tracks of the tropical cyclones that made landfall on Madagascar; and the colonial archives disclose the nature and extent of drought and flood events in Mexico since the sixteenth century.[50]

In some cases, these projects have been interdisciplinary, drawing together expertise from historians familiar with analysing the archival sources and scientists familiar with extracting, processing, and calibrating the relevant information. For example, the South-Eastern Australian Recent Climate History (SEARCH) project brought together historical climatologists, environmental historians, meteorologists, and citizen scientists to uncover the climate history of colonial New South Wales (1788–1860). By analysing documentary sources such as newspapers and the accounts of early colonists, they extended the instrumental climate record for southeastern Australia to at least 1788, which they used to examine climate variability and change in the region since the late eighteenth century (see Chap. 21).[51]

The reconstruction of colonial climates has also allowed for the development of long-term records of global phenomena, such as ENSO. In the wake of the devastating 1982/3 El Niño event, researchers drew on Spanish-, English-, German-, French-, and Dutch-language sources to compile a 400-year chronology of El Niño occurrences, which they assessed in terms of their strength or intensity.[52] Such reconstructive work has continued into the twenty-first century as a means to contextualise the nature and extent of climate change.[53]

Despite this growing focus on the climate histories of former European and North American colonies, some areas remain neglected. David Nash and George Adamson point to further opportunities in the Spanish Caribbean and Central America, as well as in Southeast Asia, Indonesia, and the Pacific Islands. The equatorial and arid areas of Africa are also under-studied, which limits continent-wide rainfall reconstructions. In addition to overcoming these gaps, the methods of climate reconstruction using documentary sources require further clarification. Such work might focus on improving the reliability of data quantification and limit the differences in the interpretation of sources.

37.5 Climates of Disaster

Climate reconstructions have allowed historians to better understand how catastrophic weather events affected colonial territories in South Asia, Africa, the Americas, and Australia. Whether drought, flood, famine, or hurricane, the study of climate disasters can reveal the ways in which colonial societies understood and responded to extreme weather events. Networks of information exchange, as we have seen, enabled colonial observers to show that such seemingly local catastrophes were part of larger climate patterns, which indicated the presence of global phenomena such as ENSO.

Climate conditions, rather than flawed imperial policies, were blamed for social unrest and economic conditions. Georgina Endfield and Sam Randalls argue that despite imperial efforts to domesticate colonial climes through the management of peoples and places, such recourse to climate as the cause of colonial instability suggests the persistence of climate as an agent of empire.[54] They cite the example of a British official, who observed of the Gujurati at the height of the catastrophic Indian famines of the late nineteenth century, '[He] is a soft man … accustomed to earn his good food easily. In the hot weather, he seldom worked at all and at no time did he form the habit of continuous labour.'[55] This example, drawn from Mike Davis' *Late Victorian Holocausts*, suggests that Indian people suffered from climate-induced apathy that was the cause of the scale of the disaster.[56]

The age of empire provides fertile ground for the study of extreme weather events and their role in the political and social upheavals of the long nineteenth century. Sherry Johnson, for instance, has shown the way El Niño, La Niña, and hurricane activity combined to help transform Atlantic economies, contributing to the outbreaks of the American War of Independence, the French Revolution, and the Haitian Revolution (see Chap. 24).[57] Richard Grove has likewise examined the role that the ENSO events of 1789–93 played in the French Revolution, as well as droughts and famine in India, Africa, and Australia (see Chap. 34).[58] In Cuba, Louis Pérez argues, the destruction wrought by a series of hurricanes in the 1840s helped to break down Spanish colonial rule.[59] Acknowledging the impact of climate on these regions is not to imply determinism. Showing the 'dynamic interplay' of climate, human, and other non-human factors instead moves the focus of climate studies away from a deterministic tradition to reveal the complexity of climate–human interactions in the past.[60]

Applying concepts from social science research, such as vulnerability, adaptation, and resilience, has offered historians new ways to analyse colonial experiences of climate variability. The lens of vulnerability encourages the study of extreme weather events in terms of social, rather than natural, processes. Differences in vulnerability, which expose some people to more climate risk than others, are the product of complex processes that historians can unravel in order to discern the interactions of human activities and the environment over time.[61] Georgina Endfield deploys this approach in her study of droughts and floods in colonial Mexico at the turn of the nineteenth century. There she shows how communities attempted to reduce their vulnerability to the impacts of climate variability through strategies of land and water management.[62] Contemporary concerns about anthropogenic climate change have imbued this research with a new sense of urgency to better understand the social and political consequences of short- and long-term changes in climate.

37.6 Conclusion

Despite the decolonisation of the Cold War era, the rise of climate change discourse has helped to ensure that agential understandings of climate have continued into the twenty-first century. Mike Hulme has argued that we face a new form of climate determinism—what he has termed 'climate reductionism'—in which human agency is confined by possible future climates.[63] Within this schema of neo-climate determinism, relics of empire persist. The tropics remain pathologised as a space of disaster and disease. This construction of tropical climates serves to portray many former colonies as destined for catastrophe.[64] Anthropogenic climate change has fuelled this image, converging with development critiques to conjure a so-called 'tropic of chaos': 'a belt of economically and politically battered post-colonial states … [which compose] that violent and impoverished swath of terrain around the mid-latitudes of the planet'.[65] Such a description suggests that the legacy of European and North

American empires continues to manifest itself in the ways in which anthropogenic climate change is experienced around the globe. Former colonies of the Global South will be among those regions worst affected by the increased frequency and magnitude of extreme weather events on a warmer planet, even though these countries and their peoples have contributed little to global warming, as Dipesh Chakrabarty has pointed out.[66]

Notes

1. Bayly, 2004.
2. Fleming and Janković, 2011.
3. Heymann, 2010.
4. Endfield and Randalls, 2015.
5. Golinski, 2007; Janković, 2001.
6. Feldman, 1990.
7. Adamson, 2015, 102; Williamson, 2015.
8. Anderson, 2005, 257.
9. Anderson, 2005, 83–130.
10. Grove, 1997, 1998; Davis, 2001.
11. Heymann, 2010, 587.
12. Humboldt, 1845, 96.
13. Heymann, 2010, 587.
14. Humboldt, 1836.
15. Cited in Coen, 2010, 846, 2011; Heymann, 2010, 588.
16. Mahony, 2016, 29–39.
17. Arnold, 1996, 148.
18. Fleming, 1998, 11–20.
19. Jennings, 2006.
20. Livingstone, 2002, 160.
21. Arnold, 1996, 142. Fears of tropical climes were not universal. See Livingstone, 2002, 161.
22. Colonel Gordon, cited in McNeill, 2010, 277.
23. Curtin, 1998, 4.
24. Harrison, 1999, 116.
25. Harrison, 2000, 57.
26. Chakrabarti, 2014, 68; Livingstone, 2002, 160.
27. Jennings, 2006, 3.
28. Kennedy, 1996.
29. Arnold, 1996, 160; Jennings, 2006, 19.
30. Jennings, 2006, 19–20.
31. Dr Smith, cited in Hancock, 1840, 86.
32. Arnold, 1996, 160.
33. Chakrabarti, 2014, 144–47.
34. For example, Anderson, 2006.
35. Grove, 1995, 3.
36. See Cushman, 2011.
37. See Grove, 1993.
38. Beattie, 2012. See also Bennett, 2011.

39. Davis, 2001.
40. Ford, 2004, 2008.
41. Beattie, 2003; Showers, 2005.
42. Maury, 1854, 54–96; Woodruff et al., 1987. See also García-Herrera et al., 2005.
43. Können and Koek, 2005; Wilkinson et al., 2011; Allan et al., 2011; Wheeler et al., 2006.
44. Nash and Adamson, 2014, 131.
45. See Williamson et al., 2015.
46. Allan et al., 2002; Können et al., 1998.
47. Nash and Adamson, 2014.
48. For southern Africa, see Endfield and Nash, 2002; Kelso and Vogel, 2007; Nash and Endfield, 2002; Nash and Grab, 2010; and Nash et al., 2016. For western India, see Adamson and Nash, 2014; Adamson, 2015.
49. Chenoweth and Divine, 2008; Berland et al., 2013.
50. Warren, 2015; Nash et al., 2015; Endfield, 2008.
51. For example, see Fenby and Gergis, 2013; Gergis and Ashcroft, 2013; Gergis et al., 2012.
52. Quinn et al., 1987.
53. Gergis and Fowler, 2009.
54. Endfield and Randalls, 2015, 38.
55. Cited in Endfield and Randalls, 2015.
56. Davis, 2007, 172.
57. Johnson, 2011.
58. Grove, 2005.
59. Pérez, 2001. See also Smith, 2012.
60. Carey, 2012, 237.
61. Hilhorst and Bankoff, 2004.
62. Endfield, 2008.
63. Hulme, 2011.
64. For the colonial construction of vulnerability, see Bankoff, 2003.
65. Parenti, 2011, 9, 11.
66. Chakrabarty, 2009, 2012, 2014.

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CHAPTER 38

From Climatology to Climate Science in the Twentieth Century

Matthias Heymann and Dania Achermann

38.1 Introduction

Research on climate changed fundamentally during the twentieth century. Scientific advances included the investigation of higher layers of the atmosphere, an improved physical understanding of atmospheric processes, the rise of atmospheric and climate modeling, and an observational revolution. These and other advances were facilitated by a host of new research technologies such as aircrafts, balloons and radiosondes, radar, rockets, satellites, and computers. They were also influenced by changing political and cultural contexts during the world wars and the Cold War and, from the 1970's onwards, by environmentalism and rising environmental interest. Not only did a new science of climate emerge, but the understanding of and interest in climate also changed radically. The meaning of the term climate changed from a more or less stable characteristic condition of local places to a complex global phenomenon subject to changes in time.

Global perspectives on climate have existed since ancient times. During the nineteenth and early twentieth centuries, however, climatology was characterized by a focus on human scales and human affairs. The Humboldtian conception of a mutual relationship between climate and human beings (see Chap. 37) retained primacy until the mid-twentieth century. Climate change on large spatial and temporal scales first attained prominence during the mid-nineteenth century as scientists discovered past ice ages and debated their causes. A fundamental shift of priorities from a "geographical" to "physical" understanding, from local concern to global science, was underway by the late nineteenth century and became hegemonic in the postwar era. This globalization became

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particularly pronounced in the development of climate models, which for technical reasons had to disregard small geographical scales (see Chap. 13).

38.2 "Classical Climatology" and its Expansion

Climatology during the late nineteenth and early twentieth centuries was not a homogeneous discipline. It involved data and methods from various fields including meteorology, geography, history, and physics.[1] Nevertheless, it retained the core concepts and interests of Alexander von Humboldt, the basis for what came to be known as "classical climatology."[2] According to Humboldt's definition, climate represented "in the most general sense all changes in the atmosphere which noticeably affect the human organs," such as temperature, humidity, barometric pressure, wind speed, and wind direction.[3] This definition of climate was linked to specific locations, to the surface of the Earth, and to human experiences. It represented a holistic concept of climate that involved all atmospheric phenomena affecting the human senses, and included the investigation of human impacts on climate, such as deforestation and urbanization (urban climatology), as well as climatic impacts on human health (medical climatology) and on agriculture and forestry (bioclimatology and agro-meteorology).[4]

Climatology at the end of the nineteenth century represented a fairly established discipline, with a range of shared interests and methodologies. Khrgian contends that "'classical climatology' put an end to the diversity, arbitrariness, and dilettantism of meteorological observation."[5] Nevertheless, within its disciplinary frame and focus on local empirical diligence, climatology accommodated a range of diverse interests. Humboldt, celebrated for his orientation on human experience and affairs, received particular acclaim for his investigation of climate on large spatial scales. Based on a series of measurements, he applied the method of mean values and invented the concept of isotherms. From 730 observations of daily minimum and maximum temperatures all over the Northern Hemisphere he calculated annual temperature averages and constructed his famous map of isotherms of the Northern Hemisphere, which showed that lines of average temperatures were not parallel to the equator (see Chap. 36).[6] With the averaging of series of temperature data, Humboldt constructed an ingenious and objective measure for climatic features that allowed global mapping and comparison, one of the accomplishments that earned him the title of "pioneer of globalization."[7]

Climatologists such as the Austrian Julius von Hann, head of the Central Office for Meteorology and Geomagnetism in Vienna, and the Russian-German Wladimir Köppen, head of the German Marine Observatory in Hamburg, adopted Humboldt's conception of climate and made it the basis of a rigorous empirical science. Their practice of climatology consisted of an effort to systematically collect and evaluate series of meteorological data and to analyze their broader relationships in order to identify the specificities of local and regional climates. Hann's *Handbook of Climatology*, first published in 1883 and expanded in later editions, defined the major features of "classical climatology" and its research program, and it became a standard reference for what came to be called the "averaging climatology."[8]

Hann was very clear about the difference between meteorology and climatology. Meteorology explained atmospheric phenomena in terms of physical laws and discovered the causal relations among sequences of atmospheric phenomena. "Meteorology essentially is theorizing; she decomposes the complex of atmospheric processes to link partial phenomena to physical laws." Climatology, in contrast, was empirical, descriptive, and not reductionist: "her task thereby is to provide a preferably lively image of the interaction of atmospheric phenomena at one location." Furthermore, in climatology, "those meteorological phenomena have priority that bear the greatest influence on organic life on earth."[9] Köppen concurred. In climatology, unlike other disciplines, "theories … step back, the ordered collection of facts is the prevailing goal."[10] Climatology needed comprehensive data collection to discern patterns and rules and to bring systematic order to the wealth of local information.

38.3 The "Conquest of the Third Dimension"

Another characteristic of "classical climatology" was that it was two-dimensional, focused only on climate at the Earth's surface. This focus was determined by technical difficulties in collecting data in the upper atmosphere, and consolidated by climatology's association with geography. As Köppen described it, climatology was "a surface-oriented discipline." While he demanded more data from higher layers of the atmosphere, particularly for improving the physical understanding of climatic processes, he admitted that climatologists might regard such efforts as not part of climatology.[11] "We have, herewith, reached a boundary where the geographical element stands back in favour of the physical [and] 'climatology' passes into 'meteorology in a narrower sense'."[12] In the much expanded, fifth edition of *Handbuch der Klimatologie* (Handbook of Climatology), published between 1930 and 1936, Köppen and his younger colleague Rudolf Geiger defined the scope of the work as the up-to-date collection of "meteorological knowledge … that is tied to geographical aspects"—in other words, a geography of meteorological and climate knowledge.[13] A paradigmatic achievement in this vein was Köppen's influential climate classification and construction of global maps of the distribution of climates, which are still widely used.[14] Using this classification, Köppen ordered climatic features such as arid, tropical, temperate, and cold along with a range of further descriptors, and he investigated and mapped their geographical distribution (see Chap. 36). This classification reflected the methodology of regional geography of that time, which treated geographical regions and settling societies as independent from each other and focused on the human–environment relation.[15] The oceans and upper atmosphere were neither inhabited nor covered by instrumental data, and were therefore less relevant.[16]

Attempts to investigate and understand the upper atmosphere had been discussed since the 1700s. In the nineteenth century, Köppen and Hann both helped to consolidate a two-dimensional 'classical climatology' and, at the same time, emphasized the need to expand meteorological observation in higher layers of the atmosphere. Observational evidence from higher altitudes was difficult to gather and in very short supply. Ideas about larger-scale processes of atmospheric circulation mainly came from theoretical considerations.[17] During the late 1800s, a growing number of mountain weather stations and observations made with the help of balloons and kites gave rise to a new climatological subdiscipline later named "aerology" (after Köppen's suggestion).[18] With the rise of aviation, especially during and after World War I, data from the upper atmosphere attracted growing interest. Regular operation of kites, balloons, and aircrafts to assemble data was expensive, however. Measurements in various parts of the world remained unsystematic and were rarely published.[19] Starting in the 1930s, with the availability of measurement sensors equipped with a radio communication device—so-called radiosondes—data coverage quickly improved. These devices sent meteorological data from balloons directly to ground stations. Early radiosondes reached altitudes of up to four kilometers. By the end of World War II, a rapidly growing number of devices sent an increasing amount of data from up to fifteen kilometers above sea level.[20]

Starting in 1935, German meteorologist Richard Scherhag constructed high-altitude weather maps based on upper atmosphere data. Such maps were an entirely novel tool, which aided the preparation of German daily weather forecasts.[21] Scherhag also discovered strong winds at altitudes of about five kilometers. Soon named "jet streams" by German meteorologist Heinrich Seilkopf, they became a focus of investigation in German meteorology and climatology. Due to geographic, language, and political barriers, the discovery of jet streams reached the USA only much later.[22] During World War II, forecasters at the German "Reich Weather Service" possessed upper-air charts for the 500, 225, 96, and 40 hectopascal levels (equivalent to ~5.5–22 km altitudes): data that proved decisive for Air Force operations during the war.[23]

The unprecedented amount of high-altitude data collected with modern instruments opened new pathways for climatology. A perspective encompassing the whole atmosphere and the physical relations of extended weather systems helped explain important climatic phenomena such as the monsoon. After World War II, Hermann Flohn, one of the leading German climatologists in the twentieth century, and Swedish meteorologist Sverre Petterssen had sufficient data to develop a consistent theory of planetary circulation.[24] Meteorologists of the Norwegian Bergen School around Vilhelm Bjerknes, to which Petterssen belonged, had already promoted this dynamic perspective of the atmosphere. Swedish meteorologist Tor Bergeron, another member of the Bergen School, called it "dynamic climatology."[25] Only the lack of high-atmosphere data had hindered climatologists from elaborating and applying it before. In Flohn's words the "conquest of the third dimension" had begun.[26]

The "conquest of the third dimension" and the investigation of the atmospheric circulation represent a key moment in the history of climatology. It not only proved immensely fruitful for the understanding of many climatic phenomena. It also indicated a significant change of the very concept of climate, from a geographical idea linked to specific locations to a dynamic concept related to the whole atmosphere. The new data helped climatologists to develop causal understandings of climatological phenomena, something increasingly demanded of geographical disciplines as the descriptive approach came under attack.[27] Accomplishments such as Köppen's climate classification met criticism because they were purely descriptive. A new generation of geographers such as Walter Christaller questioned the static traditions of regional geography and demanded recognition of larger-scale interactions and of temporal and causal relations.[28]

Flohn recognized a deeper consequence of this shift: it cut loose climatology from human perceptions and scales, which had constituted part of the discipline and its identity. He justified this shift with particularly strong words, arguing that climatologists had to oppose "this one-sided human-oriented, anthropocentric narrowing of a general valid concept … There are many things in our envelope of air, which only have minor or no relation to humans, but which for a consideration of the causes of weather … we badly need."[29]

However, this shift to the large scale by no means entailed an elimination of the small scale and human affairs. First, climatology kept its dedication to empirical data collection and local detail, upon which large-scale knowledge would be built. Second, large-scale knowledge served to inform local weather and climate conditions, and it supplemented human-centered disciplines such as bioclimatology, agro-meteorology, and medical climatology. Third, many meteorologists and climatologists continued to impart a personal and emotional relation to weather and climate. Scherhag, for example, emphasized his keen interest in personal weather observation and local weather phenomena to his students and sought to link personal observation with theoretical knowledge of large-scale weather systems.[30] If climatology had expanded to phenomena beyond human perception, it had not disregarded interest in the local and human scale.

38.4 Investigation of Climatic Changes

Starting in the mid-nineteenth century, the question of ice ages and their causes sparked numerous theories and fierce debates. Interest in climate change on geological timescales occupied naturalists, geologists, astronomers, and physicists.[31] The question of ice ages had little immediate impact on climatology, however, which was preoccupied with climates on much smaller scales.[32] Geographer and climatologist Eduard Brückner pursued comprehensive investigations of climatic changes around the world on much smaller temporal scales since 1700. He used the full range of growing climate data collections to analyze climatic variations, and he postulated a global thirty-five-year climatic cycle.[33] The investigation of long-term and secular changes in climate had a long history, but a full understanding of these changes had eluded climatologists.[34] Discussions on changing climates resurfaced when investigations of glacier volumes by Swedish glaciologist Hans W. Ahlmann and observations at meteorological stations showed a significant warming trend in Northern Europe between about 1920 and 1940.[35] This observation took the climatological community by considerable surprise.

Even in the first half of the twentieth century, climatologists were reluctant to accept global climate change, as evidenced by the reaction to British engineer Guy Callendar's theory of global warming. Building on work about the greenhouse effect by Joseph Fourier, John Tyndall, and Svante Arrhenius during the nineteenth century, Callendar suspected that rising levels of carbon dioxide were raising global temperatures. He completely reworked the theory of infrared radiative transfer, estimated the rise in carbon dioxide levels, calculated warming due to the enhanced greenhouse effect, and related his calculations to collected observational data on surface temperature trends.[36] The majority of climatologists, however, questioned the explanatory power of his conclusions or objected to such far-reaching claims. These objections included, for example, Callendar's neglect of atmospheric processes such as heat transfer and of temperature inversions and modifications of the general circulation. George Simpson, director of the Meteorological Office in London, concluded that the increase of carbon dioxide and temperature "must be taken as rather a coincidence." The observed rise in temperature "was probably only … one of the peculiar variations which all meteorological elements experienced."[37] Climatologists, immersed in a tradition of studying a great wealth of detailed data, still put great emphasis on local diversity and difference and remained highly suspicious of generalized explanations such as global climate change.[38] It was to take another three decades until carbon dioxide was undisputedly acknowledged as a potential climate change factor.

38.5 Making Climatology a Physical Science: The Physical Understanding of the Atmosphere

Although classical climatology of the nineteenth and early twentieth centuries was open to physical ideas and reasoning, it remained, in essence, a geographical science. Many of its advocates, such as von Hann and Köppen, contributed to the application of physical laws and quantitative understanding of climatic and weather processes.[39] The investigation of the physics of the atmosphere, however, was rather a marginal endeavor in climatology and usually left to meteorology. There was a tension between the empirical, holistic ambitions of climatologists and the theory-oriented, reductionist approach of physicists, who had to disregard particulars in order to arrive at quantifiable causal relations cast in mathematical equations. Climatology as a discipline belonged to and was taught in geography departments and programs; furthermore, its practitioners worked at weather services in data collection and evaluation for practical tasks and research.

Since climatologists were reluctant to turn to physics, physicists instead took up climatology and meteorology. Most notably, Norwegian physicist Vilhelm Bjerknes developed a foundational framework for the quantitative description of atmospheric processes, hoping to make meteorology an exact science of the atmosphere. In 1904, he published a famous paper laying out the basis for a solution to the problem of weather prediction. Seven non-linear partial differential equations including seven physical parameters—the so-called "primitive equations"—described in principle all atmospheric processes and meteorological states at any point in time and space.[40] An analytic solution to these equations did not yet exist. Bjerknes instead applied approximate graphical methods to integrate the equations. In 1917, Bjerknes moved to Bergen, where he built up a weather forecasting group, the aforementioned famous Bergen School of meteorology. The Bergen School developed dynamic concepts to better understand weather phenomena, namely a new cyclone model and the "polar front" theory.[41] Bjerknes' work was widely praised and much promoted, not least by Bjerknes himself and his students, so that it has been celebrated as the beginning of modern scientific meteorology.[42] His work was a decisive step in advancing a physical theory of the atmosphere, even though he had built on the work of others and meteorologists such as the Austrian Heinrich von Ficker had pursued similar ideas (Fig. 38.1).[43]

Bjerknes' theoretical work also excited many meteorologists because it laid a theoretical foundation for quantitative weather prediction based on physical laws. During World War I, British scientist Lewis Fry Richardson attempted an approximate, or "numerical," solution to Bjerknes' primitive equations. This approximation required a transformation into finite difference equations for the calculation of averaged values on a spatial grid. The solution of the problem required enormously tedious and lengthy computations. It took Richardson six weeks to calculate a weather prediction on two grid elements for a specific day in 1910. The effort failed dramatically due to numerical instabilities. Nevertheless, in principle, Richardson's approach was valid, even if much too time consuming for practical application.[44]

The complexity of Bjerknes' equations and the extravagant expense of solving them by approximation concealed at the same time a loss of complexity. Moreover, they heralded a deeper transformation in climatology: physical parameters and their causal relations cast in purely mathematical language were entirely stripped of human elements. The intricate complexities of the interactions and causal relations between the human world and climate dropped out of the equation, literally and figuratively. Human-oriented climatology was replaced by physical reductionism, which drew a neat boundary between natural and human systems. This transformation had been underway during the nineteenth century, but it was accelerated by the work of the Bergen School, and would be complete by the mid-twentieth century.

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} + fv - \frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - fu - \frac{1}{\rho}\frac{\partial p}{\partial y}$$

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - g - \frac{1}{\rho}\frac{\partial p}{\partial z}$$

$$\frac{\partial \rho}{\partial t} = -u\frac{\partial \rho}{\partial x} - v\frac{\partial \rho}{\partial y} - w\frac{\partial \rho}{\partial z} - \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)$$

$$\frac{\partial p}{\partial t} = -u\frac{\partial p}{\partial x} - v\frac{\partial p}{\partial y} - w\frac{\partial p}{\partial z} - \frac{C_p}{C_v}p\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)$$

$$\frac{\partial T}{\partial t} = -u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} - w\frac{\partial T}{\partial z} - \frac{RT}{C_v}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)$$

Fig. 38.1 Bjerknes' so-called primitive equations in modern mathematical notation. (Reproduced from Amy Dahan Dalmedico, "History and Epistemology of Models: Meteorology (1946–1963) as a Case Study," *Archive for the History of Exact Sciences* 55 (2001): 398. Permission of Springer)

38.6 The Rise of Atmospheric and Climate Modeling

Driven by World War II and the Cold War, military interests and military funding helped to make atmospheric equations work on one of the first digital computers. In 1950, using drastically simplified versions of Bjerknes' primitive equations, a team around mathematician John von Neumann and meteorologist Jule Gregory Charney simulated "weather by the numbers": the first attempt at numerical weather prediction on a computer.[45] The rise of numerical weather prediction also set the course for the simulation of climate, which began with Norman Phillips' bold experiment in 1955. Phillips, a member of von Neumann and Charney's team, simulated with a further simplified version of the weather model a forecast period of thirty days. While this was only an experiment and not a simulation based on a realistic situation, it turned out to be surprisingly successful. Phillips' model experiment reproduced patterns of the atmospheric circulation. He concluded that "the verisimilitude of the forecast flow patterns suggests quite strongly that it [the model] contains a fair element of truth."[46] The experiment was path-breaking in two ways: first, it showed that computer-based simulation could serve to simulate atmospheric phenomena; second, it proved that "[n]umerical integration of this kind … give[s] us [the] unique opportunity to study large-scale meteorology as an experimental science," as the British meteorologist Eric Eady concluded after a presentation by Phillips at the Royal Meteorological Society in London in 1956.[47]

So-called general circulation models (GCMs) became the basis for future climate models and served as virtual laboratories to investigate atmospheric processes (see Chap. 13). Initially, this research field remained small and only a few groups built and experimented with climate models. The first global circulation models represented a much simplified and idealized atmosphere with a resolution of approximately 1000 kilometers. Furthermore, computers represented a very new technology, expensive and hard to acquire. In Europe, Sweden first developed its own computer (called BESK) and weather model, which became operational on a routine basis in December 1954, half a year earlier than its US counterpart.[48] Britain, Japan, Germany, and many other countries followed suit within a few years, although often hampered by lack of computer power. In Germany, the first model calculations were even performed manually by two students and two female clerks, and later on computers in the USA and France. The German Weather Service did not receive its first computer until November 1965.[49] Numerical analysis radically changed meteorological practice from "qualitative description" to "quantitative computation."[50] Even though computer models simulated a highly simplified representation of the atmosphere, climatologists were hopeful that they could soon "ask more specific questions regarding the details of the evolution" of weather and climate.[51]

In the 1960s, only a few groups in the USA built and experimented with climate models. During the 1970s, climate modeling expanded rapidly outside the USA as well (see Fig. 38.2). Climate modeling mainly served scientists as a research tool to improve understanding of atmospheric and climate processes. At the same time, the problem of carbon dioxide emissions and the question of global warming began to receive attention in parts of the scientific community. By the early 1960s, measurements by Charles D. Keeling had established that carbon dioxide levels in the atmosphere were rising. Influential scientists such as oceanographer Roger Revelle began to push the issue with the US government.[52] William W. Kellogg, a leading American climate scientist and consultant of the World Meteorological Organization (WMO), helped put the global warming problem on the international scientific and political agenda. As early as 1970, Kellogg suggested using climate models for climate prediction, even though he was aware that these models had to use simplifications and had not yet proved their reliability.[53] "[T]here is the haunting realization that man may be able to change the climate of the planet Earth," he wrote. "This, I believe, is one of the most important questions of our time, and it must certainly rank near the top of the priority list in atmospheric science."[54]

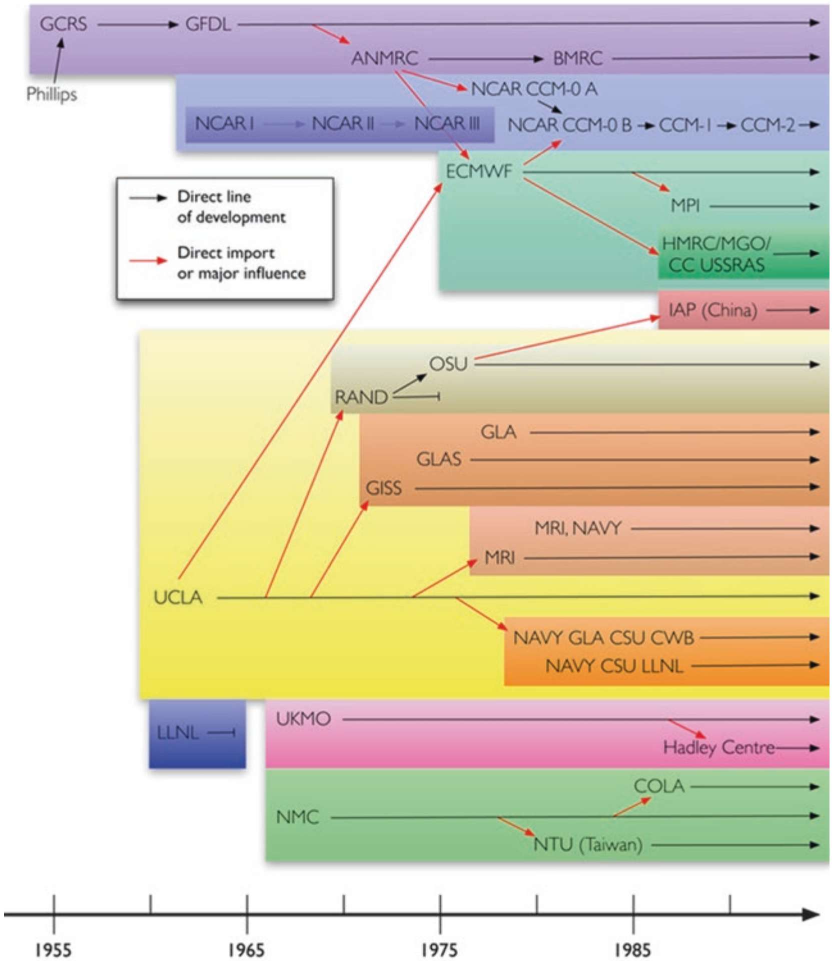

Fig. 38.2 GCM family tree (credit: Paul N. Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (Cambridge, MA: MIT Press, 2010), 169)

In a 1977 report commissioned by the WMO, Kellogg published one of the first long-term climate projections based on the results of climate simulations (see Fig. 38.3). Two years later, the US National Academy of Sciences commissioned a team led by Jule Charney to report simulation results of the newest climate models. This so-called "Charney report" concluded: "If carbon dioxide continues to increase, the study group finds no reason to doubt that climate changes will result and no reason to believe that these changes will be negligible."[55] In the same year, the WMO World Climate Conference held in Geneva came to similar conclusions in its "Final Declaration": "It is possible that some effects on a regional and global scale may be detectable before the end of this century and become significant before the middle of the next century."[56] While concern about

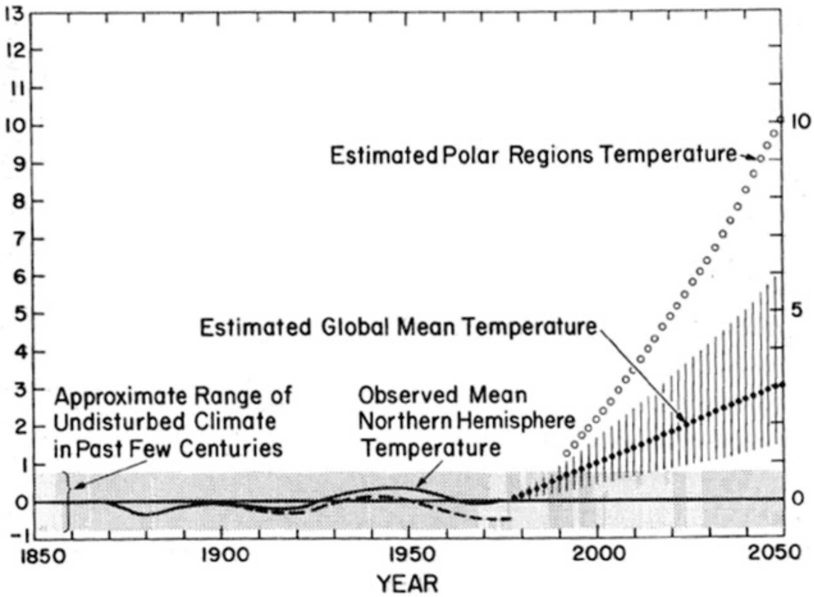

Fig. 38.3 Kellogg's climate projection (Source: William Kellogg, *Effects of Human Activities on Global Climate* (Geneva: World Meteorological Association, 1977), 24. Reproduced with permission of the WMO)

global warming had increased, it was still highly contested. Notably, the global observation of temperature trends did not show warming but rather a tendency of cooling between the late 1940s and the late 1970s (see Chap. 25).

In 1981, climate scientist James E. Hansen published his first long-term model projections in the leading journal *Science*.[57] This article encountered significant criticism from some climate scientists, because Hansen based his claims on an admittedly simple model involving tremendous uncertainties. Nevertheless, Hansen's results almost exactly resembled the projections published more than thirty years later in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Both Hansen's simple model and the result in the IPCC report, which was based on the use of forty-two climate models, predicted a warming of between 1 and 4 °C by the year 2100 and displayed very similar lower and higher boundaries of the different scenarios (see Fig. 38.4). Hansen's study heralded the future direction of climate models as tools in the emerging political debate over global warming (see Chap. 14).[58]

38.7 Data Networks and Satellites: The Observational Revolution

The evolution of General Circulation Models into a major tool for investigating climate was also linked to the development of new technologies of measurement. These technologies provided the huge increase in data required for

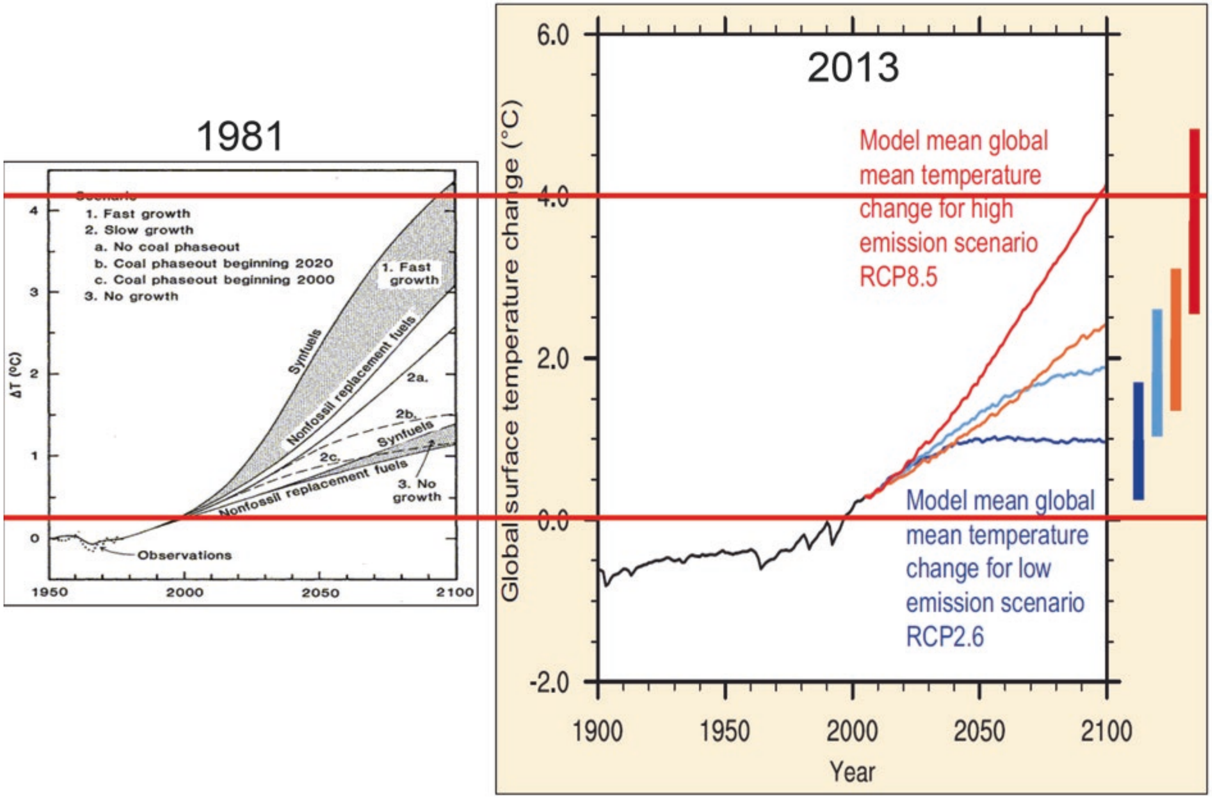

Fig. 38.4 Climate projections to the year 2100 by Hansen et al., 1981, 963 and by the IPCC, 2013, 1037. Both graphs are positioned to allow direct comparison. The red zero-line is taken for the year 2000, as in the IPCC graph (whereas Hansen et al. put for the year 1990). The range of temperature rise for different emission scenarios is almost exactly the same

climate modeling and simulation as compared to traditional approaches in meteorology and climatology. The Soviet Union launched the first satellite, "Sputnik," in 1957; during the Cold War "space race" that followed, the USA and USSR sent more and more satellites into space. While primarily of military and political impetus, these satellites soon proved to be of interest for meteorology, too. With the launch of the first successful weather satellite, TIROS-1, in 1960, satellites became indispensable for meteorological and climate research. They collected data about the heat balance of the Earth, the chemical content of the atmosphere, clouds, precipitation, and so on.[59] Along with rockets, satellites vastly expanded the reach of measuring instruments previously limited to ground stations, radiosondes, balloons, kites, and airplanes.[60]

Gathering data about the global atmosphere was also a primary goal of the Global Atmospheric Research Program (GARP) between 1967 and 1982. GARP was a response to two resolutions of the United Nations General Assembly in 1961 and 1962. These resolutions demanded intensified research in atmospheric and climate science, as well as further development of weather forecast capabilities. During the fifteen years of GARP, weather services and scientific institutions of more than twenty participating countries, with the help of vessels, radar, airplanes, and satellites, collected data with worldwide coverage. Some subprojects included up to sixty contributing countries.[61] Weather and climate models, which depended on global data, set the priorities and standards for data gathering. The quick expansion of climate modeling after 1970 was owed not least to the availability of more and better data.

38.8 Earth System Analysis

Early General Circulation Models were principally energy and moisture models. Solar radiation provided energy and drove wind circulation systems. Evaporation of water consumed energy, condensation of water set latent energy free. Obviously, the atmosphere is not a closed system: energy fluxes and hydrological cycles depend on exchange processes with other Earth systems, such as the oceans and other water bodies (hydrosphere), soils at the surface of the Earth (pedosphere), living beings (biosphere), and the height and density of vegetation—if at this point only as physical objects, not as interacting biological organisms. Two decades later, vegetation became fully represented as an interacting factor that not only influenced climate but also reacted to it. These types of models simulated the full carbon dioxide cycle including the absorption of carbon dioxide by plants (photosynthesis). Because they modeled the full Earth system, they came to be called "earth system models."[62]

Historian of science Amy Dahan Dalmedico has called this type of modeling "anti-reductionist." She explains that "Scientists … have managed, in just a few short years, to develop a methodology that … provides a de facto response to the holistic aspiration—an analytic process that moves towards complexity … This methodology is an example—obviously incomplete at this moment in time—of what could be conceived as a concrete 'anti-reductionist' analytical method."[63] Nevertheless, the claim that the increasing sophistication of (inherently simplified) models has actually overcome reductionism remains contentious.[64]

The conception of Earth as a complex and interconnected system gained momentum with the rise of systems theory during the Cold War and with rising environmental awareness during the 1960s. A notable example was the "Gaia hypothesis" proposed in 1974 by English chemist and biophysicist James E. Lovelock and American microbiologist Lynn Margulis. Lovelock and Margulis proposed "a new view of the atmosphere, one in which it is seen as a component part of the biosphere rather than as a mere environment for life."[65] They suggested understanding the biosphere—"the total ensemble of living organisms"—as a single living entity, which interacts with the inorganic environment. According to this idea, the biosphere acted as an "active adaptive control system," regulating the conditions for life and maintaining its equilibrium on Earth. The biosphere, including the evolution of species, affected the chemical composition, surface pH values, "and possibly also climate."[66] Hence, the Earth appeared as a self-regulating organism of its own. Lovelock and Margulis could not provide any proof for this hypothesis and were heavily criticized by fellow scientists, even as they were enthusiastically received in the public sphere.[67] Controversial as it was, the "Gaia hypothesis" reflected the growing interest in conceiving of the Earth as a complex system of interacting entities—an interest that Earth system models neatly accommodated.

The challenge, however, was enormous. While the atmosphere was already frighteningly complex, climate scientists now had to become masters of Earth system science (see Fig. 38.5), a term coined in 1985 by Francis P. Bretherton, director of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado.[68] Computer models were the major tools in this endeavor. They could, in principle, be expanded in complexity by adding further submodels. The "one model to fit all" strategy offered a means to create "virtual impact laboratories": artificial Earth systems in the computer, with which scenarios of global change could be simulated.[69] German climate scientist Hans Joachim Schellnhuber considered Earth system models a revolutionary accomplishment, worthy to be called a "second Copernican revolution."[70] In contrast to telescopes and microscopes in the sixteenth and seventeenth centuries, which magnified the object of investigation, an Earth system model represented a "macroscope," a tool which miniaturized the object and created "an objective distance from their specimen."[71]

On the other hand, the assembly of submodels under conditions of limited computer power required pragmatic reductionist strategies. Each of these models had to be reduced to selected algorithms and, hence, to be simplified "to a ridiculous extent."[72] In addition, many Earth system processes were not entirely understood. Earth system models became increasingly loaded with complexity and uncertainty and their computational processes increasingly inscrutable. While the holistic aspirations of Earth system models gave rise to confidence that these models represented the Earth system adequately, their

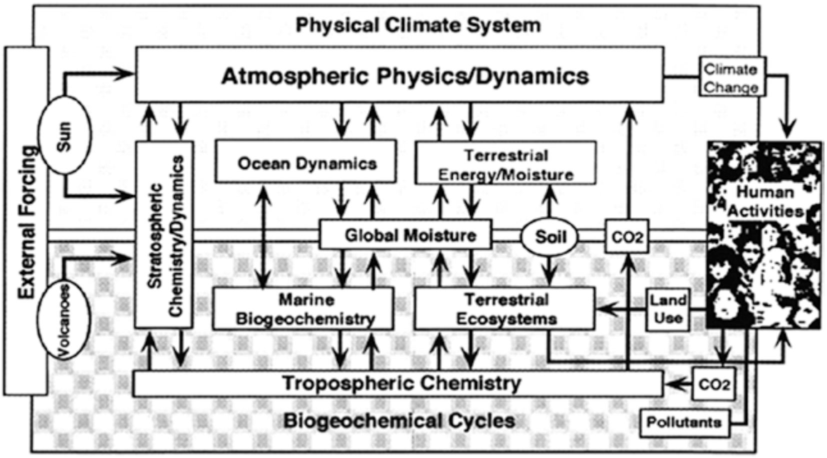

Fig. 38.5 The Bretherton Diagram of the Earth system. Source: NASA, 1986, 19

intricacies rendered "analytic understanding of complex models of climate either extremely difficult or even impossible."[73] Francis Bretherton put it in a nutshell: "the more complex the model the messier the garbage."[74] In spite of such challenges, Earth system science expanded quickly and became the backbone of climate science. Due to its global focus, geographer Nicholas Clifford described Earth system science as "a microcosm of the globalization syndrome."[75]

38.9 Ice Core Research and Paleoclimatology

Paleoclimatology, the reconstruction of past climates from the archives of nature, also played an important role in the development of climate science in the twentieth century (see Chap. 3). Due to the breadth of research objects and methods, paleoclimatologists come from disciplines that range from glaciology, geology, chemistry, and physics, to biology, astronomy, and archeology. Paleoclimatology thus exemplifies the highly interdisciplinary character of modern climate research.

The study of ice, in particular, became one of the major pillars of climate change research. Its ascent is closely tied to the development of climate science and the shift of priorities from a local to a global perspective. In the early twentieth century, ice was investigated as a part of glaciology or crystallography in order to find out more about the movement of glaciers, the metamorphosis of snow into ice, and the mechanisms of avalanches.[76] From the 1930s onward, digging or drilling into the ice became a basic method to study snow and ice layers, for example on glaciological expeditions to Greenland and in the Alps, while the USA, USSR, Denmark, Switzerland, and France became the most active countries in this field of research.[77]

The Danish physicist Willi Dansgaard played a key role in establishing ice core research as part of climate science. He developed a method to reconstruct past temperatures by analyzing the ratio between different oxygen isotopes in rainfall.[78] The method was based on the fact that the isotope ^{18}O evaporates more slowly than ^{16}O. Consequently, when temperatures were higher, the relative amount of ^{18}O in precipitation was higher. Dansgaard took care to emphasize that his results "depend[ed] on the climatic and geographic conditions" of the site where the samples were collected.[79] Conclusions could only be drawn for the temperature in the local area of investigation, in this case Copenhagen. Dansgaard realized that the mechanism is the same for rain as for snow. Hence, ice cores served Dansgaard as archives of oxygen ratios reflecting the temperature changes of the past. In the late 1960s, Dansgaard and his co-authors identified a correlation of oxygen ratios in a deep ice core from Greenland and "known and reported climatic changes in other parts of the world."[80] He took this finding as evidence that past temperature changes identified from ice cores reflected climatic changes not only in a local area but on a large geographic scale. In 1971, Dansgaard initiated the Greenland Ice Sheet Project (GISP) together with Swiss physicist Hans Oeschger and American geophysicist Chester C. Langway. As part of the program, the three scientists analyzed a 2000-meter-deep ice core from Greenland, containing ice from the last 150,000 years. They compared the results with data from lake sediments in Switzerland and suggested that there had been abrupt global-scale shifts in air temperature around 12,000 years ago.[81] These abrupt changes were later called Dansgaard-Oeschger events.

Paleoclimatic research became an indispensable part of climate research in two ways. First, data retrieved from paleoclimatological records, such as ice cores, documented that climate is not a stable condition but instead fluctuated during different geological and historical epochs. Furthermore, these fluctuations correlated with carbon dioxide content in the atmosphere, and in combination with responses to temperature change in ocean currents, they could occur very rapidly. In the eyes of many climate scientists, this finding added urgency to dealing with the problem of climate change. "We play Russian roulette with climate," concluded climate scientist Wallace S. Broecker in *Nature* in 1987.[82] Second, knowledge about past climate changes from ice cores and other paleoclimatic investigations became vital information for the validation and calibration of climate models. These models could only be tested by investigating their performance for the case of past climate change. Today, paleoclimatology, together with climate modeling and the empirical observation of climate based on instruments, is one of the three major pillars of evidence of ongoing climate change.

38.10 Conclusion

This chapter has analyzed major changes that the study of climate underwent during the twentieth century. These changes concerned many developments, including: a shift from a holistic understanding of climate–human relationships to reductionist systems thinking; the expansion of the scope of research from surface to space and from spatial distribution to temporal changes of climate; a change in research approaches from empirical to theoretical, from geographical and descriptive to physical and causal, and from local and regional to global; and the development of new technologies from balloons, kites, and radiosondes to computers, computer models, and satellites.

Modern climate science is not a scientific discipline in the usual sense of the word. It is a complex and highly collaborative enterprise comprising thousands of scientists representing different backgrounds, training, methods, and fields of research: meteorologists, physicists, climatologists, paleoclimatologists, glaciologists, chemists, engineers, oceanographers, geologists, hydrologists, and more. More recently, social scientists and researchers in the humanities have increasingly contributed to broader perspectives in the investigation of climate. Likewise, many branches in climate research, such as climate monitoring, Earth system modeling, and paleoclimatology, are intricately linked to each other, because the production of scientific evidence only works when these branches intersect. For example, the production of observational data requires model simulation, and model simulation requires observational data.[83] This systemic character of climate science is the reason historian of science Paul N. Edwards has likened it to a "vast machine."[84]

In this complex research field, General Circulation Modeling (GCM) and, more recently, Earth System Modeling (ESM) have emerged as the overarching domain of research. These computer models signify the place or space in which all scientific knowledge about processes relevant to climate needs to be represented and synthesized. The scientific, intellectual, and social repercussions of this relatively young and at the same time enormously influential research field are vast. In this respect, two considerations deserve particular attention: first, computers as a "phase change" in climate research; and second, climate research as a driver of globalizing reductionism.

Several authors, including Jon Agar, have argued that computers did not cause a "rupture" or "phase change" in science but rather provided new capacities for already existing approaches to solving particular problems.[85] Philipp Lehmann has made a similar claim for the role of computers in climatology. Conceptually, he has argued, much of postwar climate science was in place before the era of computers and "not premised on the availability of new technologies of data analysis."[86] On the other hand, there is ample evidence that computer modeling and simulation have fundamentally changed practices of knowledge production, the form and content of knowledge, and its claims to truth in many areas of research.[87]

Climate science is a particularly conspicuous example. The rise of climate modeling and simulation played a decisive role for the understanding of climate, the very meaning of the term climate, and the authority and social significance that it attained in the postwar period.[88] Climate science at the end of the twentieth century pursued different interests and different types of knowledge, marginalizing the approaches and preoccupations of pre-war climatology. The conceptual basis of physical climate science was seeded and developed in the pre-war era. After World War II, however, successes in climate modeling and simulation, particularly the numerical solution of partial differential equations, facilitated a fundamental redefinition of climate research based on computers. This redefinition not only shifted research practices and standards; it was also developed and pursued by scientists, including theoretical meteorologists and physicists, from outside the original climatology research community.[89] These innovations, along with the predominance of the physical and marginalization of the geographical research tradition, represent a "phase change" in the investigation of climate, rather than just an expansion or diversification of climatology.[90] It is unlikely that this hegemony of the physical approach to climate would have been established without computers.

Computer-based climate and Earth system models pushed and shaped globalizing agendas. Measurement technologies such as satellites and satellite observation constructed a "global gaze."[91] Globally distributed and connected monitoring stations established what historian of science James R. Fleming has called a "planetary-scale fieldwork."[92] Ice core drilling techniques opened up 800,000 years of climate history.[93] Climate science, in short, adopted a path of globalizing reductionism. That is, by the close of the twentieth century, it operated on large spatial and temporal scales, putting priority on global knowledge and marginalizing small-scale measurements and changes. The overarching question of global climate change demanded globally averaged, long-term information about climate, in which spatial and temporal detail—the human scale, in other words—played a subordinate role. Climate science at the close of the twentieth century resembled a mirror image of the iconic "Blue Marble" photograph taken from outer space during the Apollo 17 mission in 1972. This picture shows the whole Planet Earth as a solitary entity in space and has been widely disseminated as a symbol of the fragility of the globe.[94]

The globalizing tendency, culminating in Earth system analysis, has a long history in climate research. It grew out of scientific as well as technological and cultural conditions. Climate proved an immensely complex phenomenon based on globally linked interactions. How could it be properly understood without a globalizing perspective? Paul Edwards has described the emergence of planetary observation systems as "quasi-obligatory globalism."[95] Climate, on the other hand, is also a cultural phenomenon. The questions climatologists asked and in which society took an interest (such as the understanding of climates in different geographical regions or the understanding of climatic change) have depended on cultural interests and contexts. European and US overseas imperialism called for a focus on place and for the exploration of geographies and climates on Earth (see Chap. 37).[96] The age of environmental concern, in contrast, placed particular value on knowledge about environmental change due to human agency. This became, in part, a global concern, with emphasis on global interconnections and global consequences, as highlighted in the report *Limits to Growth* by the Club of Rome in 1972 and as symbolized in the "Blue Marble" and "Gaia hypothesis."

These proliferating cultural interests helped to mobilize and command intellectual and material resources.[97]

Despite its successes, globalizing reductionism came at the price of marginalizing small-scale and local perspectives; and it largely erased humans from the picture. In recent years, parts of climate science worked hard to adjust core practices in order once more to factor in small-scale and human dimensions. Climate modelers have attempted to increase spatial and temporal resolution by downscaling global models and to bring regional information back into the picture, particularly as that information has become relevant to climate adaptation policies. The mathematics of numerical approximation under conditions of limited computer power, however, have set strict limitations. It seems "ironic that we cannot represent the effects of the small-scale processes by making direct use of the well-known equations that govern them," David Randall and his co-authors have remarked with some frustration.[98] These authors, along with others, have considered the loss of the small scale as a "deadlock" and perceived the restrictions imposed on their physics as "something scandalous" and "almost shocking," as historian of climate modeling Hélène Guillemot has put it.[99]

Researchers in the humanities, particularly historians and anthropologists, have increasingly called attention to humanities perspectives in global change research in order to broaden scholarly and public discourse, to consider alternative types of knowledge about climate and culture–environment relations, and to offer more comprehensive and more robust knowledge about climate, environmental, and cultural change. "In nearly all domains of Global Change Research (GCR), the role of humans is a key factor as a driving force, a subject of impacts, or an agent in mitigating impacts and adapting to change," a group of authors led by historian Poul Holm argues.[100] They suggest a stronger focus on the "human dimension" of global change and contend that expertise on human behavior is required as much as expertise on the climate or biological systems. As Gísli Pálsson and colleagues put it, the "'Anthropos' in the Anthropocene" needs to be reconceptualized.[101] It remains to be seen how and in what ways researchers in climate science and in the humanities can help to include the human dimension, put the human and the local back into the picture, and develop perspectives for dealing with the problem of climate change on both the local and the global levels.

Notes

1. Lehmann, 2015, 51.
2. e.g. Flohn, 1954, 11–13; Khrgian, 1970, 312.
3. Humboldt, 1845, 340.
4. Humboldt's concept of climate was holistic in three ways: first, climate represented the whole of atmospheric phenomena at a defined location (synthesis of phenomena); second, it represented the whole of climates in different locations (synthesis in space); third, it focused on the relationship of humans and climate

(Heymann, 2010a, 587). Humboldt's ideas stood representative of "the basic goals of the nineteenth century climatologists … to understand the relationship between climate, vegetation, agriculture, and man" (Khrgian, 1970, 302).

5. Khrgian, 1970, 312.
6. Knobloch, 2007, 12.
7. Rupke, 2008, 175–202. Similarly, Aleksandr Ivanovich Voeikov, one of the most influential Russian climatologists and geographers, pursued an interest in large-scale climatic processes in his fundamental *Climates of the Earth, Particularly of Russia* (1884). E.g. Khrgian, 1970, 314–15; Oldfield, 2013, 517.
8. Coen, 2010, 843–46.
9. Hann, 1908, 3–4.
10. Köppen, 1895, 614.
11. Köppen, 1895, 619.
12. Köppen, 1895, 627.
13. Köppen and Geiger, 1936.
14. Köppen, 1918, 1923, 1936; Wilcock, 1968.
15. Werlen, 1993, 244; Bahrenberg, 1995, 152.
16. Köppen and Geiger, 1936.
17. Kutzbach, 1979.
18. Nebeker, 1995, 48.
19. Wagner et al., 1931, F1–F3.
20. Flohn, 1951, 201.
21. Scherhag, 1936.
22. Flohn, 1992, 19.
23. Flohn, 1950a, 142; Flohn, 1992, 7, 14.
24. Flohn, 1950a, 1950b; Petterssen, 1950.
25. Bergeron, 1930.
26. Flohn, 1951, 210.
27. Hettner, 1930; Flohn, 1950b.
28. Christaller, 1933; Kiesewetter, 2000, 79–90; Bobek and Schmithüsen, 1949.
29. Flohn, 1954, 11–12.
30. Malberg, 2007; interview with Günther Warnecke, November 26, 2015; interview with Heinz Fortak, November 27, 2015.
31. Krüger, 2013; Brönnimann, 2002; Imbrie and Imbrie, 1979, 19–57.
32. A notable exception is Brooks, 1922 and Brooks, 1949; see also Kenworthy, 2012.
33. Brückner, 1890; Lehmann, 2015.
34. Fleming, 1998.
35. Sörlin, 2011.
36. Callendar, 1938; Fleming, 2007, 65–77.
37. Callendar, 1938, 237.
38. Rudloff, 1967; Lamb, 1982.
39. Lehmann, 2015; Coen, 2010.
40. Bjerknes, 1904; Thorpe et al., 2003; Gramelsberger, 2009. Bjerknes provided a description of these equations in prose. Figure 38.1 gives six of the seven equations in the form elaborated by Lewis Fry Richardson and presented in Aspray, 1990, 124–27; see also Dahan Dalmedico, 2001, 398–99 and Nebeker, 1995, 66.
41. Friedman, 1989.

42. Friedman, 1989; Ellingsen, 2015.
43. Volkert, 1999; Gramelsberger, 2017.
44. Richardson, 1922; Lynch, 2005.
45. Harper, 2008; Nebeker, 1995.
46. Phillips, 1956, 154.
47. Quoted in Lewis, 1998, 52.
48. Persson, 2005a.
49. Persson, 2005b, 2005c.
50. Flohn, 1965, 385.
51. Craddock et al., 1962, 7.
52. Weart, 2008; Edwards, 2010.
53. Kellogg, 1971; Heymann, 2012.
54. Kellogg, 1971, 123.
55. Charney et al., 1979, xiii.
56. WMO, 1979, 714.
57. Hansen et al., 1981.
58. Heymann and Hundebøl, 2017.
59. Faust, 1960.
60. DeVorkin, 1992; Devorkin and Sanchez-Ron, 1996.
61. Henderson, 2013; Mason, 1975.
62. Dahan Dalmedico, 2010.
63. Dahan Dalmedico, 2010, 291.
64. Hulme, 2011.
65. Lovelock and Margulis, 1974, 2.
66. Lovelock and Margulis, 1974, 3.
67. Ruse, 2013; Schneider and Boston, 1992.
68. Bretherton, 1985.
69. Uhrqvist, 2015; Schellnhuber, 1998, 8.
70. Schellnhuber, 1999.
71. Schellnhuber, 1999, C20.
72. Fisher, 1988, 59.
73. Lenhard and Winsberg, 2010, 253.
74. Quoted in Fisher, 1988, 55.
75. Clifford, 2009, 359.
76. Achermann, forthcoming.
77. Jouzel, 2013, 2526; Martin-Nielsen, 2012, 2013.
78. Dansgaard, 1953.
79. Dansgaard, 1953, 469.
80. Dansgaard et al., 1969, 380.
81. Dansgaard, 2005, 69–74.
82. Broecker, 1987.
83. Edwards, 1999.
84. Edwards, 2010.
85. Agar, 2006; Sepkoski, 2013.
86. Lehmann, 2015, 69.
87. Heymann, 2010b.
88. Heymann, 2009, 2010a.
89. Heymann, 2010a, 2010b.
90. e.g. Shackley et al., 1998; Hulme, 2008.

91. Smith, 2007; see also Edwards, 2006.
92. Fleming, 2010.
93. Jouzel et al., 2007.
94. Jasanoff, 2001; Cosgrove, 2001.
95. Edwards, 2006.
96. Livingstone, 1993, 216–93.
97. Meadows et al., 1972.
98. Randall et al., 2003, 1548.
99. Guillemot, 2017, 13.
100. Holm et al., 2013.
101. Palsson et al., 2012.

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Epilogue

As several chapters in this volume explain, new evidence concerning the history of climate and its myriad meanings is tumbling forth. Not a day goes by without new findings from sediment cores, pollen assemblages, tree rings, or one of the several other climate proxies—not to mention new research in historical climatology. Few if any other arenas of history are so in flux. Thus, it is extremely useful to take stock, as this book does, even if inevitably it will soon be out of date in some details.

The spate of evidence concerning past climate is part of a more general methodological revolution in the study of history. More than half a century ago, French historians aspired to something they called *histoire totale* or total history. Its chief distinction was an embrace of the social sciences, both their theories and their varieties of evidence. But the proponents of total history stopped short when it came to the natural sciences. They offered, in effect, subtotal history. Lately, however, we see before our eyes the crystallization of consilient history, a history based on theories and lines of evidences from all the sciences, both social and natural, as well as upon the old standby of historians: textual documents.

Consilient history is at the same time both terrifying and exhilarating. It is terrifying because of the demands it makes upon readers and writers. No one can master the strengths and weaknesses of evidence and arguments concerning genetics, climatology, archaeology, evolutionary biology, and history—and yet this is what consilient history asks. It is exhilarating because it promises far greater explanatory power than history based merely on texts, or texts with the occasional assistance from archeology or art history (which historians will recognize as their basic approach over the past 150 years).

Climate history is in the vanguard of consilient history, and its recent and ongoing legitimation is telling. Until recently, few historians took climate seriously. Generations ago, some had done so but in sufficiently simplistic fashion as to discredit the entire enterprise, arguing for a straightforward determinism of climatic

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regimes. By the mid-twentieth century, such views had justifiably fallen out of fashion. The newer generation of climate history is, by and large, more interested in climate change than climate regimes. Its viability depends on plausible data concerning past climate shifts and extreme climate events, most of which is verified by the natural sciences.

The success of climate history in the last decade is indicated by the conversion of several senior historians to the view that shifts in climate have exerted strong influence over human history. Well-established historians who for two or three decades had written well-received histories that made no reference to climate, all of a sudden changed their approach and featured climate, particularly adverse climate shifts, as a crucial engine of history. They found climate useful for explaining things that they and their colleagues had long explained in other ways, such as the downfall of medieval Islamic dynasties or the turbulence of Yuan and Ming China. In doing so, they abandoned the longstanding reluctance among historians to attribute agency to anything other than human groups and individuals. By and large, they find climate shifts useful in reference to political and economic history rather than social or cultural history. If the depth and sincerity of their conversions are proportional to the length of the books that they have authored, then it is as thorough as a change of heart can be. This strikes me as a powerful affirmation of the legitimacy of climate as an influence upon human history.[1]

Nonetheless, the climate turn among historians is a delicate flower. While ever more young historians (several of them included in this book) are at work on climate history, the broader legitimacy of the subject among historians risks dismissal as mere climate determinism. For some seventy-five years, historians and social scientists have rejected explanations for just about anything related to humanity that seems to rely on the agency of anything non-human, including and perhaps especially climate. That skittishness has declined lately. But skepticism about the power of climate to affect human history remains strong in some quarters, and for several reasons.

The majority of historians work on periods since 1815 and before 1980, during which time climate shocks were few and climatic change modest and manageable. The surfeit of documentation on most subjects during this period meant that scholars have plenty of possibilities for convincing historical explanation without bothering with tree rings or speleothems (or even instrumental weather data). Moreover, the great majority of professional historians work on Europe or North America, which (since 1815) have been comparatively wealthy and resilient parts of the world, more able than most to withstand climatic variability. Thus, most historians do not see much impact from climate shifts in their chosen fields, and as a result are not easily persuaded they should be given weight anywhere. Given the surviving skepticism about the usefulness of climate history, it is important that climate historians face up to a few challenges.

The first challenge is the temptation to overstate the case about the consequences of climate and invite the charge of climate determinism. The editors' introduction to this volume alerts readers to this issue, noting that uncertainties mount as one moves from climate reconstruction to biospheric consequences and from there to economic, political, and cultural impacts. Claims that climate shifts explain the rise and fall of Chinese dynasties over two millennia, for example, made starkly by some Chinese climatologists, win no followers among historians.

To meet this challenge, climate historians must consistently identify convincing and specific pathways by which climate affected human affairs. It is rare to find any textual document (the traditional gold standard of evidence for historians) that makes a direct connection between climate and human events. One will look in vain for one that states that the Fatimid dynasty in Egypt fell as a result of prolonged drought. Historians of climate's impacts must, if they expect to be convincing, find links in any causal chain they wish to posit. In happy cases, that might take the form of price series of grain, showing rising prices that coincide with a period of anomalous weather. This would provide a persuasive link to economic history, and if combined with documentation concerning political unrest resulting from high prices, would then link persuasively to political history. But quantitative data of this sort will often be lacking, making it harder to show that a change in climate meant a change in economy or society. This, I think, is the greatest challenge for climate history. The nature of the evidence, whether textual or from natural archives, is such that it rarely delineates the pathways, the missing links between climate events and human events, and instead requires inference. Those inferences may be made well or badly, but in either case some (unimaginative) historians are allergic to inference altogether, and others are skeptical of inferences that strike them as climatic determinism.

A second challenge for climate history is the routine hazard of interdisciplinary work. A standing temptation for scholars is to seek conveniently simple explanations for things outside their own arenas of expertise. Even with a single discipline, this is normally the case. Historians who would never accept a simple explanation for the onset of the Great Depression will happily repeat one for the rise of the Mongols (and vice versa). This is human nature given that we all have limited time and cannot read up properly on all historical subjects. It is all the harder for scholars to operate responsibly outside their home disciplines. Yet this is exactly what climate history requires. Dendrochronology and palynology and all the scientific fields that generate proxy data for climate history have their fine points. Who, as an outsider, can reliably assess the weaknesses of such data or interpretation?

To meet this second challenge, aspiring historians of climate will either need to become miraculous polymaths or take part in collaborative research projects. The first of these is scarcely realistic for most mortals, although some people have made valiant attempts and remarkable progress. (Some of the chapters in this book can help ambitious readers learn about the limits of all manner of evidence.) The second has its pitfalls, such as incentive structures in the institutional settings in which most scholars work, but is a much more plausible route. Perhaps this second challenge is better seen as an opportunity.

A third challenge, which surely is an opportunity, is the awkward fit in terms of units of analysis between climate history and history in general. Chronologically, historians slice up the past into periods based typically on political criteria. Every subfield does this differently, so for example, Chinese history is organized by dynasty and African history into a tripartite scheme of pre-colonial, colonial, and post-colonial. None of this, whether in China, Africa, or anywhere else, matches up usefully with turning points in climate history. Reconciling this is a challenge for climate historians but perhaps even more so for historians generally.

Historians have no periodization for global history. Widely used terms—such as modern, early modern, medieval, and ancient—mean quite different things in different contexts. Medieval India, by some reckonings, lasted until 1857. The West African Kingdom of Mali is routinely called ancient, yet it took shape in the fourteenth century and survived into the sixteenth (which elsewhere would qualify as early modern). The few efforts to create a periodization for global history have not caught on.[2]

It could be that in the fullness of time, climate history will help achieve greater consistency among historians' schemes of periodization. But first it will likely muddy the waters further. They are already muddied thanks to other recent developments such as the rise of social history or women's and gender history, for which conventional periodizations based on politics sometimes make little sense. In the 1970s, a feminist historian asked if women had a Renaissance (the answer was no).[3] Climate history, if it continues to prosper, will add competing schemes of periodization, possibly based on climate data alone, or on the shifting relationships between humankind and climate. In 2014, John Brooke attempted something of the sort for global history.[4] At the moment, the standard terminology of climate history carries a residue of eurocentrism (Roman Climate Anomaly, Medieval Climate Anomaly) and has terms for departures from Holocene averages but not for periods that conformed reasonably well to the long-term averages. This will likely change, and a fuller and perhaps more coherent scheme of periodization for climate history will emerge.

If climate history is ever to do more than obscure periodization—if the challenge is to be converted into opportunity—somehow it will have to convince historians in general of the salience of climate for all history. At the moment, that looks unlikely, even if existing schemes of periodization are based on little more than familiarity. But should world and global history continue to gain adherents and prestige in the profession of history, they will have the effect of destabilizing existing chronologies and periodizations (which are national or regional in scope). And the more inadequate current periodization schemes appear, the greater the likelihood that historians will seek alternatives, including schemes based on climate criteria rather than political ones.

African history can be seen as instructive in this regard. Its prevailing periodization is an ungainly misfit. All African history before the 1880s falls into a single (pre-colonial) period, and its successor period (the colonial era) is only eighty years long. Terms such as "Iron Age" or "ancient" are sometimes used too, although their meanings differ for different parts of Africa. In reaction to this unhappy muddle, in 1994, George Brooks tried to organize West African history into periods based on climate shifts, mainly wetter and dryer intervals, using the scanty data available at that time.[5] His colleagues did not follow suit. One could probably do a more precise job today thanks to a quarter century more work on African climate history. But would what might fit West Africa also fit eastern or southern Africa? Probably not, except for the most macro-scale trends and shifts.

The same obstacle exists, *a fortiori*, for global history. Different regions have different climate histories. And yet there do seem to be some macro-scale shifts and trends, even if they manifested themselves differently around the world. The Little Ice Age, while not icy everywhere, seems to be a departure from longer-term norms quite widely. So, perhaps renamed, it could conceivably one day seem a coherent period of historical time for global history. In the same way, possibly also renamed, might the Anthropocene describe an age in which humans affected climate by elevating greenhouse gas levels.

Thus, for history, whether local, regional, or global, the spate of new data on climate invites a reconsideration of the schemes of periodization that are the building blocks of coherent narratives. Global history, I would imagine, is the scale on which climate criteria are likeliest to have the strongest influence, because there is no incumbent scheme. Those parts of the world where climate evidence is most abundant already have incumbent periodizations for their histories, which will be hard to modify, let alone dislodge. Nonetheless, I expect in the decades ahead that historians will continue to take on board climate considerations, and eventually bake them into the building blocks they use to construct coherent narratives.

Climate data will challenge the way historians analyze space as well as time. Historians have long preferred geographic scales that match up with political units. Indeed, the origins of professional history in the nineteenth century were often bound up with nationalist political agendas. Moreover, textual historians rely on documents kept in archives, and those archives are normally maintained by states or other political entities, and contain records generated by states and bureaucracies. For all these reasons of convenience and tradition, historians do not normally consider spaces defined by climatic criteria, such as zones affected by the North Atlantic Oscillation or by the Indian Ocean monsoon, as appropriate units of analysis.

To the extent that historians absorb the new data from climate history, they will struggle to reconcile their traditional scales with ones that correspond to climates. They may wish to lump countries of the northern Andes together as lands of ENSO, instead of choosing either smaller units, such as Peru, Ecuador, or Colombia, or larger ones such as Latin America. Rather than choose the Middle East as a whole, or its various nation-states, they may wish to bundle the Levant and Egypt together as lands united in a socioclimatic system.[6] Such reimagined units of historical analysis will be tempting in some cases, where and when climatic phenomena have intruded powerfully on human affairs, and less tempting in others.

In time, climate history could also challenge the recent emphasis of (anglophone) history on race, class, and gender. Thinking in these categories is not incompatible with climate history. In some cases, as in histories of Hurricane Katrina, it readily suggests itself. Taking climate seriously often means de-emphasizing these social categories, and correspondingly de-emphasizing social groups as drivers of history. It remains to be seen, of course, how the traditions of history-writing will evolve under the impact of new information concerning climate.

In any case, history has always been a matter of discussion and debate. As this book shows, it is now enriched by new forms of evidence that suggest climatic shifts sometimes played powerful roles in human affairs. But, as this book shows as well, the new evidence requires judicious handling, awareness of uncertainties and of contexts—in other words, the skills of the historian.

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Notes

1. See, for example, Lieberman, 2009; Bulliet, 2009; Ellenblum, 2012; Parker, 2013; Brooke, 2014; Campbell, 2016; and Brook, 2010. These historians work in the USA, Canada, the UK, and Israel, and they are all male. Is the conversion experience confined to men? Confined to Anglophone academia? If it is, it will not be for long, because younger historians, female and male, working in many countries, are taking climate into account, and indeed probably doing most of the groundbreaking research. Yet another senior historian who has taken the climate turn lately is Nicola di Cosmo, scholar of Central Asia, Mongolia and China, who has co-authored several pieces with climate scientists, e.g. Büntgen and Cosmo, 2016. One could add to this list of senior historians Michael McCormick, John Haldon, Stuart Schwartz, and others.
2. E.g., Bentley, 1996.
3. Kelly, 1977.
4. Brooke, 2014, 279.
5. Brooks, 1993.
6. As in Ellenblum, 2012 This is a socioclimatic regime because Egypt and the Levant are subject to different rhythms of drought because Egypt's water comes mainly from Ethiopian rains, governed by the Indian Ocean Monsoon, not the Atlantic patterns that affect the Levant. Thus, drought almost never strikes both at once, and each served as insurance for the other against crop failure. This pattern is hard to detect if one pays attention only to Egypt or only to Syria, and would be hard to detect if one chose one's unit of analysis on purely climatic criteria, as opposed to socioclimatic ones.

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Glossary

Most technical terms in this volume, including terms borrowed from (paleo)climatology and meteorology, will be defined as they appear in the text of the chapters. The following list is intended only to distinguish the way that common terms are typically used in historical climatology and climate history, especially when those terms may have different meanings in other fields.

Adaptation: the adjustment of human or natural systems over time to local climates, climate variability, or climatic change. In human systems, adaptation is often an active process, not merely reactive to climate impacts (see IMPACTS). The capacity to change cultural strategies usually leaves a variety of options in proactive or reactive human adaptation. Hence, adaptation is not mechanistic (see DETERMINISM)

Archives of Nature: see PALEOCLIMATOLOGY

Archives of Societies: see HISTORICAL CLIMATOLOGY

Calibration: a statistical procedure that converts direct or indirect (proxy) documentary evidence about weather and climate into meteorological units, such as degrees Celsius or millimeters of precipitation

Climate: "Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system." (IPCC, https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_Glossary.pdf)

Climate Anomaly: the difference between average climate (over a period of years or decades) and the climate during a particular month or season

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Climate Change: a long-term change in the Earth's climate, or of a region on Earth; a modification in the statistics of the weather

Climate Determinism: see DETERMINISM

Climate Forcing: a driver of climate change, such as solar irradiance, atmospheric aerosols (e.g., from volcanic sulfates or industrial output), surface reflectivity, or natural or human-induced changes in atmospheric greenhouse gas concentrations. Forcings are categorized as either natural or man-made (anthropogenic). Their relative influence is calculated and modeled as *radiative* forcing, i.e., the difference of sunlight (insolation) absorbed by the Earth and long-wave radiation reflected back to space (measured in watts per square meter, wm^{-2})

Climate History: the investigation of past weather and climate and their role in human history, usually (but not always) combining methods and insights from conventional historical research, historical climatology, and paleoclimatology

Climate Impact(s): see IMPACT(S)

Climate System: "The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere, and the biosphere and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings (see CLIMATE FORCING)" (IPCC)

Climate Variability: short-term or medium-term variations in climate, or the extent to which those variations depart from long-term averages. In historical climatology, the term may encompass extreme events (such as hail storms), persistent periods (such as droughts), or even little ages (such as the Little Ice Age), depending on context

Determinism: the reduction of human–climate interactions to linear causal chains that neglect historical contingency and human agency, including adaptability (see ADAPTATION)

Drought: a period of below-average precipitation in a given region, resulting in prolonged shortages in its water supply; the term includes:

- **agricultural drought**: a deficiency of soil moisture that affects agricultural activities, whether due to an extended period of below-average precipitation, above-average temperatures, erosion, or poorly planned agricultural endeavors
- **hydrological drought**: a shortage of water reserves available in sources such as aquifers, lakes, and reservoirs; like agricultural drought, this can be triggered by more than just a loss of rainfall
- **meteorological drought**: a prolonged period with less than average precipitation

Environmental History: an interdisciplinary subfield of history that investigates: (1) the past impact of human activities on the environment, (2) the impact of environmental factors on human history, and (3) the history of ideas and politics related to the environment

Forcing: see CLIMATE FORCING

Glacier Fluctuations: a change in mass of a glacier resulting from the balance between *accumulation* (gain of ice and snow) and *ablation* (loss of ice and snow); these changes include:

- **advance**: an increase in the length of a glacier compared to a previous point in time; as ice in a glacier is always moving forward, a glacier's terminus advances when less ice is lost due to melting and/or calving than the amount of yearly accumulation
- **retreat**: a decrease in the length of a glacier compared to a previous point in time; as ice in a glacier is always moving forward, its terminus retreats when more ice is lost at the terminus to melting and/or calving than reaches the terminus

Historical Climatology: the reconstruction of past climates and weather from physical and written sources left by humans, or what this volume calls "the archives of societies"

Historical Hydrology: the reconstruction of run-off conditions as well as extreme hydrological events such as floods, ice damming, and hydrological droughts (see DROUGHT) for the period before modern hydrological networks

Homogenization: the detection and removal of non-climatological breaks or trends in a time series of climatic or weather data, such as early instrumental records or grape harvest dates; a perfectly homogenized series reflects only climate variability, free from artificial influences such as changes in instruments or procedures for recording measurements

Impact(s): effects of climate change, climate variability, and meteorological or climatological extremes on natural and human systems. Climate historians generally focus on the latter, i.e., the effects that weather and climate have on lives, livelihoods, health, economies, societies, and cultures

Little Ice Age (LIA): a period of climatic cooling occurring between the late thirteenth and mid-nineteenth centuries, the precise definition of which remains contested. The LIA may be identified specifically with: Northern Hemisphere or global cooling between the Medieval Climate Anomaly [q.v.] and the onset of anthropogenic global warming; the period of maximum global or Northern Hemisphere cooling between around 1560 and 1710 CE; or the maximum advance of glaciers (global or Northern Hemisphere only) during the late Holocene

Medieval Climate Anomaly (MCA): a time of warm climate in the North Atlantic region *c.* 950–1250 CE, possibly related to other climate events in other parts of the world, including China. The warmest period of the last 2000 years prior to the twentieth century in the Northern Hemisphere very likely occurred between 950 and 1100; possible causes of the Medieval Warm Period include increased solar activity, decreased volcanic activity, and changes to ocean circulation

Medieval Warm Period (MWP): see MEDIEVAL CLIMATE ANOMALY

Paleoclimatology: the statistical reconstruction of past climates from physical sources left by natural processes, or what this volume calls "the archives of nature"

Phenology: recurring natural processes whose characteristics and timing can be used to help reconstruct climate and weather patterns, including:

- **plant phenology**: plant life-cycle events such as flowering and fruit maturity
- **agricultural phenology**: the dates of recurrent agricultural work, such as planting and harvesting
- **animal phenology**: the seasonal appearance of animals such as frogs and migratory birds
- **ice and snow phenology**: the seasonal formation and melting of ice bodies and snow-cover

Principle of Stationarity: in historical climatology, the assumption that a climate proxy bears the same relation to some climate variable in the pre-instrumental past as in the period of modern instrumental measurements (i.e., the period used for calibration [q.v.])

Proxies: indirect representations of past climate, such as the width of tree rings or the dates of grape harvests

Resilience: the capacity of social systems, economies, and cultures to cope with or recover from climate change, (natural) hazards, and extremes in ways that maintain their essential functioning

Resolution: temporal and/or spatial density of available data. Resolution is higher where the (temporal or spatial) distance between data points is smaller. For example, thermometer readings taken every day could provide temperature data at daily resolution, while yearly growth rings in trees could provide temperature or precipitation data at annual resolution

Transfer Function: a statistical relationship between a measurement of a proxy and some climate variable or variables

Vulnerability: the extent to which human systems are exposed to climate variability and extremes and may experience harm or damage; also a lack of capacity to adapt or cope (see ADAPTATION and RESILIENCE)

Weather: atmospheric conditions during time periods of less than a year, typically within a day, but in some cases, for weeks months or seasons (as captured by the term "Grosswetterlagen" in German)

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[1] Note: Page numbers followed by 'n' refer to notes.

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