Gabriele Gramelsberger
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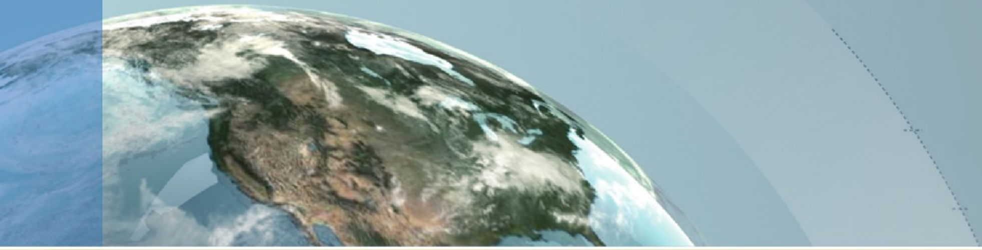

Climate Change and Policy

The Calculability of Climate Change and the Challenge of Uncertainty

Springer

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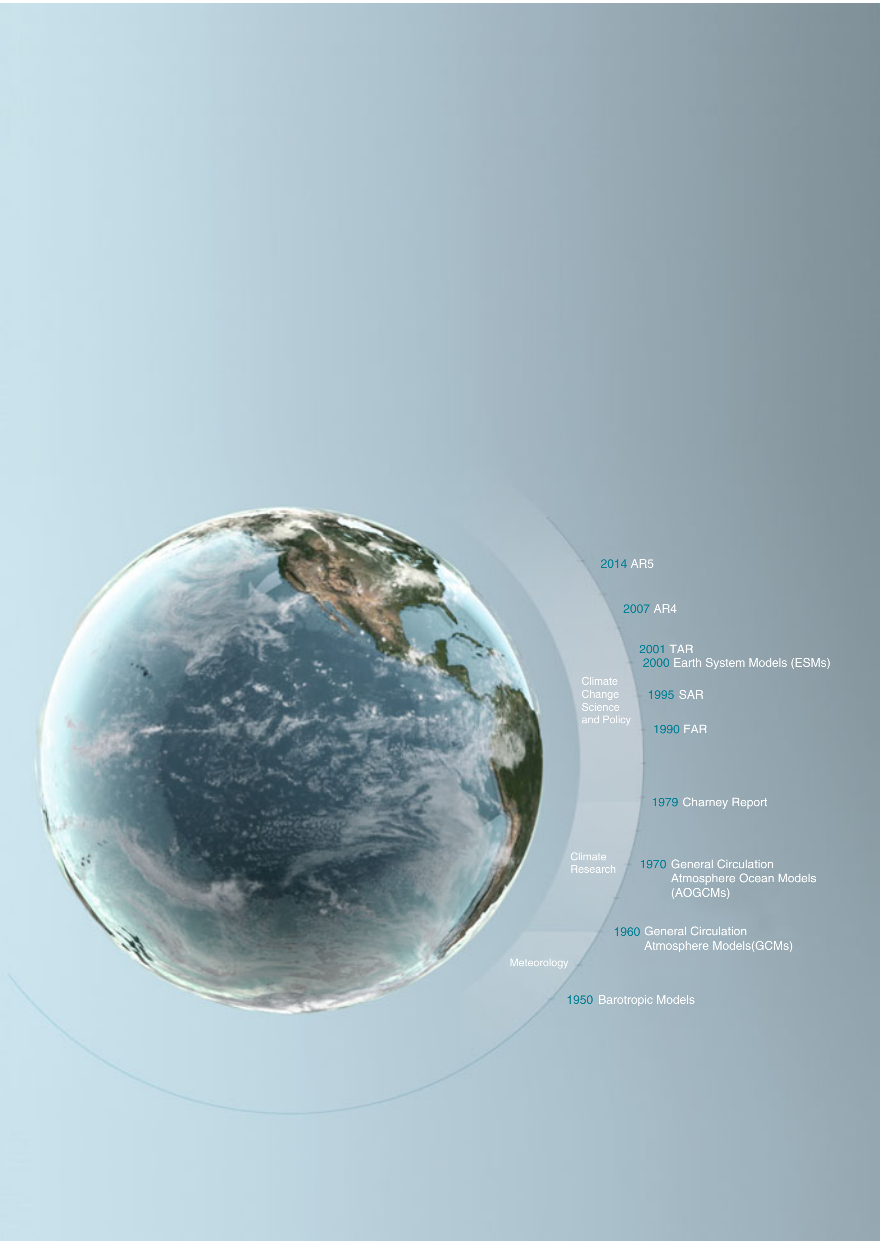
2014 AR5
2007 AR4
2001 TAR
2000 Earth System Models (ESMs)
Climate Change Science and Policy
1995 SAR
1990 FAR
1979 Charney Report
Climate Research
1970 General Circulation Atmosphere Ocean Models (AOGCMs)
1960 General Circulation Atmosphere Models(GCMs)
Meteorology
1950 Barotropic Models

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Foreword

The uncertainty in projecting climate effects is a contentious issue in science and society. On the one hand, decision-makers require certainty about the future consequences of today's behaviour. On the other hand the complexity of the climate system, of human behaviour, and global interactions, combine to make such certainty impossible. Although it has turned out that the world is not exactly predictable, advanced strategies of calculability and measurement have been developed that enable to establish 'rational prognosis'. Thus forecasting future scenarios and dealing with uncertainty has become everyday business for meteorologists ever since automatic computing machines crossed the threshold of a million operations per second in the 1970s.

Since then rational prognosis based on scientific principles has become an essential part of decision-making both in economics and in politics–challenged by the problem of uncertainty. New methods and advanced strategies fuel hopes of managing uncertainty as economics, politics, and society increasingly bank upon rational prognoses, especially where the impact of climate change is concerned. For instance, insurance companies recently converted from retrospective to prospective regulation of insurance policies using simulation-based forecasting, and industrial investments increasingly rely on scientific reports predicting future developments.

Therefore the present volume is guided by two goals. Firstly, to give firsthand insights into the calculability of climate change. Outstanding efforts have pushed meteorology into a pioneering leading role in dealing with rational prognosis as well as uncertainty. One outcome of these efforts is an internationally organised system of evaluation and model comparison–unique in science, which has been established over the last three decades to ensure the quality and validity of scientific results. In this the Intergovernmental Panel on Climate Change and other supranational organizations play a crucial role. The second aim of this volume is to explore the influence of rational prognosis and of the accompanying uncertainty on various socio-political and economical spheres, but also on the public and on science itself. Therefore we are delighted to present a selection of papers written for this volume by leading researchers.

The volume is the result of over six years of transdisciplinary collaboration between Johann Feichter (Climate Research) and Gabriele Gramelsberger (Philosophy of Science). Both this collaboration and the volume were generously supported by the Max Planck Institute of Meteorology in Hamburg.

Gabriele Gramelsberger
Johann Feichter

Contents

Chapter 1
Introduction to the Volume

Johann Feichter and Gabriele Gramelsberger

In 1979 meteorologist Jule Charney and colleagues published a globally recognized report on *Carbon Dioxide and Climate: A Scientific Assessment* (Charney et al. 1979). They finished the report with the conclusions that “our best estimate is that changes in global temperature on the order of 3°C will occur and that these will be accompanied by significant changes in regional climatic patterns” (p. 17). The estimates of the so-called Charney report were based on two, at that time state-of-the art, general circulation models of the atmosphere that carried out numerical studies on the impact of doubling carbon dioxide on the global mean temperature. This measure, called climate sensitivity, was introduced by Charney et al. and were supposed to provide some insight into the ‘vast geophysical experiment’ mankind was about to conduct (Revelle and Suess 1957). A full two decades before the release of the Charney report, Charles D. Keeling had begun measurements of atmospheric carbon dioxide concentration at Mauna Loa Observatory in Hawaii in order “to make sure that man’s ‘vast geophysical experiment’ would be properly monitored and its results analyzed” (Keeling 1978, p. 38). The ‘Keeling Curve’, a time series of annual departures from 1958 on, clearly shows the increased CO_2 concentration in the atmosphere. This curve has become one of the icons of man-induced climate change today. However, this kind of ‘vast geophysical experiment’ should be subject to a digital climate, not to nature. Therefore climate models are indispensable tools for the emerging climate change science. Rooted in simple barotropic models of the atmosphere,[1] first computed by Charney and colleagues on ENIAC in 1950, these models have developed into complex Earth system models—incorporating knowledge from not only meteorology, but also oceanography, hydrology, biology, geochemistry, economy, and other fields. Within the last six decades,

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[1] Barotropic models idealize atmospheric flow insofar that the air pressure only depends on the air density.

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climate models have turned from purely meteorological into multidisciplinary objects of Earth science. Similarly, forecasts of changes in air pressure fields based on barotropic models have developed into projections of climate change and its impact on ecology using vast software machineries.

The 1979 Charney report provided a numerical study on climate change that was not only outstanding for its time, it marked a watershed that transformed climate change into a public policy issue—interlinking climate science and politics by establishing a growing number of international research programs, conferences, working groups, intergovernmental panels, and committees. The list of activities undertaken since the early 1980s to establish an infrastructure of worldwide coordination and negotiation for dealing with climate change is impressive, as politicians and the public have become increasingly aware what the alteration of climate could mean for mankind's future. Unrestricted change in land cover and pollution on the one side, and reduction of ecological resilience, the loss of biodiversity, regional inequity and vulnerability on the other, characterize the challenge and impact of climate change as a global phenomenon with regional effects. The effort of a global response to climate change by the United Nations involves three main endeavours: better knowledge of the current situation (measurement campaigns), better understanding of relevant processes and future trends (modelling and projecting), and a framework for negotiating the adequate response to climate change (a property rights regime for human use and modification of the carbon cycle). Numerous regional responses to climate change by governments and NGOs in terms of mitigation and adaptation are supplementing international and intergovernmental activities.

However, the link between climate change science and climate change policy are projections of future climate change and impact. As scientists are denied the possibility of conducting experiments with the real climate, only climate models can give insights into man-induced climate change, by experimenting with digital climates under varying conditions and by extrapolating past and future states into the future. But the 'nature' of models is a purely representational one. A model is good if it is believed to represent the relevant processes of a natural system well. Whether it does so can be evaluated by comparing the output of the model with observations. This empirical method of scientific evaluation assumes that when a prognosis inferred from a set of hypotheses (as modelled) concurs with observations from the field or experiments, the accordance corroborates the adequacy of the underlying hypotheses (model). This method holds only for sets of hypotheses among which the relation is clearly defined and among which feedback is limited to linear influences exerted on each other. In other words: Only very simple models can be verified. Most models, and in particular climate models, which interconnect countless hypotheses, are only to some extent testable. This situation of increasing model complexity and dissatisfactory methods for the evaluation of such complexity characterizes climate change science. As there is no way back to over-simplified models, which in any case do not sufficiently represent nature due to their simplicity, the development of advanced evaluation strategies and uncertainty metrics responding to the increasingly advanced style of modelling is a current challenge for science. This challenge involves strategies of model intercomparison, ensemble prognoses, uncertainty metrics on the system and component levels, uncertainty assessment, new ways of learning, and other strategies as outlined in this volume.

The challenge of developing advanced evaluation strategies can also be reformulated as the challenge of dealing with uncertainty in science. But this challenge of uncertainty is in conflict with socio-political expectations. Climate change policy requires accurate information for decision-making, and climate change science needs accurate information on economic development. Since neither of these can be achieved, climate change policy has to learn decision-making under uncertainty, and climate change science has to base its projections on possible scenarios and storylines. For a while climate change policy tended to deal with uncertainty by requiring scientists to eliminate all uncertainties before any policy action could be considered. However, this approach has changed as it has been recognized that inaction on climate change is a form of action in itself—resulting in the unmitigated pollution of the atmosphere and changes to land surface properties—and that complexity and uncertainty go hand in hand. Neither can be avoided without avoiding the other, and certain predictions belong to the realm of desires and ideals rather than to applied science. Today's attempt to define and classify uncertainty in terms of likelihood and confidence reflect this awareness of uncertainty as an integral part of human knowledge, in particular on knowledge about possible future developments. It is now up to society to come to decisions on reductive and adaptive activities as one thing is certain: every year of inaction marks an increase in atmospheric carbon dioxide concentration.

Against this backdrop the volume addresses various aspects of an emerging climate change science and policy, in particular the calculability of climate change and the challenge of uncertainty. Calculability and uncertainty are two sides of the same coin, and this coin constitutes the currency of climate change science and policy (Gabriele Gramelsberger and Johann Feichter, Chap. 2). In order to understand the idea of climate prediction, the possibilities and limits of the calculability of temporal and spatial developments of a system based on physical laws has to be explored. During the late nineteenth and early twentieth centuries, meteorology turned from a descriptive and purely empirical science into one based on theory and models. This shift resulted from conceiving the atmosphere as a mechanical and physical object—a giant 'air mass circulation and heat engine' driven by solar radiation and gravitational forces expressed in terms of local differences in velocity, density, air pressure, temperature, and humidity. The main advantage of subordinating the atmosphere to physical laws is that it can be mathematically modelled so that forecasting algorithms for the computation of future states can be inferred from the mathematical model. As these computations require recourse to enormous computing power, meteorology could take advantage of these forecasting algorithms only when automatic calculating machines came into use during the late 1940s. In 1950 Charney and his colleagues computed the first weather forecast—a forecast of air pressure change for a 15 × 18 grid of 500-mbar contour surface—and in 1956 Norman Phillips computed the first climate experiment for the northern hemisphere, successfully reproducing the global circulation cells (Charney et al. 1950; Phillips 1956). Both experiments were based on simple barotropic models of the atmosphere, marking the beginning of numerical modelling in meteorology. Since the 1950s modelling as well as available computer power have advanced by leaps and bounds. This allowed the increasingly advanced models—general circulation models (GCMs) and later, coupled atmosphere-ocean general circulation models (AOGCMs)—to be used for specific experiments, and climate science to be applied to practical problems, e.g. for investigations on the impact of doubling CO_2, on deforestation, and on other environmental problems. With these experiments meteorology turned into climate change science, and purely scientific interest in the field was complemented by sociopolitical demands. Growing efforts to coordinate climate modelling and climate change response negotiations on an international level have accompanied this shift. Today, Earth system models (ESM), model intercomparison, advanced evaluation methods, and the IPCC Assessment Reports are the cornerstones of an internationally organized climate change science and policy. This development has opened up the community of GCM/ESM modellers—more than a dozen institutes around the globe—to new and rapidly growing groups of model users, model output users, and modellers that have extended the variety of climate models by adding regional models, Earth system models of intermediate complexity, integrated assessment models, and other types of climate change and impact models.

A driving force of this development has been the Intergovernmental Panel on Climate Change (IPCC) and the regular release of the IPCC Assessment Reports. Since the early 1990s the reports have reviewed and accumulated state-of-the-art knowledge on climate change and given projections of possible future developments. Furthermore, they have introduced an international rhythm of model development, improvement, evaluation, and intercomparison which is unique in science. This concerted cycle has substantially improved the new method of computer-based simulation for knowledge production. However, the IPCC Assessment Reports play a crucial role on both sides: climate change science and climate change policy (Arthur C. Petersen, Chap. 3). As a 'boundary organization' the IPCC has introduced procedures and rituals for interconnecting science and policy, but also ensures the stability of the boundaries between the two. The most decisive and urgent task of IPCC is the mediation of 'robust conclusions' on climate change. Therefore, the main types of uncertainties had to be identified: unpredictability (the evolution of society, chaotic components of climate system), structural uncertainty (inadequate and incomplete modelling of processes, ambiguous system boundaries, lack of knowledge on significant processes and relations among variables, etc.), and value uncertainty (inaccurate, missing, and non-representative data due to inappropriate spatial and temporal resolution). Furthermore, the uncertainty of climate change projections had to be assessed on scales of confidence and likelihood in order to support decision-making under uncertainty for policy makers. This process of identification and assessment of uncertainty is an integral part of the extended review process of the IPCC Assessment Reports. Hundreds of authors and reviewers, considering ten thousands of statements from the community on the assessment of results, take months and years to prepare the scientific basis and conclusions until the Summary for Policymakers is finally approved line by line by the participating governments. This extended review process and the ritual of wording is unique in science, though not without its critics. The example of the Summary for Policymakers in the third IPCC Assessment Report shows the careful and complex process of adequately incorporating information and wording it carefully, in particular for the uncertainty level of the statements. From this perspective, the IPCC Assessment Reports are seen less as instruments to create ‘scientific consensus’ than as ‘policy-relevant assessments acknowledging uncertainty’.

Such an uncertainty assessment is indispensable for policy options, as there is social pressure for robust advice (Hermann Held, Chap. 4). Therefore a paradigm shift from deterministic to probabilistic climate projections, new data sources, and new forms of learning are required. The last of these refer to a concept of uncertainty that is seen more as a ‘catalyst for self-awareness on silent assumptions within disciplines’—accepting the challenge of uncertainty—than as an unsolvable problem. This awareness stimulates constructive interaction among disciplines, in particular among climate science, economic, and statistics. Over the course of the IPCC Assessment Reports scientists have further developed the debate on uncertainty. In particular during the work on the third report, they began discussing the problems of intra-model uncertainty, of climate sensitivity (CS) as a key uncertain property, and of system-immanent response time scales. This stimulated the exploration of new methods such as Bayesian statistics for intra-model uncertainty, strategies for retro-reduced CS uncertainty, and the study of restoring mean time scales in historical records—following the idea that, if climate’s main response time could be reconstructed, the uncertainty about global mean temperature could be reduced. However, besides these scientific efforts to deal with uncertainty, society has to decide which view should be assumed with regard to climate change: that of a ‘climate-impact-pessimist’ following the ‘precautionary principle’, or that of a ‘climate-impact-optimist’. The second view takes the scattered knowledge on climate change into account, mainly the positively known information. Combining both views recently led to the debate on the ‘2°C-target’ and on the economic costs to realistically achieve at least this target.

The debate on how mankind should respond to climate change is diverse, as the appropriate strategy depends on local and regional circumstances. Besides mitigation and adaptation, the concept of geo-engineering emerges on and off the agenda, although most scientists do not regard geo-engineering as an appropriate strategy. However, the more interesting question is not necessarily what can be done, but which concrete mechanisms are needed in order to realize a diverse set of strategies. These mechanisms will decide whether at least the 2°C-target will be achieved. Therefore Chaps. 5–8 of this volume explore a mix of exemplary mechanisms, which can help, or not, to respond to climate change: the market mechanism for reducing greenhouse gas emissions, the possibilities and limitations of insuring risk, and the awareness that is created by such insurance policies, the disillusioning lessons which can be learned from weather modification in order to assess climate engineering, and the utilization of participatory approaches to design proactive responses to regional climate impacts. The case studies demonstrate the sensitive interdependency between climate change science, climate change policy, and the various mechanisms. This interdependency is influenced by different types and sources of uncertainty and, depending on the specific mechanism, requires specific ways of dealing with uncertainty.

Probably the most ambitious attempt at a global response to climate change is the introduction of market mechanisms for reducing greenhouse gas emissions by the United Nations Framework Convention on Climate Change, outlined in the Kyoto Protocol of 1997 (Alex Vasa and Axel Michaelowa, Chap. 5). This global response is based on various market mechanisms: trading Certified Emission Reductions (CERs), and the components of Joint Implementation (JI), Clean Development Mechanism (CDM), and International Emission Trading (IET). IET allows governments to sell unused shares of their emission budget; JI permits the generation of emission credits through emission reduction, and the CDM allows projects that reduce emissions to generate emission credits. In this system one CER is considered to be equivalent to one metric ton of CO_2 emissions. The Kyoto Protocol stipulated an 'orientation period' from 2008 to 2012, which has to be extended by a post-2012 strategy. After the disappointing results concerning a reliable post-2012 strategy of the UN Climate Change Conference (COP-15) at Copenhagen in 2009, the next UN conferences will show whether agreement can be achieved. Although managing emissions is one of the fastest-growing segments in financial services, the key uncertainty is whether such an international regime is manageable and how long it will last. Therefore the post-2012 strategy will decide how market participants will behave. Besides the uncertainty of the inconsistent application of the rules of these market mechanisms by the institutions governing the market mechanisms, these uncertainties influence the prices on the Kyoto market and the carbon market. However, only a long-term orientation on global climate policy can lead to substantial effects on reducing greenhouse gas emissions.

Another market-relevant aspect is addressed by the question of the insurability of climate change and its relation to climate change policy (Michael Huber, Chap. 6). Of course climate change itself cannot be insured against, but various effects of climate change which can be transformed into a set of insurable risks are insurable. As losses due to disasters are measures of economic costs, and as these losses are increasing significantly, insurance and reinsurance companies as well as policy makers are paying increasing attention to these developments. Between 1990 and 2008 a total of 600,000 people died as a direct consequence of more than 11,000 extreme weather events, and economic losses of 1.7 trillion USD were insured (Harmeling 2010). Local communities have to rely on insurance solutions to be more resilient to climate risks. But this would privatize climate change effects, which is not really advisable due to the size and global scale of the problem. As flood risk insurance has shown, states tend to shirk responsibility for effective climate policy by offloading the costs of climate change onto insurance companies. The problem is exacerbated because insurance fosters adaptive strategies, while climate change requires preventive policies. Another problem is the state-dependency of insurance regimes, which establishes an unequal treatment of climate change effects. The various regimes, in turn, influence the political weight of events.

Besides market mechanisms for greenhouse gas emissions and insurance solutions, another segment of an emerging climate change market seems to be preconceived: climate engineering (William Cotton, Chap. 7). Most scientists are extremely cautious in considering climate engineering as an option, and there are good reasons for this wariness as climate is a complex and multifaceted system of feedback interaction. Nevertheless, there is a fear that climate engineering could be considered as a 'last gasp' measure to prevent the catastrophic consequences of climate change because political decision-making fails—and COP-15 was a good example. Such a scenario could be the case notwithstanding the unforeseeable side effects of climate engineering, which would trigger a risk spiral of quasi-infinitely regressive human interventions in the climate. Climate engineering would involve major uncertainties. At present the effects of climate engineering cannot even be evaluated, as the cause-and-effect chains of global warming are not sufficiently known, and because an accurate benchmark for natural climate variability is lacking. Obviously, there is no trial-and-error method available to figure out appropriate climate engineering designs. However, the history of weather modification in the US shows that while operational programs were supported with considerable resources, scientific research to study the possibility and impact of weather modification decreased to a low level in the 1980s. This led to commercial applications without the guidance of sound scientific investigations.

The fear of the catastrophic consequences of climate change is engaging scientists and policy makers to search for solutions on a global scale. Nevertheless, global climate change is the sum of countless local interventions like pollution, deforestation, extensive agriculture, urbanization, traffic, and others. In fact, a possible success in achieving the 2°C-target is rooted in an appropriate way of linking mitigations and adaptations on the local scale in an integrated and participatory manner (Livia Bizikova, Sarah Burch, John Robinson, Alison Shaw, and Stephen Sheppard, Chap. 8). The case studies from British Columbia show how a participatory scenario-building process for local, proactive responses to climate change can be developed, and how uncertainty can be communicated in this process. In accounting for the human dimension, scales of likelihood are not very useful to support decisions and choices. Instead, diverse tools like storylines, 3D visioning, and backcasting are used to explore plausible futures. The results of these attempts indicate that uncertainty can be addressed efficiently. In particular visualizations, for instance of rising snowlines or sea levels, help to develop a typology of resilience for local scenarios.

Participation directly involves local communities in climate change response activities. This direct engagement is urgently needed as citizens are otherwise restricted to public media as their source of information about climate change. Such a restriction forces citizens to passively monitor the activities of policy makers, which seems less than beneficial for proactive responses. Furthermore, it puts them at the mercy of the media's image politics of climate change (Birgit Schneider, Chap. 9). As the case studies from British Columbia indicate, visualizations are important tools for envisioning possible effects of climate change and for assessing decisions and choices together with local communities. Images are considered to have a pedagogical ability to show complex connections in an easy way. But this view of images is misleading, as climate images are highly complex knowledge sources, overloaded with information that require ‘visual literacy’ in order to decipher the incorporated information. As climate itself is not a perceptible phenomena but a scientifically constructed object, images on climate and climate change, such as the well-known ‘hockey stick graph’, are also highly constructed objects—in particular those images that picture possible futures. The main question here is how uncertainty about these possible futures can be communicated within images. Various designs like blurred areas, bifurcated curves and others have become common elements in climate visualizations. However, the human necessity for visioning in order to comprehend possible developments endows images with power. The media benefit from this fact. The fever curve of global warming and the lonely polar bear drifting on a sheet of ice seem to bear witness to the impact of climate change.

Summing up, climate change and policy have turned the physics of the atmosphere and the ocean into a multifaceted picture of the Earth system. Although the physical models based on hydro- and thermodynamics are still at the core of climate change science in order to achieve computability, the applicability of these models has introduced various sources of uncertainty, e.g. the intra-model uncertainty of parameter values. These uncertainties propagate into the output of the models and into policy options. However, as these uncertainties are an integral part of human knowledge, in particular on possible future developments, rather than capitulating, it is time to develop strategies for dealing with uncertainty. As the papers in this volume indicate, various strategies and mechanisms are on their way to constituting not only an international arena of climate change science and policy, but also a climate change market and a framework for local and proactive responses. A balanced mix of strategies and mechanisms, accompanied by scientific progress in understanding climate change, will decide whether at least the 2°C respectively 450 ppmv target can be achieved.

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Chapter 2
Modelling the Climate System: An Overview

Gabriele Gramelsberger and Johann Feichter

A Google search for the keyword ‘climate’ on a cold summer day in August 2010 delivered more than 150 million links in 0.23 s, and ‘climate change’ brought another 58 million. Obviously it is no problem to find floods of information about these topics on the net, yet understanding the scientific concept of climate and climate modelling is not so easy. The trouble with ‘climate’ starts when it is mixed up with the idea of weather, and when extreme weather events and short-term trends in temperature or precipitation are interpreted as effects of climate change. Usually, these interpretations are linked to an individual’s memory of experiences in childhood and other periods of life. But the trouble results not from this individual definition, which does not accord with the World Meteorological Organization’s official definition of climate as the statistics of weather.[1] The trouble is raised by the scientific concept of climate as a mathematical construct that cannot be experienced directly. This problem is hitting science now that socio-political demands are coming into play. For responding to such demands, science has to break down its statistical and general concepts into individual and local conclusions, but this is—at the moment at least—not possible. The reason lies in the top-down approach of modern science, which uses globally valid equations to achieve increasingly higher resolution. The great challenge for meteorology during the next years and decades will be to translate statistical and general results into individual and local knowledge. Or in other words, science has to connect its global view with local

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[1] “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 2007a, p. 249).

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circumstances. Regional modelling and downscaling are just the beginning, although these methods are still far removed from any particular individual or local view of a particular city or area. Of course, one can ask why humans do not simply get used to the scientific concept of climate. But when concrete environmental activities are required, individual needs and local effects play the main role, not the annual mean global temperature.

In order to set the stage for this challenge to meteorology, the present chapter will provide an introductory view on its background: the current practices of climate modelling and predictions, and their roots in the development of science. First of all, in Sect. 2.1 the scientific view on the climate and Earth as systems will be outlined. Section 2.2 will then give a historical retrospective in order to show why science is so dependent on numerical models and, in Sect. 2.3, how the climate is modelled today. Section 2.4 will continue with insights into the extensive structure for the international coordination of climate modelling, and in Sect. 2.5 the purpose of undertaking these huge efforts will be questioned. The answer, of course, is: to project future trends, but this poses another question. What kind of projections are provided and what can we expect from them—especially considering the uncertainties associated with this computable view into the future? Finally, in Sect. 2.6 limits of scientific arguments will be discussed.

2.1 Understanding the Climate System

2.1.1 Climate Stability

Paleo-data show that for the last 12,000 years we have lived in a relatively stable climate period called the Holocene (Stott et al. 2004). This stability supported the development of civilization based on the Neolithic Revolution around 10,000 B.C., when agriculture and cities were invented and the population multiplied (Gupta 2004). But history also demonstrates the sensitivity of particular human civilizations that collapsed upon encountering regional climate changes, as the ancient Mayan culture proved. This sensitivity to environmental conditions—both stable and unstable—has long shaped regional knowledge about the climate, but it took several thousand years before mankind reflected on the differences between climate zones. Based on a spherical world concept, in the sixth century B.C. the Greek philosopher Parmenides classified different zones from torrid and temperate to frigid climates. The term 'κλιμα' thereby referred to the slope of the Earth. Various theories on the number of zones followed—Parmenides listed five, Ptolemy later seven—, as well as on the portion of the world that is habitable, on the climatic influence of the length of days, and finally, on the synonymy of climate and latitude on maps by Ptolemy in the first century A.D. Ptolemy, in particular, became quite influential in the Arabic world as well as in Medieval and Renaissance Europe (Sanderson 1999). Climate zones were used as marks of orientation on maps until degrees of latitude were introduced in the sixteenth century. From the eighteenth century on, measurables such as temperature and precipitation were employed to indicate climate zones. But even though such measurables were used, the Ancient classification persisted.[2]

However, climate was seen as a stable phenomenon that shaped the form of climes. At the beginning of the nineteenth century a major debate on the origin of surface deposits, from clay to boulders, began among geoscientists. The dominant belief at this time was that the deposits were witnesses of the Biblical deluge. Consequently this period was coined ‘Diluvium’, the Latin word for deluge. Apart from the Biblical narratives, nature was considered to be invariant, inspired by the belief that only invariance provides objective truth. Later, in 1813, George Cuvier proposed that several catastrophic events could have been responsible for the deposits. In 1840 Charles Lyell hypothesized that floating icebergs might have dropped the erratic boulders rather than marine currents. Finally, the concept of widespread continental multiple glaciations gained ground at the end of the nineteenth century, giving rise to the idea that climate can change. But what were the reasons? In 1864, James Croll proposed an astronomical theory, speculating that changes in the earth’s orbital parameters might have triggered the sequence of cold and warm periods (Odroyd and Grapes 2008). The geophysicist Milutin Milankovic developed a mathematical model to calculate the changes in solar insolation due to orbital variations. His results were published in 1941, but the computed changes in insolation were too small to significantly perturb the climate system. Therefore, his theory was ignored for some decades until observational evidence from deep-sea sediment data taken in the 1960s was found to support his hypothesis. Numerical climate models have demonstrated that the Milankovic cycles initiate a suite of positive (amplifying) feedbacks in the climate system, which finally result in the occurrence of glacial and warm periods (Berger 1988; Ganopolski et al. 1998). Milankovic’s theory of celestial mechanics, causing changes between Warm Ages and Ice Ages, influenced the perception of climate research as an exact science. It fueled the hope that future climate developments were predictable.

2.1.2 The Physical and Mechanical Understanding of Climate

In order to understand this paradigm shift from an invariant climate to the perception of climate as a kinetic system, a physical and mechanical understanding of climate, as it is common for today’s science, is required. This understanding is

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[2] “The first quantitative classification of world climates was made by the German scientist Wladimir Koeppen in 1900. Koeppen was trained as a plant physiologist and realized that plants could serve as synthesizers of the many climatic elements. He chose as symbols for his classification the five vegetation groups of the late nineteenth-century French botanist De Candolle, which was based on the climate zones of the Greeks: A, the plants of the torrid zone; C, the plants of the temperate zone; D and E, the plants of the frigid zone, while the B group represented plants of the dry zone. A second letter in the classification expressed the moisture factor (an Af climate is tropical and rainy)” (Sanderson 1999, p. 672; see also Koeppen 1936).

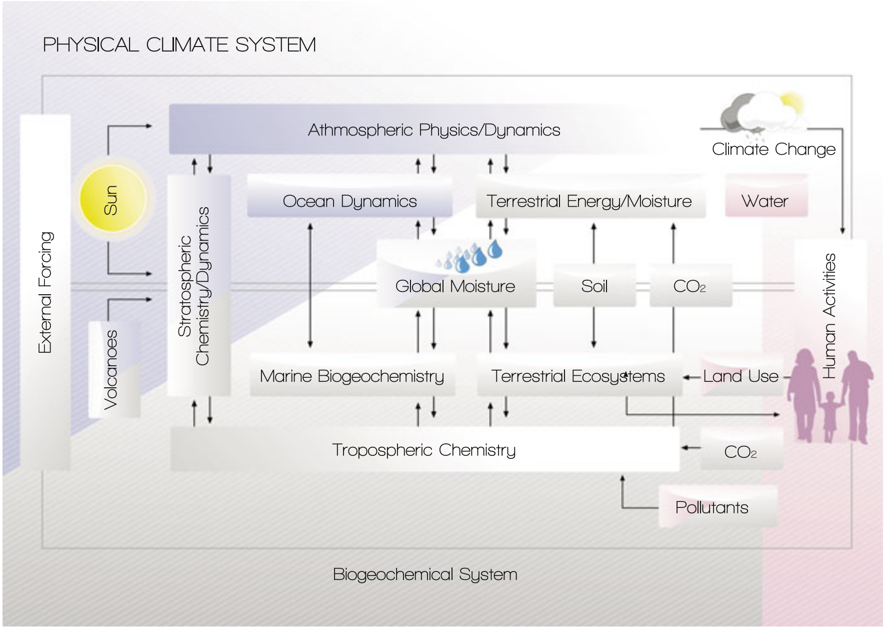

Fig. 2.1 Bretherton diagram. Various interactions and driving forces of climate change
Source: Replotted by the authors from *Earth System Science Challenges*, *The Strategic Plan 2003–2010*, Max Planck Institute for Meteorology 2003

based, on the one hand, on a view of nature as a complex system compounded of various components, each ruled by a set of interacting entities (see Fig. 2.1).[3] While climate used to be connected mainly to the atmosphere, today's approaches include the atmosphere, the ocean, the cryosphere (sea-ice and the large ice shields and glaciers), the pedosphere, and the marine and terrestrial biospheres. On the other hand, the physical and mechanical understanding combines two views which are two faces of the same coin: energy and motion. Driven by solar radiation, the atmosphere and the Earth absorb, transform, reflect and emit incoming energy.[4]

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[3] The system approach was introduced into science in nineteenth-century thermodynamics by the physicist Nicolas L.S. Carnot. He envisioned the relations between heat and work done by heat in an ideal heat engine, i.e., in a closed body. In 1824, his experiments led him to the following theorem: "When a gas changes in volume without change of temperature the quantities of heat which it absorbs or gives up are in arithmetical progression when the increments or reductions of volume are in geometrical progression" (Carnot 1824, p. 28).

[4] The relevant electromagnetic spectrum of radiation ranges from short-wave radiation emitted by the sun mainly as visible light (about 400–780 nm), to long-wave radiation emitted by the Earth and the atmosphere, mainly as heat (infrared light about 780 nm–1 mm). According to Wien's law the wavelength of emitted radiation is indirectly proportional to the absolute temperature. Thus, solar radiation is in the short-wave range (the sun's temperature ~5,800 K) and the infrared radiation emitted by the surface or the atmosphere is in the long-wave (or thermal) range. The increase in wavelength goes along with a decrease in energy.

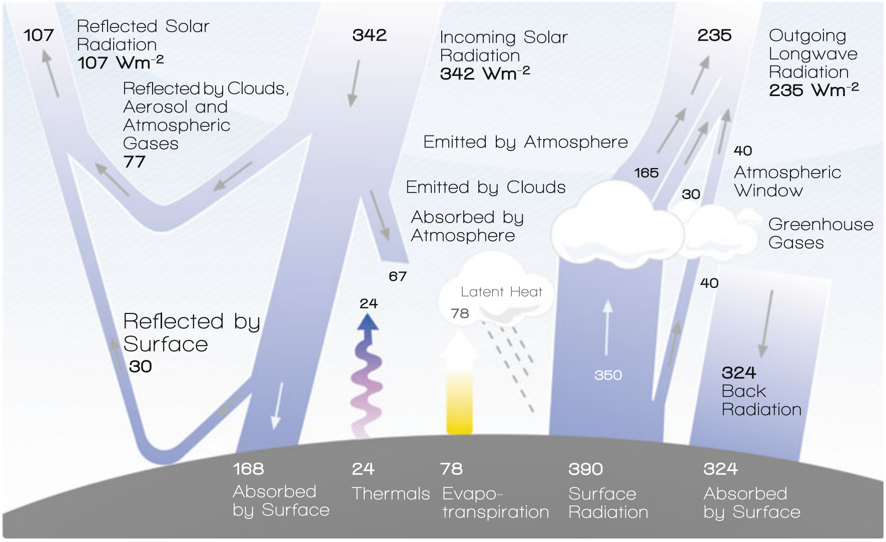

Fig. 2.2 Estimate of the Earth's annual and global mean energy balance. As displayed above, the planetary albedo, which is the fraction of solar radiation reflected, amounts to about 31%. The other 69% are used to heat the Earth-atmosphere system (20% the atmosphere and 49% the Earth's surface). The energy leaves the Earth-atmosphere system by conduction (rising hot air), as latent heat (energy is used to evaporate water which condensates in the atmosphere, where the energy is released again and carried from the surface to the atmosphere) and by thermal radiation. The thermal radiation from the surface is absorbed by greenhouse gas molecules in the atmosphere and radiated back to the surface, enhancing the temperature or escaping into space. The Earth remains at a constant temperature if averaged over a longer period, because the outgoing radiation equals the incoming
Source: Replotted by the authors from Kiehl and Trenberth 1997, p. 206

The view on energy focuses on the balance of energy flows by reflection, absorption and emission. These energy flows are based on the reflection of incoming solar radiation by air molecules, water droplets, ice crystals, and other particles; the absorption and transformation of incoming solar radiation into heat by the same particles; the reflection by the different surfaces of various albedos like water, vegetation, and snow;[5] the absorption of the energy not reflected and transformation into heat by these surfaces; the horizontal energy flow between the poles and the tropes by advection; and the latent heat flow of the water cycle (see Fig. 2.2). The overall energy radiated by a surface, according to Stefan-Boltzmann's law, is directly proportional to the fourth power of their absolute temperature. These energy flows are influenced by the behaviour of greenhouse gases and clouds. An atmosphere without greenhouse gases would lead to a surface temperature of –18°C. The greenhouse gases—the most important among them water vapour—act like a shield that keeps the surface temperature of the Earth at a lively +15°C.

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[5] Albedo is the fraction of reflected solar radiation to the total incoming solar radiation; $A = 1$ means all radiation is reflected.

If we neglect feedbacks, it is easy to calculate a rough estimate of the temperature change due to an increase in carbon dioxide (CO_2). The equilibrium surface temperature can be derived as

$$T_G = 4\sqrt{\frac{S_0(1-A)}{2\sigma(2-\alpha)}},$$

with S_o the solar constant, the incident solar radiation at top of the atmosphere; *A* the planetary albedo, or (*1−A*), the fraction of solar radiation absorbed by the Earth's atmosphere; α the long-wave absorptivity of the atmosphere as controlled by greenhouse gas concentrations; and σ the Stefan-Boltzmann constant. According to this equation, the surface temperature increases if the solar constant or the absorptivity (or the greenhouse gas concentrations of the atmosphere) increases, and decreases if planetary albedo increases. Short-wave radiation heats up the Earth's surface and to a smaller extent the atmosphere, and is emitted back to the atmosphere as long wave-radiation. Carbon dioxide, methane, and other gases as well as water vapour, clouds, and aerosols absorb and emit radiation within the thermal infrared range. Thus, a complex flow of energy, depending on the Earth's surface properties and the chemical composition of the atmosphere and modified by numerous feedback processes, determines the thermodynamic state of the atmosphere.

Energy causes motion. The view on motion focuses on the dynamics of the atmosphere caused by the effects of local differences in energy input and output, which create mechanical work in terms of motion.[6] Spatial and temporal variations in the energy balance drive the motions of the atmosphere as well as the ocean. For instance, the annual amount of energy received at the equator is a factor of 2.4 greater than that at the poles. This difference in solar radiation in polar and tropical zones lead to global circulation: Warm air in the tropics expands, becomes lighter, rises, drains off to the side in higher regions of the atmosphere (air pressure falls), and causes a vertical flow which drives the global circulation. Conversely, cold air sinks and becomes heavier (air pressure rises). Thus differences in temperature result in differences in air pressure and, in turn, differences in air pressure result in mechanical work, that is, motion based on the air's expansion and contraction. The gradients in temperature and pressure decisively influence the atmosphere's circulation, but other factors also play a role. The deflective effects on air masses by the Earth's rotation, angular momentum, gravity, and the Coriolis effect contribute to the global circulation and form typical wind patterns (see Fig. 2.3). Furthermore, global circulation interacts with regional conditions like surface properties and mountains to produce regional patterns such as the monsoons. Variations in local energy budgets are controlled by land-sea distribution, by soil type, by vegetation cover, by clouds and by the chemical composition of the atmosphere. In turn,

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[6] Because about 90%of the atmosphere's mass is located in the troposphere—from the ground up to an altitude of 16 km (about 1,000–100 hPa)—most circulation takes place here.

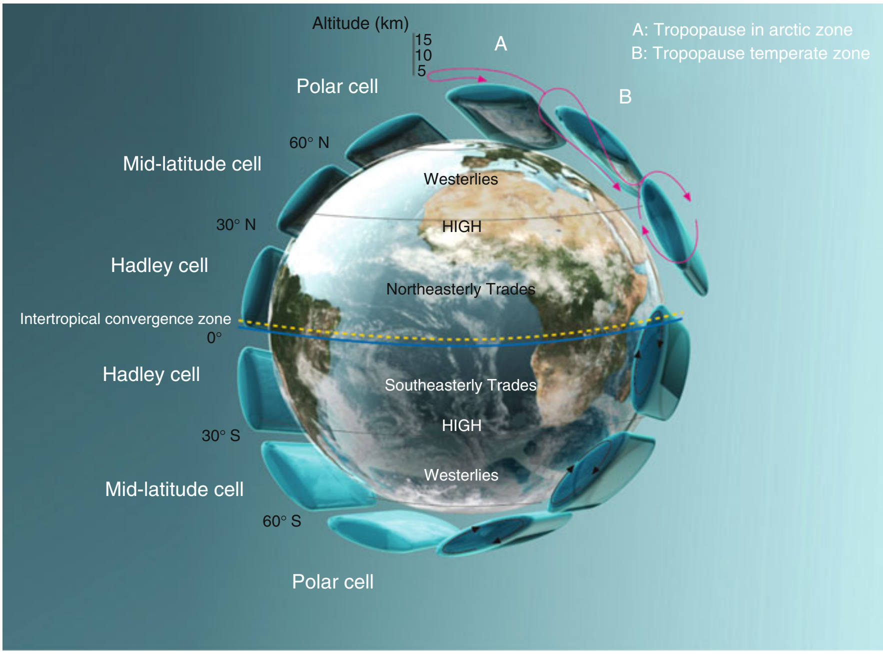

Fig. 2.3 The global circulation of the Earth: The polar cells, the mid-latitude cells (about 30°N to 60°N and 30°S to 60°S with the westerlies) and the Hadley cell (about 30°N to 30°S latitude with the northeasterly and southeasterly trade winds). When shipping increased in the sixteenth century, a scientific understanding of wind patterns became important. At the beginning of the seventeenth century it was known that around 30° latitude there is a 'torrid zone' with weak winds, and that south of this zone regular, northwesterly winds, called Trade Winds, exist (Persson 2006)
Source: Replotted by the authors from NASA, http://sealevel.jpl.nasa.gov/overview/climate-climatic.html

clouds, vegetation and chemical composition are influenced by the energy fluxes and other meteorological parameters.

While motion is caused by energy differences, it is slowed down by friction. Differences in wind velocity cause eddies, which propagate energy down to micro turbulences and molecular motion—where motion is transformed into heat. Both sides of the coin, energy and motion, are reunited within a general circulation model (GCM) which interconnects the two in terms of differences in velocity, humidity, density, pressure, and temperature, and thus models the complex physical and mechanical system of the atmosphere.

2.1.3 *Greenhouse Effect and Climate Sensitivity*

As mentioned above, without greenhouse gases the atmosphere would provide us with a mean surface temperature of –18°C instead of a lively +15°C. But this energy balance is a fragile one. Back in 1896 the physicist Svante Arrhenius already recognized that CO_2 supports a greenhouse effect. The meteorologists of that period first discussed the question as to whether "the mean temperature of the ground [is] in any way influenced by the presence of heat-absorbing gases in the atmosphere?" (Arrhenius 1896, p. 237). According to Arrhenius, "Fourier maintained that the atmosphere acts like the glass of a hothouse, because it lets through the light rays of the sun but retains the dark rays from the ground" (p. 237). This absorption of heat "is not exerted by the chief mass of the air, but in a high degree by aqueous vapour and carbonic acid, which are present in the air in small quantities" (p. 239; Rodhe et al. 1997). It was not today's motivation of understanding and preventing anthropogenic greenhouse effect that posed the above question, but the interest in the cause of Ice Ages that drove climate research in the late nineteenth century. The basic hypothesis at that time was that mankind will face a new Ice Age; therefore an increase of temperature was welcomed. In 1938, the British engineer Guy S. Callendar published his groundbreaking studies on the increase of CO_2 concentration in the atmosphere. He pointed out that since the 1880s more than 150,000 million tons of CO_2 had been added to the air, and estimated that this would cause an estimated increase in temperature of about 0.003°C per year. For Callendar, this increase was embraced because the "return of the deadly glaciers should be delayed indefinitely" (Callendar 1938, p. 236). Therefore "the combustion of fossil oil [. . .] is likely to prove beneficial to mankind in several ways" (p. 236).

However, this opinion changed once scientists recognized the trend towards global warming. But it took another two decades before scientists became alarmed about the release of CO_2, because their main hypothesis was that the oceans would absorb it. The study by Roger Revelle and Hans E. Suess in the 1950s showed that the oceans cannot absorb CO_2 as rapidly as it is produced by mankind and that mankind was about to conduct "a vast geophysical experiment" (Revelle and Suess 1957). In 1957 Bert Bolin and Erik Erikson investigated the buffer and exchange mechanisms of the ocean en detail. Taking the rapid increase of fossil fuel emissions into account, they argued that the CO_2 content in the atmosphere would rise about 25% or more by 2000—in agreement with a study by Callendar at the same time (Bolin and Eriksson 1959; Callendar 1958).[7] Thus, the plan for a worldwide network of CO_2 monitoring stations was broached in the 1950s. The measurement of CO_2 concentrations began in Scandinavia back in 1955 (Bischof 1960), and in 1958 Charles D. Keeling begun measurements using an infrared CO_2 gas analyzer at the Mauna Loa Observatory in Hawaii as part of the International Geophysical Year.[8] This new instrument, as well as the site of Mauna Loa, allowed the collection of highly accurate results. Today the 'Keeling Curve', a time series of annual departures from 1961 on, clearly shows the increase of CO_2 concentration in the

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[7] A seminal study on *The Discovery of Global Warming* and a substantial bibliography is provided by Spencer Weart: URL: http://www.aip.org/history/climate/bib.htm (Weart 2003).

[8] Keeling's measurements were supported by Revelle, who "wanted to make sure that man's 'vast geophysical experiment' would be properly monitored and its results analyzed" (Keeling 1978, p. 38).

atmosphere at a site that was thought to be unpolluted. This curve has become one of the icons of man-induced climate change (Keeling 1978; Weart 2003; see also Chap. 9 of this volume).

In the 1970s, once simulation methods had gained ground, the question arose as to what temperature would result from a doubled increase of CO_2 concentrations (Charney et al. 1979). This value, called ‘climate sensitivity’, is still one of the key questions in climate research. Climate sensitivity is defined as the globally averaged near-surface temperature change per greenhouse-gas-induced radiative perturbation. It can only be assessed by model-based simulations since controlled laboratory experiments with the atmosphere are not an option, although the model-based estimates of climate sensitivity vary by a factor of three. The main reason for this uncertainty is the fact that only 40% of warming is due to the relatively well-known direct greenhouse gas effect on thermal radiation, with 60% caused by feedbacks within the climate system. For instance, a warmer atmosphere retains more water vapour, and since water vapour is the most important greenhouse gas, this increase in water vapour concentrations enhances warming. The major uncertainty arises from feedback effects concerning clouds. Therefore, in order to diminish uncertainties and to enhance the understanding of the behaviour of the Earth’s system, more and more processes have to be parameterized and implemented in the models.

Ever since Charney posed the ‘CO_2 doubling question’ the endeavour of understanding the complex interplay of atmospheric processes has taken on entirely new dimensions. Today it is known that man’s activities impact the climate system via three mechanisms: by increasing greenhouse gases or ozone (which also absorbs in the solar radiation spectrum) in the atmosphere; by emitting aerosol particles or aerosol precursor gases; and by changing land surface properties. The greenhouse gases emitted by man, ordered according to their importance, are the long-lived species carbon dioxide (CO_2) and methane (CH_4), chlorofluorocarbons (CFCs), nitrous oxide (N_2O, laughing gas) and the short-lived species ozone. Greenhouse gases affect the thermal radiation budget and exert a warming effect. Aerosols are liquid or solid particles in the atmosphere ranging in size between some nanometers to some micrometers. Aerosol particles are either emitted as particles (e.g., soot, dust from industry and road traffic) or formed by the condensation of vapours in the atmosphere (e.g., ammonium sulfate, ammonium nitrate, organics).

The man-made aerosol precursor gases are sulfur dioxide, nitrogen dioxide, ammonia and volatile carbon compounds. These particles absorb or scatter solar radiation and reduce solar insolation at the surface (solar dimming). Thus, in polluted regions we experience the paradox that although temperatures are rising, solar insolation is decreasing. Absorbing aerosols like soot warm the earth-atmosphere system; scattering aerosols like ammonium sulfate, ammonium nitrate and organics cool it. Furthermore, aerosols act as cloud condensation and ice nuclei. Cloud droplets and ice crystals form on aerosols, and the particle number concentration and chemical properties affect the microphysical properties of clouds. Aerosol pollution enhances the albedo of water clouds and thus exerts a cooling effect. The effects of aerosol pollution on ice clouds are not yet well understood and could amount to either warming or cooling. Land-use change, by deforestation and covering soil through urbanization and infrastructure construction, changes the surface albedo, the capacity of soils to hold water, and the evaporation rate. Pastures and cropland have a higher albedo than forests, thus land-use change in temperate and tropical latitudes enhances the amount of solar radiation reflected back to space, exerting a cooling effect. In tropical regions, deforestation reduces the evapotranspiration rate and results in warming. The overall effect of land-use change is to lower temperatures. However, with increasing deforestation in the tropics, the warming effect due to reduced evapotranspiration might dominate in the future.

2.1.4 Climate Variability

Based on this understanding of the fragile balance of direct and indirect feedbacks between the various components of the climate system, climate is defined as a statistical description in terms of the mean values and variability of relevant meteorological quantities over a period of time (WMO 2010). This definition unveils two basic concepts of climate research: averaging and variability. In fact, climate variability refers to changes in the mean state of climate (the standard deviation), or the occurrence of extremes on spatial and temporal scales beyond the variability of weather events. The variability of climate is caused by internal factors (internal variability) and by natural and anthropogenic forcings (external variability). Numerous interactions between the components of the climate system and nonlinear feedback loops induce random climate fluctuations on various temporal scales, a kind of noise in the climate system. Even in the absence of any radiative forcing or perturbation, weather patterns differ from year to year. These fluctuations, also called ‘internal variability’, are inherently chaotic and thus not predictable—some regions experience stronger, some weaker variability. Furthermore, some parameters are more variable than others; for instance, temperatures at high latitudes show stronger variability than in the tropics, and precipitation fluxes are characterized by higher variability than are temperatures.

External mechanisms cause changes in the state of climate, such as changes in solar radiation, changes in the Earth’s orbital parameters, plate tectonics, strong volcanic eruptions, and human influences. The sign and magnitude of these perturbations is expressed in terms of the net radiative imbalance at the top of the troposphere or atmosphere. Man-made perturbations of the radiative imbalance are termed ‘radiative forcing’, with negative forcing causing cooling and positive causing warming. The radiative imbalances and forcings are calculated using general circulation models of the atmosphere. The radiative forcing due to a man-made increase in CO_2 concentrations between 1750 and 2005, for instance, is +1.66 W/m^2. In contrast, the CO_2 concentration after the eruption of Mount Pinatubo in June 1991, the best investigated volcanic eruption, was in the order of –3 W/m^2 one year after eruption, but dropped to pre-eruption values within few years. Compared to anthropogenic and other natural forcings in the climate system, volcanic radiative forcing acts on a short time-scale.

Knowledge of internal climate variability is mandatory to detect anthropogenic impacts on the climate. As both external forcings and internal variability impact climate, only climate models can separate internal from forced variability. Internal variability might change in a changing climate—and a specific forcing can excite a particular mode of this internal variability, leading to a kind of resonance. The magnitude of the climate response to a specific forcing can thus be weak or very intense, depending on the actual mode of internal variability when the forcing is applied. As a consequence of these chaotic internal fluctuations, the time evolution trajectory of the past climate can never be reproduced exactly by a climate model, because each simulation is just one realization of many possible states. Hence, simulations reproduce past climates only in a statistical sense, that is, models provide the range of possible climate states associated with a specific forcing (Bengtsson et al. 2006). The internal variability of the climate system thus constitutes an upper limit for the detection of anthropogenic climate change. An anthropogenic climate signal is detectable only if it exceeds the noise or the internal variability. The contribution of natural variability in explaining recent temperature increases is one of the key issues in the current climate change debate.

The important outcome of meteorological investigations since Arrhenius is that climate is a complex phenomenon. As such, it denies the application of mono-causal explanations and, more important, mono-causal interventions. The awareness of this complexity is an indispensable result of series of long-term observations, but also of the increasing use of numerical models in meteorology. In particular, numerical models are needed to conduct ‘experiments’ with a digital atmosphere to acquire analytical knowledge. Only models allow scientists to separate internal from forced variability and to run feedback interactions. For instance, according to model simulations, we know that only 40% of the temperature response due to an increase of greenhouse gas concentrations in the atmosphere arises from the greenhouse effect (change in the thermal radiation budget). The other 60% are caused by feedbacks with the water cycle, emphasizing the importance of feedback processes. And these feedbacks can only be studied in a digital atmosphere. But there are other reasons why science needs numerical models.

2.2 The Need for Numerical Models in Science

2.2.1 From Observation to Forecasting

The briefly outlined picture of the physical understanding of climate is rooted mainly in developments of nineteenth and twentieth-century meteorology. The transformation of meteorology into the physics of the atmosphere was accompanied by the increasing use of models. Models have been a common tool of knowledge production for physicists since the seventeenth century, but are newer to meteorologists because meteorology lacked a theoretical foundation in the eighteenth and nineteenth centuries. It was mainly a descriptive science, based on the measurement and recording of empirical data. But pure data provide no insights into phenomena; they need to be interpreted on the basis of theory. Therefore the introduction of physical laws gradually transformed meteorology from a descriptive science into one based on theory and models.[9] This transformation began when meteorologists tried to apply the physical theories of hydrodynamics and thermodynamics to meteorology, with the consequence that the correlation between global circulations and regional patterns was fully recognized. While weather is defined as the actual state of the atmosphere in a period of several hours up to a few days, climate is the statistics of weather over a longer period, of months, years and decades. Therefore the scientific basis—the physics of the atmosphere—is the same for both, but the application of this scientific basis differs for weather and climate models, e.g., in terms of temporal and spatial resolutions, as well as in their boundary conditions.

A look at the history of meteorology unveils the step-by-step transformation of meteorology into a theory- and model-based science.[10] While the measurement and recording of meteorological variables like temperature, air pressure, and humidity dates back to the seventeenth and eighteenth centuries when the thermometer (temperature), barometer (pressure), and hygrometer (humidity) were developed,[11] the theoretical analysis of these data did not begin until the nineteenth century. One reason was that the available records were not comparable with each other, as they were based on individual measurement devices and periods carried out by singular scholars. As early as 1667 Robert Hooke had presented a *Method for Making a History of the Weather* to the audience of the Royal Society at London, where he demanded the standardization of measurement devices, of measurement periods, and of the style of records (Hooke 1667). But it took another century until the Societas Meteorological Palatina finally coordinated internationally standardized measurements for the first time in 1781.[12] By the end of the nineteenth century a growing

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[9] Models in this sense are defined as the concretizations of a theory. This so-called semantic view on models is widespread in the theory of science (Fraassen van 1980).

[10] There is an increasing body of historical studies on meteorology (see for example Friedman 1989; Fleming 1990, 1998; Nebeker 1995; Harper 2008). A *Bibliography of Recent Literature in the History of Meteorology* is provided by Brant Vogel (Vogel 2009). A review of *The International Bibliography of Meteorology: Revisiting a Nineteenth-Century Classic* is given by James R. Fleming (Fleming 2009).

[11] In 1597 Galileo Galilei developed a water thermometer which was advanced by Daniel Fahrenheit's mercury thermometer in 1714. In 1643 Evangelista Torricelli developed the barometer, and in the eighteenth century Horace-Bénédict de Saussure invented the hair tension hygrometer when he discovered that hair under tension expands relative to the surrounding humidity.

[12] In 1781 the Societas Meteorological Palatina, located in Mannheim, operated 39 weather observation stations around the globe. Because it took more than 100 years to introduce the standard of the Greenwich Mean Time in 1884 (and Coordinated Universal Time in 1972) to globally synchronize measurements, the Societas introduced the 'Mannheim hour' as a global standard for time measurements. By using measurement devices of identical construction for measurements recorded simultaneously all over the world, at 7, 14, and 21 Mannheim hour, they set a standard for meteorological measurements that would fulfill even today's requirements (Wege and Winkler 2005).

network of weather observation stations covered Europe and the US, but measurement instruments and practices still “remained discrepant, and it was enormously difficult to coordinate them. For years [. . .] the failure of coordination appeared on most weather maps in the form of a wholly artificial cyclone over Strasbourg” (Porter 1995, p. 27). Problems in the coordination and exchange of data were the other reason why the theoretical analysis of measurement data was deferred. The exchange of data, too, was as difficult to achieve as their standardization and synchronization, but it made little sense to study weather or climate as local phenomena, since there is no way to escape their dependence on regional and global conditions. Therefore meteorologists had to exchange data, but before the invention of the electric telegraph in 1835 this exchange was difficult and tedious as it was based on the use of printed weather almanacs. During the 1840s the exchange of data by telegraph increasingly allowed the daily analysis of weather conditions from a wider area, with the expanded data rounding out a regional picture of the actual weather situation.

However, the growing amount of data led to a new problem, because tables started to overflow with digits without providing any synoptic insight. Meteorologists had to develop methods to compile a synoptic view from these singular data, thus forcing them to switch from a purely typographic to a hybrid typographic and graphic medium. This switch resulted in a new epistemic tool—weather maps—about which the Norwegian meteorologist Vilhelm Bjerknes later said that “in the hands of these researchers weather maps have developed into a basic—immaterial—instrument of the physic of the atmosphere, analogous to the material instruments of experimental physics” (Bjerknes 1938, p. 61). Although early weather maps could not do full justice to Bjerknes’ claim, they opened up new insights by graphically generalizing singular data with isolines and complex graphical items like wind vectors. For instance, diagrams with overlapping isobars and isotherms presented a picture of the major thermodynamic factors of weather conditions. The combination of these items simultaneously visualized various factors of the weather system, so that meteorologists began to see anticyclones and cyclones: “high- and low-pressure areas roaming over the maps” (p. 50). As they realized that weather was caused by travelling air masses, the development of cyclones (cyclogenesis) became a research topic.

Based on these new insights of synopsis, meteorologists could now think about developing methods for prolonging the synoptic picture into the future. It was Robert Fitzroy, a British Admiral to the Navy, who optimistically promoted the practical utilization of meteorology in his *Weather Book: A Manual of Practical Meteorology* in 1863. As he was particularly interested in forecasting storms, he concentrated on the ‘dynametry’ of air—the movement, force, and duration of motion—which he intended to extract from local measurement data by combining statistical and mathematical methods.[13] He applied a qualitative knowledge of the

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[13] The disastrous Royal Charter storm in 1859, which caused the loss of over 800 lives and the steam clipper Royal Charter, inspired Fitzroy to develop charts for weather forecasts and storm warnings.

atmosphere's dynamics, based on observations and the known physical explanations of the causes of circulation. Back in 1686 Edmund Halley had explained that solar radiation differs for low and high latitudes. Heated tropical air is replaced by cooler air from polar regions, thus causing a north–south circulation. This circulation is, as George Hadley pointed out in 1735, deflected by the Earth's rotation. Because the speed of rotation differs at each point on Earth, as Heinrich Dove explained in 1837, the deflection of air masses differs as well, causing a difference in rotational speed between moving air masses and the places to which these masses have moved. These differences slowly change the direction of the currents, for instance when they come from the North Pole, from north to northeast to east. In 1858 William Ferrel rediscovered the Coriolis effect and applied it to the atmosphere (Halley 1686; Hadley 1735; Dove 1837; Ferrel 1858; Fleming 2002). Fitzroy's dynametry was based on these theories. He took into account the northeast and southwest motion as the 'wind poles', as Dove called them, assimilating all intermediate directions to the characteristics of these extremes. He traced them back to the polar and tropical currents and distinguished them from local effects. He also considered dynamic forces caused by heat or cold, by the expansion of air masses, or other causes. Furthermore, he was aware that changes in weather and wind were preceded and accompanied by alterations in the state of the atmosphere, and that these alterations were indicated sooner in some places than others. Therefore changes in temperature, pressure, and wind direction could be seen as "signs of changes [of weather] likely to occur soon" (Fitzroy 1863, p. 177). On this basis of knowledge and measurement data—compiled from 30 to 40 weather telegrams daily—he introduced his concept of weather forecasting to the newly founded Meteorological Department of the Board of Trade, the forerunner of the British Meteorological Office. Fitzroy coined the term 'weather forecast', defining it as "strictly applicable to such an opinion as is the result of a scientific combination and calculation" (p. 171). In August 1861 the first forecast was published for Scotland, Ireland, and England and he vividly described the practice of this new service in his manual:

> At ten o'clock in the morning, telegrams are received in Parliament Street, where they are immediately read and reduced, or corrected, for scale-errors, elevation, and temperature; then written into prepared forms, and copied several times. The first copy is passed to the Chief of Department, or his Assistant, with all the telegrams to be studied for the day's forecast, which are carefully written on the first paper, and then copied quickly for distribution. At eleven—reports are sent out to the Times (for second edition), Lloyd's, and the Shipping gazette; to the Board of Trade, Admiralty, and Horse Guards (p. 194).

Although Fitzroy was sure that the dynametry of air would become a subject for mathematical analysis and accurate formulas, he had to improve the more accessible tool of weather maps because of the limited capacity of computation at that time. He introduced maps with movable wind markers and 'nodes'–centrical areas around which the principal currents circulate or turn.[14] He used colour gradients to

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[14] According to Alexander Dieckmann, the concepts of both Heinrich Dove and Robert Fitzroy should be seen as forerunners of the 'polar front' theory outlined by Vilhelm Bjerknes in 1919 (Dieckmann 1931; Bjerknes 1919).

mark the energy differences in polar (blue) and tropical (red) air streams. These maps and the knowledge of dynamical principles guided meteorologists in their work of forecasting. But this work was more an art than an exact science. It was based mainly on experience and a feeling for the dynamical principles than on computation or geometrical construction. Nevertheless, the method of 'synoptic meteorology' became a promising approach. In 1941 the meteorologist Tor Bergeron pointed out in a retrospect on his domain:

> Synoptic Meteorology based on telegraphic weather reports appeared in practice simultaneously in England and France in 1861, met with the greatest expectations in all Europe. As a consequence meteorological institutes were established in most other European countries in the ensuing 20 years (in Sweden in 1873) with the main object of issuing weather forecast and storm warnings based on synoptic maps [. . .] Meteorology was, however, then only a new-born science and by far not an exact one. [. . . It] had to get on with mainly empirical, formal and one-side methods, which were quite un-fit to the extreme complexity of its main problems (Bergeron 1941, p. 251).

This lack of complexity led to false prognoses and gave synoptic meteorology a bad reputation until the methods of weather analysis and databases advanced in the 1910s.

2.2.2 Meteorology as Physics of the Atmosphere

Synoptic meteorology, which had its heyday during the first half of the twentieth century when concepts of cyclogenesis gained ground (Bjerknes 1919), followed a qualitative approach of physics. While synoptic meteorology applied its approach from the perspective of the synoptic scale to the atmosphere—a horizontal length scale on the order of 1,000–2,500 km, a complementing perspective from the scale of the infinitesimal, applied to the global scale, began entering meteorology at the end of the nineteenth century, known as 'dynamical meteorology'. This new perspective resulted from the purely theoretical area of hydrodynamics. The problem of motion was of practical interest not only for meteorologists. For centuries it had occupied the greatest minds of science. In 1755 the mathematician Leonhard Euler had derived the general equations of motion from Isaac Newton's Second Law of Motion, stating that a body experiencing a force F experiences an acceleration a related to F by, in Euler's notation, $F = ma$. Euler applied Newton's law to fluids—gases and liquids—by mathematically describing the flow of an idealized fluid without friction. In consideration of the conservation of mass and energy, he received a set of five coupled equations and five unknowns—velocity in three directions, pressure, and density. To close this system an equation of state is required, which specifies the state of matter under a given set of physical conditions: e.g., the ideal gas law, which describes the state of a gas determined by its pressure, volume, temperature, and the amount of substance. The Euler equations were among the very first partial differential equations in science to deal with the concept of infinitesimals. They were later expanded by Claude Navier and George

Stokes for viscous fluids.[15] The Navier–Stokes equations are used to describe the flow of a fluid of a certain mass experiencing various forces such as pressure, gravitation, and friction. The Euler equations correspond to the Navier–Stokes equations if viscosity and heat transfer are neglected. Today's general circulation models of the dynamics of both the atmosphere and the ocean are based on the Navier–Stokes equations.

It was the vision of Vilhelm Bjerknes that meteorology should become an exact science, a physics of the atmosphere, based on thermo- and hydrodynamical theory. Trained as a physicist, he was not interested in meteorology at first, but a mathematical problem regarding idealized assumptions in hydrodynamics directed him towards meteorological considerations. In his study *Appropriating the Weather: Vilhelm Bjerknes and the Construction of a Modern Meteorology*, Robert Friedman describes Bjerknes' situation in the 1890s when he tried to apply hydrodynamic analogies to electric and magnetic phenomena. His results "contradicted the well-established theorems of Helmholtz and Lord Kelvin which claimed vortex motions and circulations in frictionless, incompressible fluids are conserved" (Friedman 1989, p. 19).[16] Bjerknes' results pointed in another direction. He realized that density in a fluid without any restrictions on compressibility depends not only on pressure, as in the concepts of Helmholtz and Kelvin, but on other variables as well, for instance temperature. In 1897, and again in 1898, he presented his results to the audience of the Stockholm Physics Society. The present meteorologists Nils Ekholm and Svante Arrhenius immediately realized the relevance of Bjerknes' "general circulation theorem" for meteorology. The rise of interest in cyclogenesis paved the way for Bjerknes, who started to seriously consider a research program of an exact science of the atmosphere based on the laws of physics—encouraged by the leading meteorologists Cleveland Abbe and Julius Hann.[17] The general circulation theorem laid the basis for a view of the atmosphere as a "turbulent fluid

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[15] George Stokes conceived the motion of a fluid differently than Claude Navier had done. He developed a method that "does not necessarily require the consideration of ultimate molecules [as Navier did]. Its principle feature consists in eliminating from the relative motion of the fluid about any particular point the relative motion which corresponds to a certain motion of rotation, and examining the nature of the relative motion which remains" (Stokes 1845, p. 185).

[16] This claim implied that vortices cannot be created or destroyed in such idealized fluids (Helmholtz 1858). But the appearance and disappearance of vortices was a common phenomenon to meteorologists. Therefore the idealized theoretical and mathematical models of hydrodynamics were not applicable to meteorology.

[17] Bjerknes' concept did not appear out of nowhere, e.g., the meteorologist Sir William N. Shaw had derived equations from physical laws for meteorological problems. In 1866 Julius Hann had already used thermodynamics to explain the warm, dry winds from the Alps. In the mid-1990s the physicists J.R. Schütz and Ludwig Silberstein also extended Helmholtz's vorticity equations to the case of a compressible fluid (Thrope et al. 2003). In 1901 Max Margules calculated the change of pressure within columns of differing temperature, and in 1902 Felix Exner computed a prognosis of air pressure. Bjerknes' outstanding achievement was to consolidate the fragmented field of dynamic meteorology on a sustainable basis of theoretical, practical and computational research (Gramelsberger 2009).

subjected to strong thermal influences and moving over a rough, rotating surface" (Rossby 1941, p. 600).

The concept of such an exact science of the atmosphere was outlined in Bjerknes' seminal 1904 paper, *The Problem of Weather Prediction, Considered from the Viewpoints of Mechanics and Physics*.[18] Rooted in the deterministic approach of physics, Bjerknes stated that

> the necessary and sufficient conditions for a rational solution of the problem of meteorological prediction are the following: 1. One has to know with sufficient accuracy the state of the atmosphere at a certain time. 2. One has to know with sufficient accuracy the laws according to which a certain state of the atmosphere develops from another (Bjerknes 1904, reprinted in 2009, p. 663).

If both are known sufficiently, the future states of the atmosphere can be extrapolated. This is the underlying principle of weather forecasting as well as climate prediction. In opposition to the purely empirical and statistical methods of synoptic meteorology, he understood atmospheric processes to be of a mixed mechanical and physical nature. In his mathematical model the state of the atmosphere was determined by seven variables: velocity (in three directions), and the density, pressure, temperature, and humidity of the air for any point at a particular time. For the calculation of these variables Bjerknes proposed a mathematical model based on the three hydrodynamic equations of motion (describing the relation between the three velocity components, density and air pressure), the continuity equation (expressing the continuity of mass during motion), the equation of state for the atmosphere (articulating the relation between density, air pressure, temperature and humidity of any air mass), and the two fundamental theorems in the mechanical theory of heat (specifying how the energy and entropy of any air mass change in a change of state). Such a mathematical model can be used to compute prospective states of the atmosphere, expressed as the computation of these seven variables into the future.

However, the analytical solution of such a complex mathematical model was, and still is, not achievable. An arithmetical way to calculate it seemed too laborious considering the limited power of human computers at that time. Therefore Bjerknes proposed a mixed graphical and mathematical way for computing future states. In the 1904 paper he outlined some ideas for reducing the complexity of his model by following the principles of infinitesimal calculus with several unknowns.

> For mathematical purposes, the simultaneous variation of several parameters can be replaced by sequential variations of individual parameters or of individual groups of parameters. If this is accompanied by using infinitesimal intervals, the approach corresponds to the exact methods of infinitesimal calculus. If finite intervals are used, the method is close to that of the finite difference and of the mechanical quadratures, which we will have to use here. However, this principle must not be used blindly, because the practicality of the method will depend mainly on the natural grouping of the parameters, so that both

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[18] The paper was published in the *Meteorologische Zeitschrift* in January 1904–entitled "Das Problem der Wettervorhersage, betrachtet von Standpunkt der Mechanik und Physik". An English translation is provided in the *Meteorologische Zeitschrift* of December 2009 (Bjerknes 2009).

> mathematically and physically well-defined and clear partial problems will result (Bjerknes 2009, p. 665).

According to Bjerknes, a “natural dividing line” of the problem is given by the boundary between the dynamical and the physical processes—separating the hydrodynamic from the thermodynamic problems. Although Bjerknes followed this natural dividing line, he avoided the practice of theoretical hydrodynamicists who, in order to simplify computation, cut the link between both theories by disregarding temperature and humidity in the equation of state. But Bjerknes had already overcome this idealization, which has led others to the simplifying assumption that density is related solely to pressure.[19] Instead of omitting temperature and humidity, his mathematical model of the atmosphere considered both as “parameters for shorter time intervals, using values that are either given by observations or previous calculations” (p. 665).

Although the 1904 paper outlined Bjerknes’ mathematical model and gave a very clear vision of a rational method of weather forecasting, it did not contain any equation or computing plan. Nevertheless, Bjerknes was very optimistic about the possibility of computing his model, which would turn meteorology into an exact science. In fact, in the following years he devoted his work to achieving a way of computing forecasts. He had a mixed graphical and mathematical method in mind for performing the computations directly upon the charts. This, he pointed out in 1911, “will be of the same importance for the progress of dynamic meteorology and hydrography as the methods of graphical statistics and of graphical dynamics have been for the progress of technical sciences” (Bjerknes 1911, p. 69). When Bjerknes became director of the Leipzig Geophysical Institute in 1913 he claimed in his inaugural lecture that “there is only one task: to compute future states of the atmosphere” (Bjerknes 1913, p. 14).[20]

2.2.3 *Limitations of Analysis and the Need for Numerical Methods*

The idea of computing future states of the atmosphere has become the driving force for meteorology as physics of the atmosphere, or as Bjerknes claimed, as an exact science. The idea of an exact science is related to the use of numbers and laws, the

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[19] While hydrodynamics deals with the motion of fluids, thermodynamics studies the energy conversion between heat and mechanical work. “Indeed it can be cut so easily that theoretical hydrodynamicists have always done so in order to avoid any serious contact with meteorology” (Bjerknes 2009, p. 665).

[20] Bjerknes had to give up his ambitious program and successfully developed a more practical way of weather forecasting when he moved from Leipzig to Bergen in 1917. He improved the methods of synoptic meteorology based on an advanced theory of cyclogenesis (the polar front theory), which he had developed together with his son Jacob and others, now called the ‘Bergen school’ (Bjerknes 1919; Friedman 1989).

latter articulated as equations. The basic promise of exact science is: if the current state of a system, e.g., of the atmosphere, is known by measurement and the laws of its behaviour are understood, future states are computable. This promise was largely fulfilled for very simple models in 1846, when the French scientist Urbain Le Verrier forecasted the existence of planet Neptune based solely on calculations. His numerical forecast was confirmed several days later by the Berlin Observatory through observation (Galle 1846). However, predictability is not so easy to achieve, for reasons of complexity and efficiency. In fact, the lack of both led to a stagnation in science which hindered scientific—and, in particular, technological—development in the late nineteenth and early twentieth centuries. Mathematical models like the one Bjerknes suggested for weather forecasting were far too complex to be solved analytically, that is to deduce an exact solution. An exact solution describes the behaviour of a system at any time and place. Exact solutions can be derived for very simple systems like two-body systems without any disturbance. But such systems are extremely idealized and do not occur in nature. In the case of two bodies—e.g.,, planets idealized as the midpoints of perfect spheres—the influence of the bodies on each other is linear and their behaviour can therefore be deduced and predicted. But even a tiny disturbance can cause a non-regular behaviour that is no longer easy to predict. The disturbance introduces a more complex feedback into the two-body system of nonlinear nature. Small changes can produce complex effects, such that the output of the system is no longer directly proportional to the input. For more complex systems it is not possible to derive an exact solution. This limitation of analysis made science 'blind' for the prediction of the behaviour of complex systems like the atmosphere, although they could describe them mathematically. Therefore scientists had to decide whether they wanted to theoretically analyze the behaviour of idealized, i.e. simplified, systems that do not occur in nature, or investigate more complex and realistic ones in a practical way.

This situation of science at the end of the nineteenth and the beginning of the twentieth centuries led to a schism between theory and application in various disciplines. Its effects were felt most prominently in the fields of hydrodynamics and fluid dynamics.[21] The flow of air or water could be studied theoretically without any reference to real circumstances like friction or turbulent flow. Alternatively, scientists and engineers could use experiments to collect particular data for individual cases that did not provide much general insight into the nature of fluid phenomena. Only numerical models and their computation—so-called simulations—are able to overcome this schism, but the price for this is uncertainty

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[21] In his study *The Dawn of Fluid Dynamics* Michael Eckert described the situation dramatically: "More than a 100 years after Bernoulli's and Euler's work, hydrodynamics and hydraulics were certainly no longer regarded as synonymous designations for a common science. Hydrodynamics had turned into a subject matter for mathematicians and theoretical physicists—hydraulics became technology. Aerodynamics, too, became divorced from its theoretical foundations in hydrodynamics. [. . .] In all these areas of application, air resistance was the central problem. Aerodynamic theory could not provide a single formula that accounted for the various practical goals" (Eckert 2006, pp. 25, 26).

(see also Sect. 2.5). Nonetheless, at the beginning of the twentieth century science lacked efficient tools for computation and scientists had to find other ways to perform practical investigations of complex systems. One of the methods to overcome the schism was experimentation. Scientists tried to cope with this problematic situation by using experiments for computation and to derive empirical formulae. In particular, wind tunnels and water tanks were used to study the influence of scale models, e.g., of ships or air planes, on the flow of a fluid. A text book for aircraft construction stated in 1929: "Our knowledge of surface air friction is wholly based on experience, but the model rules suggest a convenient formula for its magnitude". These model rules "are of immense practical use, and they refer to all kinds of flow, not only to theoretical ones" (Munk 1929, p. 137). Using experimental devices like analogue computers delivered numerous empirical formulae for all kinds of cases and parameter ranges.[22] But the validity and precision of these experimental devices were limited and often not comparable with results acquired from other devices. It turned out that early wind tunnels produced turbulent flows rather than the uniform flow of air needed. Therefore "the data collected here [Langley Laboratory]", as a report on wind tunnels concluded, "must be considered, primarily, as data concerning the tunnel, and not the models tested here" (Reid 1925, p. 219). Furthermore, such empirical formulae "although fulfilling well enough the purposes for which they were constructed", as George Gabriel Stokes had already pointed out in 1845, "can hardly be considered as affording us any material insight into the laws of nature; nor will they enable us to pass from consideration of the phenomena from which they were derived to that of others of a different class, although depending on the same causes" (Stokes, 1845, p. 76). Science was stuck between idealization and complexity, between the limitation of analysis and the limitation of experiments and empirical formulae.

2.2.4 Introduction of Computers and Forecasting Algorithms

Fortunately, another way of dealing with this schism emerged in the 1940s. When in 1946 Herman Goldstine, an U.S. Navy officer, and John von Neumann, a Hungarian-American mathematician, referred to the situation of analysis and science as "stagnant along the entire front of nonlinear problems" (Goldstine and von Neumann 1946, p. 2), they had in mind numerical models and automatic computing machines that were supposed to help overcome this stagnation. The basic question they posed was: "To what extent can human reasoning in science be more efficiently replaced by mechanisms?" (p. 2). The mechanisms Goldstine and von Neumann had in mind were the integration of differential equations with automatic computing machines.

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[22] "In 1896 a textbook on ballistics lists in chronological order 20 different 'laws of air resistance', each one further divided into various formulae for different ranges of velocity. [. . .] No physical theory could provide a logical framework for justifying these empirical 'laws'" (Eckert 2006, p. 26).

These machines should replace "computation from an unquestioned theory by direct measurement. Thus wind tunnels are, for example, used at present, [. . .] to integrate the non-linear partial differential equations of fluid dynamics. [. . .] It seems clear, however, that digital (in the Wiener-Caldwell terminology: counting) devices have more flexibility and more accuracy" (p. 4). In other words: Instead of using experiments for computation, computers should be used for experiments by numbers.

Computation, however, is laborious work. Back in the 1600s Johannes Kepler had already required vast computations to calculate the orbit of Mars. In fact, he needed years for his computations, but at the end he had turned astronomy into a number-crunching science. Before the invention of automatic computing machines, calculation was carried out by humans, called 'computers'. In his study on *When Computers Were Human* David Grier explored the history of human computing groups, whose work

> might be best described as 'blue-collar science', the hard work of processing data or deriving predictions from scientific theories. [. . .] Though many human computers toiled alone, the most influential worked in organized groups, which were sometimes called computing offices or computing laboratories. These groups form some of the earliest examples of a phenomenon known informally as 'big science', the combination of labor, capital, and machinery that undertakes the large problems of scientific research (Grier 2005, p. 5).

These computing laboratories were the forerunners of today's computational departments. Their computing planes have turned into forecasting algorithms and numerical simulations. And their machinery—mechanical desk calculators, slide rules, and tabulator machines—have become giant supercomputers. Since numerical prediction by hand reached its first peak in the late nineteenth century, the need for computation has increased heavily, so that the development of numerical methods and computing devices has become a core challenge for science. The race for better and faster computational devices and machines was and still is fueling the progress of science and engineering. Prediction, optimization, and planning are the main reasons for this need. The U.S.-American computer pioneer Vannevar Bush called this mode of knowledge production 'instrumental analysis'. "Under instrumental analysis is to be grouped all analysis proceeding by the use of devices for supplementing pure reasoning" (Bush 1936, p. 649). Bush concluded, referring to the latest advances at the beginning of the computer age in the 1930s, that "there is a great deal more arithmetic and better arithmetic in the world than there used to be" (p. 652). This statement is extended by today's supercomputers into the immeasurable.

In order to strengthen instrumental analysis two things were required: efficient automatic computing machines and advanced numerical methods. The computer age began when the flow of energy and the flow of symbols fused and general-purpose computing machines entered the scene. Vannevar Bush's Differential Analyzer, a mechanical analog computer for the integration of differential equations, built between 1928 and 1932 at the Massachusetts Institute of Technology, was a forerunner of these new machines. Another was Konrad Zuse's binary electrically driven mechanical calculator Z1, which attained limited programmability, followed by the

Z3 in 1941, the first fully operational electro-mechanical computer. Finally, in 1946 the first general-purpose electronic computer was announced: the ENIAC Electronic Numerical Integrator and Computer.[23] ENIAC consisted of 18,000 vacuum tubes, with an arithmetic design influenced by "mechanical desk calculators, electrically powered and hand operated; and electromechanical card operated IBM machines" (Burks 1980, p. 315). Computation was unbelievably fast for this time. While an experienced human computer needed 7 h to compute a single trajectory based on 750 operations of a ballistic calculation, and Bush's Differential Analyzer required 10–20 min, this time was reduced to 2.25 s by ENIAC (Goldstine and von Neumann 1946). But working with ENIAC was slowed down by the fact that each new calculation had to be hard-wired. A maze of cables had to be unplugged and re-plugged, and arrays of switches had to be set manually (Ceruzzi 1998). While computation itself was fast, setting up ENIAC took days.

ENIAC was built to solve differential equations. John von Neumann joined the ENIAC team in 1944, as he was known as one of the rare experts in solving differential equations numerically. At Los Alamos he was involved in ballistic calculations, and was well aware that to overcome the limitations of analysis fast automatic computing machines would be imperative.[24] But automatic computation needed a method for "calculating routines involving stepwise integration" of variables (Neumann von and Richtmyer 1947, p. 653). The equations had to be translated into a numerical model that could be solved step by step. Such a method is not new. The computing planes of the astronomers used a step-by-step numerical method to manually advance planets and comets forward by small distances. But now the whole computation had to be prepared in advance and then the machine set up for the entire calculation. Therefore the differential equations had to be transformed into difference equations, and the plan for step-by-step calculations had to be 'coded' and plugged in. "Coding", Goldstine and von Neumann explained in 1947, "begins with the drawing of the flow diagrams [... and] the coding of every operation box, alternative box and variable remote connection" (Goldstine and von Neumann 1947, p. 103). The flow diagram displays the step-by-step run

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[23] "The ENIAC was an electronic calculator that inaugurated the era of digital computing in the United States. Its purpose was to calculate firing tables for the U.S. Army, a task that involved the repetitive solution of complex mathematical expressions" (Ceruzzi 1998, p. 15). ENIAC was built between 1943 and 1946 at the Moore School of Engineering at the University of Pennsylvania by J. Presper Eckert and John Mauchly. Herman Goldstine was the responsible U.S. Army coordinator and J. G. Brainerd was the project manager. In 1947 ENIAC was delivered to the Ballistic Research Laboratory of the U.S. Army in Aberdeen, Maryland.

[24] Stanislav Ulam described the situation at Los Alamos in 1943: "The blackboard was filled with very complicated equations that you could encounter in other forms in other offices. This sight scared me out of my wits: looking at these I felt that I should never be able to contribute even an epsilon to the solution of any of them. But during the following days, to my relief, I saw that the same equations remained on the blackboard. I noticed that one did not have to produce immediate solutions. [...] Little as I already knew about partial differential equations or integral equations, I could feel at once that there was no hope of solution by analytical work that could yield practical answers to the problems that appeared" (Ulam and von Neumann 1980, p. 95).

through the calculations, in which each operation box contains the actual calculations. But a flow diagram does not necessarily present a linear computing process. In fact, it is a complex choreography of loops and alternative loops that conceives various paths through the computation of a numerical model. And the computer

> will, in general, not scan the coded sequences of instructions linearly. It may jump occasionally forward and backward, omitting (for the time being, but probably not permanently) some parts of the sequence, and going on repeatedly through others. It may modify some parts of the sequence while obeying the instructions in another part of the sequence (p. 82).

Goldstine and von Neumann called the actual path of computing through the instructions the 'modus procedendi'. This modus procedendi unveils the behaviour of a system that is computed for each time step. In the case of ballistic calculations it works step by step through the expansion of a blast wave based on a numerical model of hyperbolic equations. In the case of atmospheric calculations, it computes the step-by-step development of a pressure, temperature or wind field. Thus, the simulation of a numerical model—coded and plugged in—enables the behaviour of a system to be predicted. When the first programming language FORTRAN Formula Translator was released in 1954, coding and manually plugging in merged into a single procedure: writing forecasting algorithms. Since then science, and in particular meteorology, has been dominated by a research style, as Frederik Nebeker pointed out in his instructive study on *Calculating the Weather*, "that results from making a forecasting algorithm one's ultimate objective" (Nebeker 1995, p. 152).

2.3 Calculating the Climate System

Vilhelm Bjerknes described a mathematical model of the general circulation of the atmosphere based on the three hydrodynamic equations of motion, the continuity equation, the equation of state for the atmosphere, and the two fundamental theorems in the mechanical theory of heat. However, to deduce an exact solution for this set of equations is not possible, and to derive a forecasting algorithm is not easy. While Bjerknes used graphical computing methods, during the 1910s Lewis F. Richardson, a British scientist, tried to achieve a computing scheme which he could calculate by hand. His scheme filled more than 200 pages of his book on *Numerical Weather Prediction*, which was published in 1922. He argued that

> whereas Prof. Bjerknes mostly employs graphs, I have thought it better to proceed by way of numerical tables. The reason for this is that a previous comparison of the two methods, in dealing with differential equations, had convinced me that the arithmetical procedure is the more exact and more powerful in coping with otherwise awkward equations (Richardson 1922, p. VIII).

In order to apply his scheme and to numerically compute it, Richardson had to divide the atmosphere horizontally into a grid, with 130 km between each grid point. This magnitude was related to the distribution of weather observation stations in Britain at that time. Although these stations were irregularly distributed, Richardson used a regular grid.[25] For the vertical resolution he defined seven layers. For this three-dimensional model of the distribution of air masses he tried to compute the development of pressure fields for 6 h. It took him 6 weeks to manually calculate his prognosis for only two of the squares of his grid for 4 am to 10 am of 20 May 1910, but he failed. He predicted a rise in air pressure of 145 mb instead of the actual 1 mb (Nebeker 1995, p. 76). Although his approach was groundbreaking for computational meteorology, his data, assumptions and idealizations were too simple due to his limited capacities for manual computation.[26] Nevertheless, in the great words of Nebeker, "Bjerknes pointed out a new road, Richardson travelled a little way down it, and his example dissuaded anyone else from going in that direction until they had electronic computers to accompany them" (Nebeker 1995, p. 82).

2.3.1 The Advent of Computational Meteorology

These electronic computers came into reach in the 1940s. John von Neumann was not only involved in the construction of some of the very first electronic computers, such as ENIAC, NORC, and the IAS computer, he also participated in the very first computer-based weather forecast. When von Neumann was working on his new IAS computer at the Institute for Advanced Study (IAS) at Princeton during the late 1940s, he chose meteorology as a test application for his computer. Von Neumann was advised by the Swedish-American meteorologist Carl-Gustav Rossby, who was the most influential figure of early numerical weather prediction—in the U.S. as well as in Europe. John von Neumann invited Jules Charney, who was working on a method that avoided the mistakes of Richardson's numerical prognosis, to lead his Meteorological Project. Charney had developed a filtering method which reduced the noise caused by energy waves with a high-phase velocity that complicated the solution of a weather model (Charney 1948). From 1948 on, Charney and his colleagues developed the very first computer model for weather forecasting, a simple barotropic model with geostrophic wind for the area of the United States

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[25] Fitting the irregularly distributed measurement data into the regular grids of simulations is still a challenging practice for meteorology.

[26] "Richardson ascribed the unrealistic value of pressure tendency to errors in the observed winds which resulted in spuriously large values of calculated divergence. This is true as far as it goes. However, the problem is deeper [. . .] A subtle state of balance exists in the atmosphere between the pressure and wind fields, ensuring that the high frequency gravity waves have much smaller amplitude than the rotational part of the flow. Minor errors in observational data can result in a disruption of the balance, and cause large gravity wave oscillations in the model solution" (Lynch 1999, p. 15).

of America (Harper 2008).[27] In a barotropic model pressure is solely a function of density; fields of equal pressure (isobars) run parallel to fields of equal temperature (isotherms), and the geostrophic wind moves parallel to the fields of equal pressure (isobars). These simplifications were necessary in order to derive an effectively computable model at that time (Persson 2005b). In 1950 Charney and his colleagues used the ENIAC (the IAS computer was not yet completed) for four 24-h and two 12-h predictions of changes in the pressure of the 500 mb contour surface, corresponding to a height of about 5,500 m. The space interval was 736 km and the grid consisted of 15 × 18 space intervals (Charney et al. 1950). Even for this single level, ENIAC had to carry out more than 200,000 operations (Neumann 1945). While von Neumann later optimistically claimed that these results were as good as the results 'subjective' forecasters could achieve, others had their doubts, commenting that "500 mb geopotential is not weather" (Arakawa 2000, p. 6). Nevertheless, dynamical models gained influence in meteorology; in 1956 Norman Phillips conducted the first climate simulation based on a simple two-level model. His results, published in the seminal paper *The general circulation of the atmosphere: a numerical experiment* (Phillips 1956), reproduced global wind patterns (see Fig. 2.3), although his quasi-geostrophic and hydrostatic model lacked mountains, a contrast between land and sea, and other more 'realistic' details (Lewis 2000). However, Philips' numerical experiment showed that global circulation and cyclogenesis (the development of low-pressure areas which are responsible for weather phenomena) depended on each other. His findings helped to establish the new General Circulation Research Section at the U.S. Weather Bureau in 1955, which inaugurated numerical weather prediction (NWP) and climate modelling in the U.S. This section later became known as the Geophysical Fluid Dynamics Laboratory (GFDL).

Although computer-based NWP started in the US, it must be mentioned, as the meteorologist and historian Christine Harper pointed out in her study *Weather by Numbers*, that "this 'American Story' is full of Scandinavian characters—scientists imported to bridge the gap separating meteorological theorists and operational weather forecasts in the United States" (Harper 2008, p. 4) and leading Japanese scientists like Akio Arakawa and Syukuro Manabe. Outside the United States, too, computing and numerical modelling took off rapidly in the 1950s. Starting in the 1940s I. A. Kibel used hydrodynamic methods for weather forecasting in Russia, developing a model that was employed "for about 15 years to produce 24-h forecasts in Russia" (Wiin-Nielsen 2001, p. 33). In 1954, S. Belousov computed a one-level model on the Russian BESM and later on the Arrow computer (Blinova and Kibel 1957; Karo 1995). Also in 1954, a group of Scandinavian meteorologists associated with von Neumann's Meteorological Project carried out a barotropic forecast on the Swedish BESK computer, which was completed in 1953 (Persson 2005a).

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[27] Christine Harper reconstructed the introduction of computational meteorology in the U.S. between 1919 and 1955 and the major influence of Scandinavian meteorologists in her instructive study *Weather by the Numbers* (Harper 2008). A study on *Early Operational Numerical Weather Prediction Outside the USA* is given by Andres Persson (Persson 2005a, b).

Similar efforts took place in other countries, for instance the development and integration of baroclinic models by the British meteorologists John S. Sawyer, Fred H. Bushby, and Marvis K. Hinds on the LEO computer (Sawyer and Bushby 1953; Bushby and Hinds 1954); by the French scientists Guy Dady, Robert Pône, and Jean Andreoletti on the CAB2022 computer (Dady 1955); by the German meteorologist Karl-Heinz Hinkelmann (Hinkelmann et al. 1952); and others. As early as 1948 the British Meteorological Office held a workshop together with the Imperial College on *The Possibilities of Using Electronic Computing Machines in Meteorology* (Persson 2005a, b). Akio Arakawa, a leading climate modeller, called the period between 1950 and 1960 the "epoch-making first phase":

> Through this work, the relevance of such a simple dynamical model for daily change of weather was demonstrated for the first time in history, and thus dynamic meteorologists began to be directly involved in the practical problem of forecasting. In this way, dynamic meteorology and synoptic meteorology began to merge during this phase (Arakawa 2000, p. 7).

In the 1960s, according to Arakawa, the "magnificent second phase" of numerical modelling of the atmosphere began, based on general circulation models (GCMs) with less restriction than the barotropic models. Arakawa himself made a major contribution to this second phase in 1961 by designing a primitive equation model together with Yale Mintz at the University of California at Los Angeles. Besides the models by Phillips and Arakawa-Mintz, other groups followed at GFDL (Smagorinsky 1963; Manabe et al. 1965), at Lawrence Livermore Radiation Laboratory (Leith 1964) and at the National Center for Atmospheric Research (Kasahara and Washington 1967).[28] In this second phase the modelling community grew and modelling was improved: the primitive equations of the general circulation were increasingly supplemented by new model strategies and processes influencing weather and climate. While weather forecast models are concerned only with the atmosphere, climate models in their simplest form also need to treat at least the ocean and sea-ice coverage. The reason for this is that the top few meters of the oceans hold more heat energy than the entire atmosphere. Thus, for long-time integrations the exchange of energy between atmosphere and ocean has to be taken into account as well as the ocean's circulation. Sea-ice also has a dramatic impact on the Earth's energy budget, meaning that changes in sea-ice coverage amplify climate change. The so-called ice-albedo feedback—the fact that when the climate gets warmer, sea-ice melts and the open ocean takes up more radiation from the sun or vice versa—is the main reason why greenhouse gas warming is considerably higher at polar latitudes than at tropical latitudes. Therefore, atmosphere models have to be expanded by ocean models. In 1969 Syukuro Manabe and Kirk Bryan published their results of the first coupled ocean–atmosphere model developed at GFDL, which was able to reproduce the effects of ocean currents on the atmosphere's temperature and humidity (Manabe and Bryan 1969). Later on sea-ice

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[28] These early models created a family tree of GCMs (Edwards 2000). Or in other words, today's GCMs are rooted in an evolution of five decades of coding and reusing the same primitive equations of the dynamic core again and again.

models were added to the coupled ocean–atmosphere models, completing the simplest set-up suitable for climate simulations.

During this second phase a diversity of models for various objectives was coded, such as cloud-resolving models, mesoscale models, and regional models. This diversity has increasingly allowed meteorologists to investigate the whole spectrum of atmospheric phenomena. These models enabled specific in-silico experiments, for instance on the effect of doubling CO_2 concentrations (Manabe and Wetherald 1975), on the effect of tropical deforestation (Charney 1975) or the study of the paleo-climate (Gates 1976). These experiments were urgently required since measurements at the Mauna Loa Observatory showed a distinct increase in atmospheric CO_2 concentrations, and since Charney intended to focus on the question of climate sensitivity: What temperature would result from doubling CO_2 concentrations? As climate sensitivity can only be assessed by simulations, climate models have become growing ‘organisms’ incorporating an increasing amount of scientific knowledge. This growth heralded the third period in the 1990s, which Arakawa called the ‘great-challenge third phase’. This period is characterized by coupled atmosphere-ocean models, the assessment reports of the Intergovernmental Panel on Climate Change (IPCC), and model intercomparisons.

However, this development is still continuing. Processes between the atmosphere and the land surface have been simulated in greater detail, including heat exchange and evaporation. Today biological processes are increasingly implemented in the models as well, in order to simulate anthropogenic perturbations of the chemical composition of the atmosphere, the carbon cycle, and the climatic effects of land clearing and agriculture. As the simulation of biological processes is far more challenging than that of physical processes, models of the marine and terrestrial biosphere have been developed only recently. Climate models, which include subsystems such as air chemistry or biosphere models, are often termed ‘Earth system models’ (see Fig. 2.4). Perhaps years from now the 2010s will be declared the fourth phase—the age of Earth system models. Besides these enormous advances in weather and climate models and in computer resources, the dynamic core of these models and the strategy of building them has remained nearly identical same since the very early days of dynamic meteorology. But the rest has changed dramatically.

2.3.2 Model Building–Dynamic Core

General circulation models consist of two parts: the dynamic core and the subscale parametrization. Both parts must exist in a discrete version—normally using the ‘grid point method’ (Messinger and Arakawa 1976). As already outlined above, climate models are based on the laws of physics. They employ equations of fluid motion, of thermodynamics and of chemistry. These laws are formulated as nonlinear partial differential equations, which are too complex to be solved analytically. This means that an exact solution is not known and a numerical method has to be found to approximate the unknown, exact solution. Therefore, from a purely mathematical perspective, computer-based simulations are in principle inexact

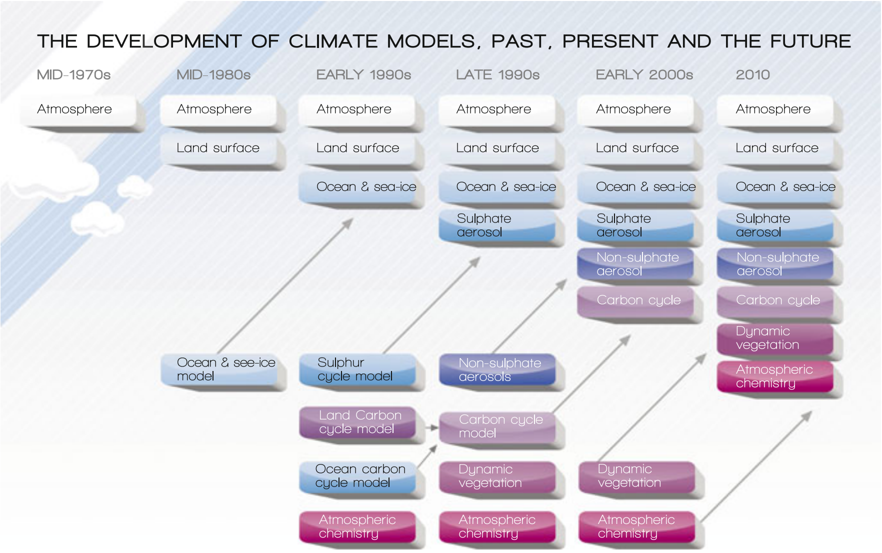

Fig. 2.4 The Development of the Earth System Model: Past, present and future. From barotropic models to general circulation models, coupled atmosphere-ocean models, and finally Earth system models
Source: Replotted by the authors from IPCC 2001, p. 48

methods, and some of the uncertainties result from this aspect.[29] However, to solve the differential equations of a general circulation model, the method of finite differences is applied. This method approximates the derivative expressions in the differential equations by differences. For instance, the differential in time of the function y, which depends on time and space, is approximated as the difference

$$\frac{\partial}{\partial t} y(t,x) \approx \frac{y(t,x) - y(t-T,x)}{T},$$

where T denotes the time interval.

To facilitate the formulation of differences, the model domain is subdivided into grid boxes, and continuous variables such as temperature, density, or humidity are converted into discretized differences (see Fig. 2.5). The discretized equations are solved for each grid point, such that the results represent grid-box averages. “Existing GCMs used for climate simulation typically have on the order of 10^4 grid columns. The average grid cell of such a model is about 200 km across”

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[29] Discretization treats a continuous problem as a discrete one and therefore results in a discretization error. Numerical computation is an approximation which approximates the unknown solution using iterative methods that are stopped after a certain number of iteration steps. Therefore the computation results in a truncation error. Furthermore, numbers in computers are represented by a limited number of digits, which creates rounding errors.

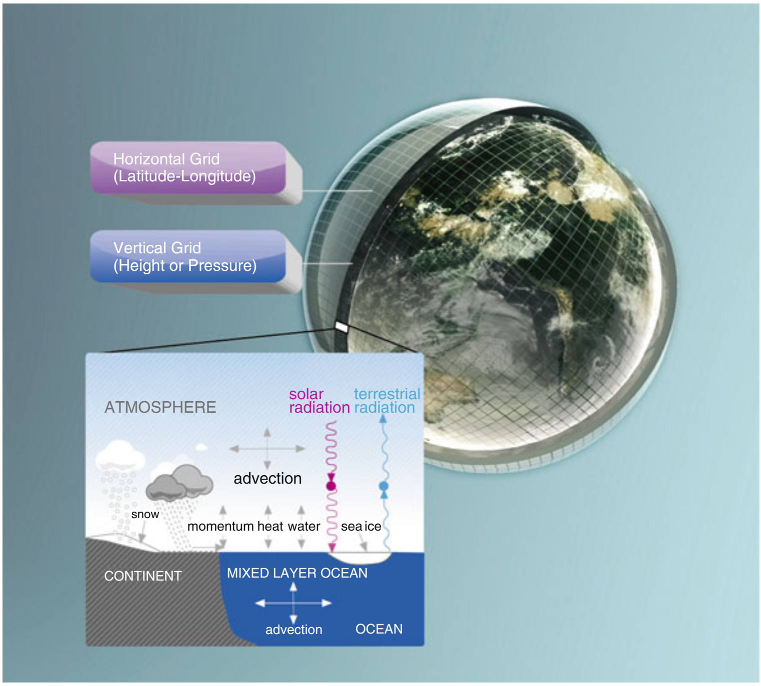

Fig. 2.5 Discretization by subdividing the atmosphere into grid cells, grid boxes, and grid columns. Subscale processes are calculated one-dimensionally within the vertical columns
Source: Replotted by the authors from NOAA, http://celebrating200years.noaa.gov/breakthroughs/climate_model/modeling_ schematic.html

(Randall et al. 2003, p. 1,553). This number of grid columns has to be computed for each time interval. While Charney and his colleagues in 1950 had to start with a 15 × 18 grid for one layer at 500 mb, covering the area of North America, the increase in spatial and time resolution has driven numerical weather forecasting and climate prediction, and still does. Higher resolution enables a better 'image' of the computed atmospheric processes, and this increase in resolution is a direct result of the tremendous improvement in computing performance.[30] Today's weather models usually consist of a resolution as fine as 6 km, while climate models vary between 500 and 60 km depending on the time period they compute, which can be some decades or centuries (IPCC 2007a, p. 113).

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[30] In terms of computing time, this means that Charney and his team needed 33 days to compute their prognoses, mainly because ENIAC had to be set up by physically plugging in the operations. Around 100,000 punch cards were needed to carry out the computations and to store the intermediate and final results. Nevertheless, compared to manual computing capacities, ENIAC was an unbelievably fast computer. When in the 1970s George Platzman, who had conceived the diagram of the operations on ENIAC, repeated the computation for one of the 24-h ENIAC prognoses on an IBM 5110 PC, the actual computation time took 1 hour. A current laptop would need milliseconds for this simple model (Lynch 2008).

However, no process is considered by the equations in a GCM that takes place on a scale smaller than the horizontal and temporal resolution achieved. But the scale of meteorological effects ranges between centimeters (micro turbulences) and several 1,000 km (planetary waves). Therefore, so-called 'subscale processes' have to be incorporated in the model, expressing the influence of unresolved processes on the global processes. Thus weather models and climate models are divided into a dynamic core (the adiabatic part) and subscale processes, so-called 'parametrizations', (the non-adiabatic part).

The adiabatic, or resolved part of the model numerically solves the fundamental laws of physics, the 'primitive' equations—primitive in the sense of primary. This is a set of nonlinear differential equations used to approximate the global general circulation of the atmosphere or the oceans. The dynamic core is still based largely on Vilhelm Bjerknes' mathematical model of 1904, as outlined above. The hydrodynamical flow on the surface of a sphere is described by the so-called Navier–Stokes equations. Thereby the assumption is made that vertical motion is much smaller than horizontal motion, and that the fluid layer depth is small compared to the radius of the sphere. The thermal energy equation relates the temperature change to heat sources and sinks. The continuity equation describes the transport of properties as momentum, heat or other quantities, which are conserved. These differential equations have to be discretized, and the resulting algebraic difference equations are solved by numerical methods, dividing the atmosphere into a number of grid cells and several vertical layers. Each grid point is determined for each time step by the computed variables for velocity in three dimensions, temperature (heat energy), density, air pressure, and humidity (vapour, water, and ice). Thus, the flow of air masses across the grid cells, the impact of various forces on the flow, the distribution of energy, water, vapour, etc., and the density of a fluid depending on pressure, temperature, and humidity are expressed. This computable model of a 'digital atmosphere' is written in FORTRAN or other programming languages. The result is a set of files which the computer has to run through for each time interval in order to reveal the behaviour of the digital atmosphere over time.

2.3.3 Model Building–Subscale Parametrization

The other part of a weather or climate model is the non-adiabatic part, which calculates the effects of subscale processes on the large-scale (resolved-scale) variables depending on large-scale parameters. Typical parametrizations include radiation transport, processes on the surface, stratiform clouds, cumulus convection, subscale orographic effects, and horizontal diffusion. While the dynamic core has not changed much during the last decades,[31] tremendous research efforts have

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[31] In the 1970s the computation of the dynamic core was transferred from the Gaussian grid into the spectral space for stability reasons (Bourke 1974). Currently, the dynamic core of some GCMs is being re-coded on icosahedral grids, which better model the spherical shape of Earth.

been devoted to identifying, measuring, and modelling subscale parametrizations. Parametrizations are major sources of uncertainties. The basic problem results from the fact, as Randall et al. pointed out aptly, that

> even though the basic physical equations in which we have the most confidence describe small-scale processes, in practice it is the effects of those small-scale processes that are incorporated into our models through the use of uncertain closure assumptions. It is ironic that we cannot represent the effects of the small-scale processes by making direct use of the well-known equations that govern them (Randall et al. 2003, p. 1548).

These closure assumptions are delivered by the subscale parametrizations until weather and climate models achieve a resolution of some centimeters. Another problem of parametrization is the use of diverse knowledge resources. The development of parametrizations can be divided into four different methods: Derivation of parametrizations from first principles, from laboratory studies, from focused measurement campaigns, and from models with finer resolution (Lohmann et al. 2007a).

All of these methods have in common that they are based on theory and/or measurements valid for small scales and mostly for only specific regions or situations. But in a climate model the parameterization is applied to any part of the globe, to any climate state, and to the model's coarse spatial and temporal resolution. A widely used methodology for adapting parameterizations to changing environments and scales is to adjust or 'tune' them in order to achieve a more 'realistic' match with available local data. A better method would be to use observational data at adequate scales to infer these parameters. Satellite-derived relationships, for instance, can provide clues about how specific parameterizations should work on the scales relevant for large-scale modelling. The advantage here is that statistical correlations from satellites are temporally and spatially more robust than individual measurements. Moreover, because correlations analyze relative changes, limitations to the absolute accuracy are acceptable. Relations are supposed to be valid even in a changing climate, whereas absolute values and currently measured distributions are not. However, for various processes neither measurement, laboratory study, nor simulation data are available. Modellers have to decide whether they want to include key parameters which govern these processes. If so, assumptions are the only way to incorporate them until measurement data become available. Of course, these assumptions inherit major uncertainties. Another problem is unknown processes. All of these problems introduce uncertainties into the model. Every parameterization first has to undergo tests in stand-alone versions, and then the results have to be compared to observations. After this the new parameterizations have to be implemented into the model system and the results compared with the previous version of the model and with assimilated data fields (Table 2.1).

Prominent examples of parametrization in atmosphere models are cloud parametrizations. Many processes on which clouds depend are not resolved in GCMs. Clouds play a major part in the energy balance of Earth as well as in the hydrological cycle. From the perspective of a GCM, clouds are defined by volume-averaged contents of cloud water and cloud ice, and by the total fractional area. Although the

Table 2.1

Derivation of subscale parametrization	
First principles	An analytical solution or an approximation based on some simplifications can be derived.
Laboratory studies	Utilization of data from laboratory studies because it is too difficult to measure the process in-situ. An example is the study of ice crystal formation in cirrus clouds. The advantage of laboratory studies is that they take place under controlled conditions.
Measurement campaigns	Data from focused measurement campaigns of various continental and marine sites are used to derive robust relationships between various parameters. The information is prepared in compiled data sets which represent the spatial and temporal variability of the parameterized process. It has to be mentioned that measurement data represent every influence on the investigated process, whether these influences are known or not. In this regard, this method complements the laboratory method for processes that are more complex than can be studied in a laboratory setting. The sample size in a field experiment is normally not large enough to stratify these empirical data according to all influences in question.
Models	Data and information from models with finer resolution are used to derive parameterized processes that occur on small scales. Their statistical behaviour can be described by a stochastic relationship, which is derived from model simulations with finer resolution that are able to resolve some of the processes in question. This method is questionable as it lacks an observational database.

Source: Lohmann et al. 2007a

effects of clouds on the large-scale behaviour of the atmosphere are not yet entirely known or fully understood, GCMs have included representations of some interactions between cloudiness, radiation, and the hydrological cycle since the 1960s. These representations have advanced from simple diagnostic schemes to schemes which increasingly include a sound physical basis. Cloud parametrization started with a fixed cloud approach based on information about cloud fraction and cloud optical depths compiled from observational data. Within this early approach "clouds were not allowed to influence climate except through essentially prescribed short- and long-wave radiation effects" (Fowler et al. 1996, p. 489). In the 1980s diagnostic cloud parametrizations followed. Cloud cover was diagnosed as a function of various variables, e.g., vertical velocity and relative humidity, and optical properties were prescribed as functions of cloud heights and types, while the prediction of the occurrence of clouds was based on a prescribed saturation threshold of relative humidity. In the late 1980s cloud optical properties were parameterized as functions of temperature and therefore expressed, to some extent, the feedback between cloudiness and climate. Since the 1990s GCMs have included prognostic cloud water parameterizations in order to simulate the interactions of cloud microphysics, cloud dynamics, and radiative processes (Fowler et al. 1996).

Current atmosphere models include various cloud schemes, usually one cumulus convection scheme and another for stratiform clouds. The parameterization of clouds differs in each GCM but, generally, it predicts the cloud cover, the cloud liquid water and ice water amount the concentrations of cloud droplets and number of ice crystals, the precipitation flux and the evaporation of precipitation. The following example of one specific process in ice clouds will illustrate the modelling of parametrization (Lohmann et al. 2007). The change in the ice water mixing ratio r_i is given in kg ice per kg air in time t and is written in a budget equation as follows:

$$\frac{\overline{\partial r_i}}{\partial t} = Q_{Ti} + Q_{sed} + Q_{dep} + Q_{tbi} - Q_{mli} - Q_{sbi} + Q_{frh} + Q_{frs} + Q_{frc} - Q_{agg} - Q_{saci}$$

The term on the left side of the equation denotes the change in the ice water mixing ratio r_i over time; the terms on the right denote the transport of r_i by wind, diffusion and cloud updrafts (Q_{Ti}), the sedimentation of r_i (Q_{Ti}), the sublimation of r_i if $Q_{dep} < 0$ (Q_{dep}), the generation or dissipation of r_i through turbulent fluctuations (Q_{tbi}), the melting of r_i if the temperature exceeds the freezing point (Q_{mli}), the sublimation of r_i transported into the cloud-free part of the grid cell (Q_{sbi}), the homogeneous freezing of water droplets (Q_{frh}), the stochastical and heterogeneous freezing of water droplets (Q_{frs}), the contact freezing of water droplets (Q_{frc}), the aggregation of r_i when ice crystals clump together and form snowflakes (Q_{agg}), and the accretion of r_i by snow when a precipitation particle captures an ice crystal (Q_{saci}).

Every single term on the right of the equation is parameterized. The last term, for instance, the accretion of ice water mass by falling snow (Q_{saci}), is parameterized as

$$Q_{saci} = \frac{\pi E_{si} n_{0s} a_4 q_{ci} \Gamma(3 + b4)}{4\lambda_s^{3+b4}} \left(\frac{\rho_0}{\rho}\right)^{0.5},$$

in which the collection efficiency is $E_{si} = exp(0.025(T - T_o))$, with T the ambient temperature and T_o the melting temperature. As the temperature is below 0^{o}C—since ice crystals melt at higher temperatures—the exponent is negative and the efficiency is higher at warmer temperatures. This because at higher temperatures ice crystals are more likely to stick to snow than at lower temperatures. λ_s is the slope of the size distribution of the snow particles and n_{0s} is the intercept parameter.[32] The parametrization is based mainly on parametrizations of a finer-resolution two-dimensional model by Y.L. Lin, L. Levkov, and B.E. Potter (Lin et al. 1983; Levkov et al. 1992, Potter 1991). The intercept parameter is obtained from measurements (Gunn and Marshall 1958). The equation presented is just one

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[32] Interception means that particles stick together due to small stochastical motion (Brownian motion) if the distance between an ice crystal and a snowflake is smaller than the radius of the crystal.

of several dozen that describe processes within clouds. Some of these equations date back to concepts of the 1940s as published in the relevant literature; others refer to current research. The example shows how parametrization incorporates diverse knowledge resources like measurements or parameters derived from finer-resolution models. Although all of the approaches employed are mere simplifications of reality, the growing role of parametrization increases the atmosphere model's complexity due to the large number of processes and the manifold interactions between all of these variables.

2.3.4 Simulation Runs

Following the partitioning between the dynamic core and the parametrization, an atmosphere model is initialized with atmospheric measurement data and data sets from the ocean model. It usually computes the general equations of the circulation for each grid point first, delivers results, then continues computing the effects of the subscale parameterizations and delivers results for the first time step. The data sets of the first time step are delivered to the ocean model and used to initialize the atmosphere model for computing the second time step. The spatial resolution determines the lengths of the time steps. For instance, the 110-km grid (T106) of the Fourth IPCC Assessment Report scenarios needed a ten-min time step. Thus, a simulated day consisted of 144 simulation runs, a year of 52,560 runs, and a century of more than five million runs. Each simulation run computes several hundred thousand operations. Although a coupled atmosphere-ocean model fits on any 2-MB USB drive, the computation of climate scenarios requires powerful supercomputers.

Before a coupled atmosphere-ocean model is used to compute climate scenarios it undergoes months, sometimes years, of testing and improvement. Every tiny change has to be tested on the component and the system levels. And every simulation run is followed by a test run for a higher resolution in order to check the stability of the results. When the results behave stable, it is assumed that, from a mathematical perspective, the exact but unknown solution has been approximated. Furthermore, the model must be able to represent actual climate states and patterns (see also Sect. 2.5). At a certain point the model version is frozen and released to the scientific community for simulation runs, e.g., for computing IPCC scenarios. In particular, these efforts are needed when meteorologists want to use the 'digital atmosphere' to conduct experiments. As meteorologists cannot perform controlled laboratory experiments and cannot draw on measurements alone, 'in-silico' experiments are key tools for gaining a better understanding of the system behaviour of the earth's climate, e.g., by conducting climate equilibrium simulations. If future projections are required, only in-silico experiments can give results, e.g., by conducting transient climate simulations.

Climate equilibrium simulations compare two different climate states by introducing sustained forcing, e.g., pre-industrial greenhouse gas concentrations and doubling of the CO_2 concentration. The model is computed until a new equilibrium is reached. To obtain statistically robust results, a further 30–50 years are integrated; then the statistics of these two simulations are compared. In this kind of simulation the ocean component simply takes up and releases heat but does not mimic changes in ocean circulation. By their very design, equilibrium experiments cannot reproduce the observed time evolution of climate change, but serve as useful tools to explore the effects of a specific perturbation to the climate system. These experiments are used to derive a result for climate sensitivity under certain conditions. Climate sensitivity expresses the change in global mean surface temperature per one watt per square-meter forcing.

Transient climate simulations prescribe or calculate the temporal evolution of natural and anthropogenic forcings. Such simulations are performed by complex climate models, with the ocean model simulating the dynamics of the circulation. Before an in-silico experiment can be performed, the state of the ocean is integrated to equilibrium. Thus, for initialization the ocean is forced by atmospheric variables observed as wind-stress and heat-fluxes and integrated over some 100 years (500–1,000 years).[33] Transient climate simulations attempt to reproduce observed climate change. However, what is reproduced is not the observed year-to-year meteorology, but the multi-year statistics. More recently, ensembles of simulations applying the same forcing but varying the initial conditions or some of the parameters within the uncertainty range have been performed, to obtain statistically more robust results. Because climate compounds like the deeper ocean and the cryosphere react on longer time-scales, the system will not be in equilibrium with the rate of heating of the atmosphere, but will lag behind the rate of forcings. Thus, transient climate simulations calculate a climate sensitivity slightly smaller than do equilibrium simulations.

Besides these basic experiments, the digital climate can be used for every conceivable set-up. It enables meteorologists to study the behaviour of single processes, the interplay of various processes, the behaviour of the digital atmosphere under unrealistic, past, or future conditions, and so forth. For this purpose not only GCMs, but a diversity of models of different complexity has been developed during recent decades (see Table. 2.2). This model variety is sometimes seen as a hierarchy from more conceptual (e.g., EBMs, box models) to more comprehensive (e.g., GCMs, ESMs) models (Henderson-Sellars and McGuffie 1987) or from inductive (conceptual) to quasi-deductive (comprehensive) models (Saltzman 1985, 1988; Claussen et al. 2002). As quasi-deductive models include many inductive elements hidden in the subscale parametrization, these hierarchies and classifications are not very useful. In fact, in the everyday business of climate

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[33] Very recently, the actual state of the ocean has been used to start transient climate simulations. This much more realistic approach has become possible due to the new measurement network, ARGO, which since the year 2000 has continuously sounded the uppermost 2 km of the oceans by means of buoys and floats to measure the profiles of temperature, currents and salinity. These measurement data are assimilated to generate three-dimensional fields of the ocean's parameters, which then serve as an initial field for model simulations.

Table 2.2

Variety of climate models

Box	Box models are simplified versions of complex models that reduce them to boxes and describe flows across and within the different components of the climate system. They are used for testing parametrizations and for deriving analytical formulas.
EBM	Energy Balance Models calculate the radiative fluxes and the surface temperature, assuming that all transport is diffusive.
CRM	Cloud Resolving Models consist of a fine resolution that resolves cloud-scale and mesoscale circulations.
EMIC	Earth Models of Intermediate Complexity include more processes and integrate more climate components than simple energy balance models. EMICs consist on a coarse horizontal resolution, but allow long-time integrations for paleo-climate studies or sensitivity studies.
RCM	Regional Climate Models increase the resolution of a GCM in a small, limited area of interest. The climate calculated by a GCM is used as input at the edges of the RCM. RCMs represent regional land surfaces (mountains, coastlines, changing vegetation characteristics etc.) on much smaller scales than GCMs.
GCM	General Circulation Models for the atmosphere and the ocean, as described in this section.
ESM	Earth System Models based on coupled ocean–atmosphere models, which additionally include biosphere and/or chemistry modules. ESMs simulate the behaviour of the atmosphere, the ocean, the cryosphere and the biosphere, and the interactions between these different components of the Earth system as well as the impact of human activities on climate.

Source: Henderson-Sellars and McGuffie 1987; Saltzman 1985, 1988; Claussen et al. 2002

modelling and simulation the whole spectrum of models is used. For instance, box models are used for testing parametrizations in GCMs, EMICs are used to explore the solution space of processes of GCMs, and GCMs are used to develop and evaluate parameterizations used in EMICs. However, there exist far more models for specific purposes today. For instance, in the context of climate change modelling, energy models and integrated assessment models (IAMs) play a crucial role.

2.4 International Coordination of Climate Modelling

In 1950 dynamical meteorology started with a singular weather forecasting model developed by a small group of scientists at Princeton. Only few computers were available at the time and computation, even of highly simplified models, required days to deliver any results—e.g., for a coarse resolution of a pressure field at 500 mb. Today, the situation has changed entirely. Weather and climate modelling has become a conjoint international endeavour engaging a growing community of thousands of meteorologists and hundreds of research programs worldwide. Sub-communities of model users and data users have propagated. Measurement and simulation methods have been standardized and exabytes of data are available. These developments have completely reshaped the scientific discipline of meteorology over the last decades. Since the late 1980s the Intergovernmental Panel on Climate Change (IPCC) has introduced a conjoint rhythm of model development, improvement, and evaluation which is unseen in other scientific disciplines. These conjoint efforts have improved climate modelling and put meteorology into a leading position in exploring the use of computer-based simulations for the production of scientific knowledge. However, these efforts toward coordination and standardization on an international level are the indispensable precondition to make a forecasting algorithm one's ultimate objective and to enable reliable projections into future climate trends. Over the last two decades these efforts have transformed meteorology into an 'e-science' based on a growing cyberinfrastructure of supercomputers, computing centers, coded knowledge, and advanced data analysis.

2.4.1 The International Structure of Climate Research

Because weather forecasting and climate prediction require global data, meteorology can look back on a long tradition of international measurement and research campaigns. The International Meteorological Organization (IMO) was founded way back in 1873, and the first International Polar Year took place in 1882 and 1883. Today the World Meteorological Organization (WMO) of the United Nations represents 188 member states. The WMO organizes various international climate research programs, including the World Climate Programme (WCP) and the World Climate Impact Assessment and Response Programme (WCIRP) since 1979, the Intergovernmental Panel on Climate Change (IPCC) since 1989, the Global Climate Observing System (GCOS) since 1992, the Climate Information and Prediction Services (CLIPS) since 1995, and the IPCC Data Distribution Centre (DDC) since 1998 (see Table 2.3).[34]

Some of the WMO programs are coordinated along with the United Nations Environment Programme (UNEP), the International Council of Scientific Unions (ICSU), and the United Nations Framework Convention on Climate Change (UNFCCC) in order to support Agenda21. According to the Swiss Forum for Climate and Global Change (ProClim), there are currently 110 international organizations, agencies, networks, and committees and 112 international programs (ProClim 2010, Research information service).

A characteristic feature of these organizations is that they create an interface between scientific knowledge and socio-political interests. However, meteorology has always been interlinked with society and politics. Since the nineteenth century, agricultural and military needs for weather forecasting have driven the field's development. But the emerging interest in environmental issues in the 1970s installed a new dimension of the interlinking between meteorology, in particular climate science, and politics—introducing national and international conferences,

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[34] The WMO website provides an overview of milestones since 1875, when the first International Meteorological Conference was held in Brussels. URL: http://www.wmo.int/pages/about/milestones_en.html. The Swiss website ProClim offers a research information service of international environmental organizations. URL: http://www.proclim.ch

Table 2.3

Scientific and technical programs and projects of the World Meteorological Organization (WMO)	
WMO World Weather Watch (WWW) Programme	
GOS	Global Observing System
GDPFS	Global Data-processing and Forecasting System
WWW/DM	Data Management and System Support Activities
OIS	WWW Operational Information Service
ERA	Emergency Response Activities
IMOP	Instruments and Methods of Observation Programme
	WMO Polar Activities
TCP	Tropical Cyclone Programme
WMO World Climate Programme (WCP)	
CCA	Climate Coordination Activities
AGM	Agricultural Meteorology Programme
WCIRP	World Climate Impact Assessment and Response Strategies
WCDMP	World Climate Data and Monitoring Programme
WCASP	World Climate Applications and Services Programme, including the Climate Information and Prediction Service Project
WMO Atmospheric Research and Environment Programme (AREP)	
GAW	Global Atmosphere Watch
WWRP	World Weather Research Programme
THORPEX	Observing System Research and Predictability Experiment
WMO Applications of Meteorology Programme (AMP)	
PWSP	Public Weather Services Programme
AeMP	Aeronautical Meteorology Programme
MMOP	Marine Meteorology and Oceanography Programme
AMDAR	Aircraft Meteorological Data Relay
AMP	Agricultural Meteorology Programme
WMO Hydrology and Water Resources Programme (HWRP)	
BSH	Basic Systems in Hydrology
HFWR	Hydrological Forecasting in Water Resources Management
CBH	Capacity-building in Hydrology and Water Resources Management
CWI	Cooperation in Water-related Issues
APFM	Associated Programme on Flood Management
WHYCOS	World Hydrological Cycle Observing System
Other major WMO programs and projects	
TCP	Technical Cooperation Programme
RP	Regional Programme
SAT	Space Programme
ETRP	Education and Training Programme
DRR	Disaster Risk Reduction Programme
ClimDevAfrica	Climate for Development in Africa
DBCP	Data Buoy Cooperation Panel
HOMS	Hydrological Operational Multipurpose System
IFM	Integrated Flood Management Helpdesk
INFOHYDRO	Hydrological Information Referral Service
SWIC	Severe Weather Information Centre
WAMIS	World AgroMeteorological Information Service
WHYCOS	World Hydrological Cycle Observing System
WIS	WMO Information System
WIGOS	WMO Integrated Observing System
WWIS	World Weather Information Service

Source: http://www.wmo.int

programs, and organizations. While the first World Climate Conference (WCC-1) in Geneva in 1979 still followed a mainly scientific approach, which led to the establishment of the World Climate Programme and the IPCC, the WCC-2 in 1990 had a more political agenda, highlighting the risk of climate change. Even as early as 1985 the Villach Conference put the emphasis on the role of an increased CO_2 concentration in the atmosphere by establishing the Advisory Group on Greenhouse Gases (AGGG). The Villach Conference, along with the first IPCC Assessment Report in 1990 and the WCC-2, created a worldwide awareness about the impact of CO_2 among scientists, policy makers, and the public. This awareness has led to the appointment of the Intergovernmental Negotiating Committee on Climate Change (INC) and to the United Nations Framework Convention on Climate Change (UNFCCC) in order to ensure stabilization of greenhouse gas concentrations in the atmosphere at a viable level.[35] In 1997 the adoption of the Kyoto Protocol introduced a measure of CO_2 equivalents (CO2-eq), based on the benchmark emission levels published in the second IPCC Assessment Report in 1990, as well as emissions trading and the clean development mechanism (CDM) (see also Chap. 5 of this volume). All of these measures and conventions refer to preindustrial conditions before 1750 of a CO_2 concentration around 280 ppm (IPCC 2007b) and try to deal with the effects of human-induced global warming.

The interlinking of climate science with politics has been widely analyzed from the perspective of policy studies (Jasanoff and Martello 2004; Grover 2008; Halfmann and Schützenmeister 2009). These studies take into account that the international organizations that drive climate science can be described as boundary organizations with dual agency, stimulating scientific knowledge and social order. Boundary organizations "facilitate collaboration between scientists and non-scientists, and they create the combined scientific and social order through the generation of boundary objects and standardized packages" (Guston 2001, p. 401). But the agency of the international organizations which drive climate science has a unique characterization because they can act only by influencing the behaviour of their members—states, national institutions, and programs. They use scientific procedures—conferences, workshops, networks, peer reviews, etc.—in order to facilitate collaboration among scientists as well as collaboration between scientists and non-scientists. These organizations have to interconnect scientific knowledge and political decisions, which entails various problems for both scientific and political autonomy (see also Sect. 2.5). They have turned meteorology into an open 'big science'.[36]

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[35] The Convention on Climate Change was negotiated at the Earth Summit in Rio de Janeiro in 1992, followed by the annual Conferences of the Parties (COP) since 1995. In November and December 2011 the COP-17/MOP-7 will take place in South Africa.

[36] The term 'big science' was coined for large programs in science which emerged in industrial nations during and after World War II: for instance, the Manhattan Project to develop the atomic bomb led by the United States, involving more than 130,000 people at 30 research sites. These military-based programs are termed as 'closed big science', while meteorology is characterized as an 'open big science', since free access to data and computer codes is provided to researchers worldwide (Halfmann and Schützenmeister 2009).

Table 2.4

World Climate Research Programme (WCRP). A program sponsored by the World Meteorological Organization (WMO), the International Council of Scientific Unions (ICSU), and the UNESCO Intergovernmental Oceanographic Commission (IOC)	
CliC	The Climate and Cryosphere Project
CLIVAR	Climate Variability and Predictability (including the Seasonal Prediction Model Intercomparison Project (SMIP))
GEWEX	Global Energy and Water Cycle Experiment
SPARC	Stratospheric Processes and their Role in Climate
WGCM	Working Group on Coupled Modelling (organizing numerical experimentation for IPCC, including the Model Intercomparison Projects AMIP and CMIP)
WGNE	Working Group on Numerical Experimentation (improvement of atmospheric models)
TFRCD	Task Force on Regional Climate Downscaling (translating global climate predictions into useful regional climate information, e.g. COordinated Regional Climate Downscaling Experiment CORDEX)

Source: http://www.wmo.int

However, sociopolitical decisions are made on the basis of scientific results, and these results draw strongly on models—as only models can study climate sensitivity, the influence of various gases on radiative forcing, and future developments. Therefore, the international coordination of climate science also has to be analyzed from the perspective of modelling. International cooperation here means to ensure a comparable, transparent, and sound scientific basis for understanding climate change. Related to these requirements, the World Climate Research Programme (WCRP), launched in 1980 by ICSU, WMO, and IOC, has the mission "to develop and evaluate climate system models for understanding, assessing and predicting Earth climate change and variations" (WCRP 2009, Activities page; see Table 2.4). In 1980, the Working Group on Numerical Experimentation (WGNE) was established, followed in 1997 by the Working Group on Coupled Modelling (WGCM) and in 2008 by the Task Force on Regional Climate Downscaling (TFRCD). These groups help to improve numerical models and they organize numerical experimentation for the IPCC Assessment Reports. The WCRP working groups and task force reflect the requirements on modelling that emerged over the last decades: the coupled atmosphere-ocean models that were the standard of the third and fourth IPCC Assessment Reports, model intercomparison, the improvement of parametrization, the new domains of Earth system modelling and of downscaling, as well as a framework for the seamless prediction of weather and climate variations. All of these requirements need international collaboration and sufficient computational capability, since higher resolution and higher complexity are core prerequisites. With regard to these requirements, in May 2008 the WCRP held the World Modelling Summit "to develop a strategy to revolutionize the prediction of the climate to address global climate change, especially at regional scale" (Shukla 2009, p. 2). Four objectives were identified as main priorities of future model development: representation of all aspects of the climate system within the models, an increase in accuracy, advanced computational capabilities, and establishment of a world climate modelling program. One of the recommendations is to launch multi-national high-performance computing facilities (Shukla et al. 2010; Shapiro et al. 2010). These facilities are needed not only to increase resolution and complexity, but also to conduct new evaluation methods like ensemble tests and prognoses, for model intercomparison, and for data assimilation methods.

Model intercomparison, in particular, requires international cooperation. In 1990 the WCRP's Working Group on Coupled Modelling agreed on the Atmospheric Model Intercomparison Project (AMIP), a standard experimental protocol for global atmospheric general circulation models. In 1995 the Coupled Model Intercomparison Project (CMIP) followed, as a standard experimental protocol for coupled atmosphere-ocean general circulation models. AMIP and CMIP are both community-based infrastructures for model diagnosis, validation, intercomparison, documentation, and data access. Both projects collect output from model control runs for standardized scenarios (e.g., CMIP for constant climate forcing, 1% CO_2 increase per year until 1970 and doubling after 1970, 'realistic' scenarios, atmosphere only, etc.). The output is used to diagnose and compare the participating models, in particular those models taking part in the IPCC process. Or in other words, as it is pointed out on the CMIP homepage: "Virtually the entire international climate modeling community has participated in this project since its inception in 1995" (CMIP 2010, Overview). CMIP currently is conducting the fifth phase (CMIP5) for the fifth IPCC Assessment Report in 2014. The purpose, as outlined by the WGNE, is to provide

> a comprehensive set of diagnostics that the community agrees is useful to characterize a climate model; a concise, complete summary of a model's simulation characteristics; an indication of the suitability of a model for a variety of applications; information about the simulated state and about the processes maintaining that state; and variables that modeling groups and users would like to see from their own model and from other models. [Finally, the model intercomparison should] allow model developers to compare their developmental model with other models and with AMIP vintage models to determine where they currently stand in the development process (PCMDI 2010, Projects: AMIP).

AMIP as well as CMIP are carried out by the Programme for Climate Model Diagnosis and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory in the U.S. Besides AMIP and CMIP other model intercomparison programs have been established, for instance the Seasonal Prediction Model Intercomparison Project (SMIP), the Aqua-Planet Experiment Project (APE), and the Paleoclimate Modelling Intercomparison Project (PMIP).

Besides model intercomparison, Earth system modelling relies on collaboration. Earth system models (ESMs) are vast clusters of various models developed by various modelling communities. Usually, an atmospheric and oceanic general circulation model is coupled with other multi-layer models of vegetation, soil, snow, sea ice, land physics and hydrology, chemistry, and biogeochemistry. Examples of community-based networks and programs include the European Partnership for Research Infrastructures in Earth System Modelling (PRISM) of the European Network for Earth System Modelling (ENES), the Community Earth System Model (CESM) of the National Center for Atmospheric Research (NCAR) and the Earth

System Modeling Framework (ESMF) in the U.S., as well as the British Grid-ENabled Integrated Earth system modelling framework for the community (GENIE). The goal of these programs is not only to conduct and coordinate Earth system research, but also to standardize methods, formats, and data, and to develop software environments. Earth system models stimulate new developments in meteorology, like integrated assessments for evaluating Earth systems, advanced coupling technologies, and infrastructures combining modelling and data services. They require efficient strategies to deal with massive parallel platforms and other new computing architectures. For instance, the mission of ENES is "to develop an advanced software and hardware environment in Europe, under which the most advanced high resolution climate models can be developed, improved, and integrated" (ENES 2009, Welcome page). The same holds for ESMF and other programs.

2.4.2 Standardization of Methods, Formats, and Data

Imperative for international cooperation is the standardization of methods, formats, and data. As early as 1873 the need for high-quality observational data and their worldwide compatibility led to the establishment of the International Meteorological Organization (IMO), the forerunner of the WMO. At that time the aim was to define technical standards and to make the output of observation devices comparable. Since then the Commission for Instruments and Methods of Observations (CIMO) has ensured the generation of high-quality observation data by testing, calibrating, defining quality-controlled procedures, and ensuring the traceability of meteorological measurements to the International System of Units (SI) of the International Bureau of Weights and Measures (BIPM). The task of CIMO even today is to promote and facilitate the international standardization and compatibility of instruments and methods of observations, in particular for satellite data. For instance, spectra of CO_2, oxygen, and vapour are measured by downward-directed spectrometers in Earth's orbit. The increase of greenhouse gases changes the spectral distribution of outgoing infrared radiation. But the measurement data are yet not independent of the devices used or the local environments, and therefore not really comparable from one satellite to another. New benchmark strategies are under development to create absolute standards (Anderson et al. 2004). However, the growing amount of data demands further standardizations. Globally used file formats, metadata conventions, reference data sets, essential variables and indicators have been developed. Today, not only observational data but also in-silico data and their production methods (models) have to be standardized. Benchmarks are also important to improve the evaluation of models, using advanced strategies like frequentist and Bayesian statistics, optimal filtering, and linear inverse modeling (see also Chap. 4 of this volume). In fact, guaranteeing standards for the models and their results is one of the challenges for climate modelling and the integrated assessment of climate change.

The international distribution of data is built on common formats for data files like netCDF and HDF5. The Network Common Data Form (netCDF) is a widely used format for scientific data and data exchange. Measurement data as well as simulation results are stored in netCDF data files, while the Hierarchical Data Format (HDF5) is a common format for satellite data. One problem with large data sets is that they need to be completed by meta-descriptions in order to be able to clearly identify the data sources, coordinates, and other features to ensure long-term reproducibility. Without this information these data are worthless. But scientific data are not always carefully described and stored, and this applies to historical data in particular. Therefore, the CF Metadata Convention and the WMO's Gridded Binary (GRIB) format attempt to ensure that a minimum amount of metadata accompany each data set. These formats are important to create data sets that can be globally distributed and used by the entire meteorological community.

A different aspect of data standards is the assimilation of reference data sets. Reference data sets are needed to enable model intercomparison and model evaluation. They are used to initialize standardized in-silico experiments and to generate comparable and reproducible results. Various research groups worldwide have devoted their work to assimilating reference data sets, for instance the NECP/NCAR Reanalysis I and II (RA-I, RA-II) and the ERA-15 and ERA-40 data sets. The National Centers for Environmental Prediction (NECP) and the National Center for Atmospheric Research (NCAR) in the U.S. reanalyze meteorological measurement data covering the period from 1948 to 2002. The project is using state-of-the-art analysis and forecasting systems to perform data assimilation (Kalnay et al. 1996). In the same way, the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyzed the period from mid-1957 to mid-2002 in 2000 (ERA-40). ERA-40 is using data from the International Geophysical Year and provides data to the community as a GRIB file. These data files are available on the institutions' data server at no charge for research use. Reanalysis data are based on quantities analyzed within data assimilation schemes. These schemes combine measurement and modelled data because measurement data exhibit great uncertainties due to their inhomogeneous characteristics. In order to obtain data sets that meet the needs of the applications and can be used for evaluation, measurement data have to be 'improved' by combining different types with different spatial-temporal distributions and different error characteristics. Reanalysis combines information of the actual state (measurement) with physical laws, and takes into account observation error as well as model error.[37]

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[37] "The data assimilation system during reanalysis is as far as possible kept unchanged. The analysis is multivariate, and a 6-h forecast, the background, provides the most accurate a priori estimate for the analysis. Each analysis represents a state of the model after iteratively adjusting the background towards observations in a way that is optimal, given estimates of the accuracy of the background and observations. The differences between background, analysis and observations are archived for each value offered to the analysis. In addition the physical processes are 'recorded' during the model integration from one analysis to the next, the time interval during which they should be closest to the truth. All the synoptic and asynoptic observations, describing the instantaneous weather, control the data assimilation and the quality of its products over the period" (ECMWF Newsletter 2004, p. 2).

Table 2.5

Essential Climate Variables (ECV) of the Global Climate Observing System (GCOS) of the WMO, the IOC, the UNEP, and the ICSU

Atmospheric	
Surface	Air temperature, precipitation, air pressure, surface radiation budget, wind speed and direction, water vapour
Upper-air	Earth radiation budget (including solar irradiance), upper-air temperature (including MSU radiances), wind speed and direction, water vapour, cloud properties.
Composition	Carbon dioxide, methane, ozone, other long-lived greenhouse gases, aerosol properties.
Oceanic	
Surface	Sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, current, ocean colour (for biological activity), carbon dioxide partial pressure.
Sub-surface	Temperature, salinity, current, nutrients, carbon, ocean tracers, phytoplankton.
Terrestrial	
	River discharge, water use, ground water, lake levels, snow cover, glaciers and ice caps, permafrost and seasonally-frozen ground, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation (FAPAR), leaf area index (LAI), biomass, fire disturbance, soil moisture.

Source: http://www.wmo.int

Another important field of standardization is the identification of relevant indicators in order to assess current climate developments. These indicators are based on essential climate variables (ECV), which are ascertainable for systematic observation (see Table 2.5). These indicators support the work of the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC). Therefore, in 1992, the Global Climate Observing System (GCOS) was established to coordinate the worldwide observations and information of participating systems, like the WMO Global Observing System (GOS) for atmospheric physical and dynamical properties, the WMO Global Atmosphere Watch (GAW) for chemical composition of the atmosphere, and others.[38] The tasks of GCOS are to coordinate all of these data for global climate monitoring, climate change detection and attribution, and the assessment of climate change and climate variability. It does not make observations directly, but provides a global network to ensure high quality standards for effective climate monitoring. From these essential climate variables other indicators can be retrieved, such as the Global Warming Potential (GWP) of greenhouse gases, and radiative forcing, which expresses how greenhouse gases affect the amount of energy that is absorbed by the atmosphere. Radiative forcing has increased from 1990 to 2008 by about

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[38] The GOS, for instance, collects data from 1,000 land stations, 1,300 upper-air stations, 4,000 ships, about 1,200 drifting and 200 moored buoys, and 3,000 ARGOS profiling floats, as well as 3,000 commercial aircraft, five operational polar-orbiting meteorological satellites, six geostationary meteorological satellites, and several environmental research and development satellites. GAW coordinates data from 26 global stations, 410 regional stations, and 81 contributing stations to produce high-quality data on selected variables of the chemical composition of the atmosphere (WMO 2010).

26%, and CO_2 concentrations account for approximately 80% of this increase (EPA 2010).

A growing number of variables and indicators quantify aspects of climate change like the increase in the intensity of tropical storms in the Atlantic Ocean, the length of a growing season, and the frequency of heat waves, but also socio-political indicators for adaptation and mitigation strategies like cost-effectiveness indicators, performance indicators, and so forth. All of these indicators require adequate concepts of measurement, long-term data series, and knowledge about inherent uncertainties. It is not easy to conceive and measure them because questions of the appropriate timing (period covered), rating the weight of current and historical data, and considerations of cause-effect delays and feedbacks have to be taken into account (Höhne and Harnisch 2002). Finally, the participation of countries in periodically submitting inventories of these indicators has to be organized, for example by the UNFCCC, and surveys for policy makers have to be compiled from these inventories by environmental agencies, e.g., by the European Environment Agency (EEA), the US Environmental Protection Agency (EPA), and other institutions (see also Chap. 5 of this volume), as these indicators also play a crucial role in the evaluation of models and in conceiving scenarios.

2.4.3 Community-Based Cyberinfrastructure

A side-effect of the outlined development of international collaboration and standardization is the opulence of data overflowing data bases and archives. GOS alone collects data from more than 12,000 stations and dozens of satellites. A direct outcome of the International Geophysical Year 1957–1958 (IGY), which provided the very first satellite data collected by Sputnik, was the establishment of World Data Centers (WDC). Today, 52 WDCs are operating in Europe, Russia, Japan, India, China, Australia, and the United States, e.g., the WDC for Atmospheric Trace Gases in Oak Ridge, Tennessee (U.S.), the WDC for Biodiversity and Ecology in Denver, Colorado (U.S.), the World Data Center for Climate (WDCC) in Hamburg, Germany, and the WDC for Glaciology and Geocryology in Lanzhou, China (WDC 2010, List of current WDCs). Besides these, other international data centers like the WMO Information System (WIS) and the IPCC Data Distribution Centre (DDC) as well as thousands of national and local databases and archives have been launched over the last decades. All of these resources provide web-based access, allowing researchers to download data worldwide. A characteristic example is the Ice Core Gateway of the National Climatic Data Center (NCDC) in the U.S. The gateway presents a list of ice-core data sets compiled by the International Ice Core Data Cooperative, which was established in 1996 to facilitate the storage, retrieval and communication of ice-core and related glaciological data (NCDC 2010, Ice Core Gateway).

Table 2.6

Standard prefixes for SI units of the International System of Units (SI) of the International Bureau of Weights and Measures (BIPM) (short scale)

Kilo	10^3 = 1,000 (thousand)
Mega	10^6 = 1,000,000 (million)
Giga	10^9 = 1,000,000,000 (billion)
Tera	10^{12} = 1,000,000,000,000 (trillion)
Peta	10^{15} = 1,000,000,000,000,000 (quadrillion)
Exa	10^{18} = 1,000,000,000,000,000,000 (quintillion)
Petaflop/s	10^{15} = 1,000,000,000,000,000 (quadrillion) floating point operations per second
Petabyte	10^{15} = 1,000,000,000,000,000 (quadrillion) bytes
Terabit/s	10^{12} = 1,000 gigabits = 1,000,000,000,000 bits (trillion) per second

Source: http://www.bipm.org

However, exabytes of meteorological data need not only to be stored but also have to be shuffled around the globe every day. Large data sets and the distribution of vast amounts of data require an infrastructure based on supercomputers (petaflop/s), large databases (exabytes), and high-speed network connections (megabit/s) (see Table 2.6). Such a community-based infrastructure is called ‘cyberinfrastructure’, ‘e-infrastructure’, or ‘high-performance computing (HPC) ecosystem’, providing shared “access to unique or distributed scientific facilities (including data, instruments, [models and model output], computing and communications), regardless of their type and location in the world” (European Commission 2010, e-infrastructure). Grids interconnect heterogeneous resources. While several years ago the distribution of models and data was organized by individual institutions and informal connections between researchers, today it is organized by the services of the community-based cyberinfrastructure via grid or cloud computing. For instance, the U.S. TeraGrid interconnects eleven research institutions including the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. These institutions are connected to the TeraGrid hub in Chicago via a 10–20-gigabit-per-second (Gbps) high-speed networking connection. Some of these institutions also act as grid hubs in their states, contributing petabytes of data storage capacity or high-performance computers, data resources and tools, including more than 100 discipline-specific databases, as well as high-end experimental facilities. An important task of grids is to create gateways. Gateways are community-developed sets of tools, applications, and data, integrated via a portal. Instead of obtaining individual allocations to a computing resource by each researcher, gateways customize the resources and applications needed by a specific scientific community (TeraGrid 2010). Examples of current gateways are the TeraGrid Geographic Information Science Gateway and the Cyberinfrastructure for End-to-End Environmental Exploration (C4E4). The C4E4 gateway allows “researchers to perform end-to-end environmental exploration by combining heterogeneous data resources with advanced tools for accessing, modelling, analyzing, and visualizing data” (C4E4 2010, Gridsphere).

Another grid related to climate science, is the Earth System Grid (ESG), which integrates supercomputers with large-scale data and analysis servers at various national labs and research centers in the US. It connects eight national and four international partners, among them the Lawrence Livermore National Laboratory, the National Center for Atmospheric Research, the Geophysical Fluid Dynamics Laboratory, the British Atmospheric Data Center, and the University of Tokyo Center for Climate System Research. The ESG provides access to various models, model output, and experiments, e.g., the Community Earth System Model (CESM), via the ESG Gateway at the National Center for Atmospheric Research. In Europe, the Distributed European Infrastructure for Supercomputing Applications (DEISA) links eleven national supercomputing centers—based on the European high-speed net GÉANT (10 Gbps). The GÉANT initiative interconnects 32 European national research and education networks and links them to other networks worldwide. The aim of DEISA is to develop a robust and permanent high-performance computing (HPC) ecosystem for research in Europe (DEISA 2010). DEISA supports several scientific projects and programs like the European Network for Earth System Modelling (ENES). These grid resources are usually available at no cost for research projects managed through the peer review process.[39] It is the vision that cyberinfrastructure or e-infrastructure should build virtual laboratories and organizations for distributed communities. These virtual laboratories and organizations are supposed to enable accelerated science discovery (ASD), scientific discovery through advanced computing (SciDAC), and open scientific discovery.

While grid or cloud-computing facilitates access to resources, it embeds services, models, and data sets in an advanced computing structure. In the case of models, this entails code migration in order to make a model run on heterogeneous computer clusters. The development of massive parallel computers has already challenged scientific modelling. In the 1980s network computing became accessible and network communication allowed thousands of CPUs and memory units to be wired up together. Since that time the development of parallel computing has advanced to more complex architectures of shared and distributed memory systems, allowing massive parallel computing. Current supercomputers consist of thousands of central processing units (CPU) for massive parallel computing (Top500 Supercomputer List 2010). In order to make use of this massive parallelism, "programs with millions of lines of code must be converted or rewritten to take advantage of parallelism; yet, as practiced today, parallel programming for the client is a difficult task performed by few programmers" (Adve et al. 2008, p. 6). This bottleneck of skilled programmers has led to new scientific degree programs in scientific computing, as software has become "the new physical infrastructure of [...] scientific and technical research" (PITAC 1999, p. 27).

These ongoing developments—massive parallelism and computing on heterogeneous, distributed platforms—are challenging scientists, because theories and models that are not conceivable as computable from the outset will become less and

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[39] Free access to data is not always practiced in science. In genetics, for instance, many data sources are commercialized. This can seriously hinder scientific progress. Fortunately, meteorology and climate science are dominated by free access to data and models as well as to computer and observation resources.

less successful as scientific practices brace for change (Drake et al. 2008). However, current practice is based on the subsequent creation of computable forms of theories and models by algorithms, and this interferes with the requirements of massively parallelized representations of these theories and models. Modelling, usually carried out by scientists, increasingly requires advanced knowledge of programming and software engineering. Either scientists have to be trained to cope with high-performance computing developments, or they need the support of software engineers. Nevertheless, scientific models are coded theory. Every change in code can cause changes in the underlying scientific concept as well as in the results. Therefore the collaboration of scientists and software engineers in the field of scientific modelling is a sensitive one. An exemplary effort to bring together climate modelling and advanced software engineering has been launched by the US-American University Corporation for Atmospheric Research (UCAR) to develop the Community Climate System Model (CCSM) respectively the Community Earth System Model (CESM)—the successors to NCAR's climate models. Work on CCSM started in 1996 and in 1999, once the importance of software engineering had been recognized, the CCSM Software Engineering Working Group was formed. The results of this collaborative approach were published in a special issue on climate modelling of the *International Journal of High Performance Computing Applications* in 2005, and involved software engineers pointing out the need for accuracy and care.

> Due to the mathematical non-linearity inherent in climate system models, it is not possible to anticipate what effect changes in one component will have on the results of other components. [. . .] Changes need to be sequenced, one at a time, so that the relative effects can be tracked and understood. This process of model development and code modification is closely linked with scientific discovery in computational science. Thus, software engineering for climate modeling must involve climate scientists at each step of the process: the specification of requirements, software design, implementation, and testing (Drake et al. 2005, p. 180).

The new paradigm of community-shared models and the community development of models requires an advanced software design. As climate models, atmosphere and ocean models are rooted in a particularly long history of coding: these models involve large bodies of legacy code, handed down from one version to the next. Most of this code is written in FORTRAN, the oldest programming language introduced in 1956. The idea of Formula Translator (FORTAN) was to give scientists "a concise, fairly natural mathematical language" (Herrick and Backus 1954, p. 112). Therefore, "Fortran's superiority had always been in the area of numerical, scientific, engineering, and technical applications" (Metcalf et al. 2004, p. 3)—especially because FORTAN programs were, and still are, noticeably faster than others. But there is another reason: FORTRAN code is easy for scientists to read and therefore supports the exchange of pieces of code, e.g., a certain parametrization, or parts of models, which is common in the climate modelling community. Although the new versions of FORTRAN, primarily the widely used f90, is capable of parallelism and grid computing, scientists increasingly are depending on advanced software design to get their coded theory to run effectively on the new computing infrastructures. The goal of advanced software design is modularity, extensibility, and performance portability—preconditions for coupling models and for using heterogeneous and distributed computing platforms. Modularity builds on component models (e.g., of the atmosphere and ocean) of a climate or Earth system model, with each component further divided into subcomponents (e.g., atmospheric dynamics and physics). It enables new capabilities and subcomponents to be adopted, and the model to be customized for specific applications by choosing between various model configurations (e.g., various physical parametrizations). Preconditions are modules and software techniques for encapsulation. Modularity enables extensibility by coupling various components, for instance those chemical and biogeochemical components actually affected by chemical coupling with the ocean and the atmosphere. Finally, performance portability has to assure that a model performs well across all platforms, based on language standards and widely used libraries like the Message Passaging Interface (MIP). As the cost per grid point of climate calculation increases heavily, performance must be improved. Therefore load balancing, a technique to distribute workload across CPUs, flexible data structures, data decompositions, and other methods must be considered by software engineers.

However, because every change to the code can have a major influence on the results, the set-up of the Software Engineering Working Group (SEWG) as part of the CCSM project in 1999 was an important step. The software engineering process includes the documentation and review of each stage of model improvement, starting with the outline of new requirements, both scientific and computational. The next step is the design of the software architecture, including interface and data structure specifications. Finally, each new implementation has to be tested on several levels (unit testing of individual subroutines and modules, integrated testing of entire models, and frequent regression tests). As the Community Climate System Model (CCSM) and the Community Earth System Model (CESM) are community models, code correctness standards are needed for each change. Furthermore, "changes reproducing more than round-off differences in the results were not permitted by a single developer. The [Change Review Broad] (CRB) required much longer simulations, broader discussions, and scientific review when new modules were introduced which changed the model climate" (Drake et al. 2005, p. 180).

This ongoing development demonstrates that developing climate models today, which was started decades ago by small groups, involves growing teams of scientists from various disciplines related to the climate as well as software engineers, computer specialists, and mathematicians. The CCSM/CESM development includes twelve working groups and more than 300 researchers from various disciplines. These researchers come from different institutions all over the country. Coordinating the community development of scientific models takes place not only in meetings and workshops, but is also based on widely used software tools and standard processes. Tools like version control systems, software repositories, and procedures for introducing new code are common. Community development will "become easier as the community moves toward componentization and shared utility infrastructures" (Drake et al. 2005, p. 180), for instance by using climate and Earth system modelling frameworks, model coupling toolkits, common component architectures, and specific libraries. Besides the modelling community, other communities have propagated during recent years. The number of model users and model output users has increased since access to models and data has been facilitated by cyberinfrastructures. The goal is to make climate simulation as easy as possible for model users. Climate and Earth system models will become operational tools like measurement and observation devices, accessible

> via a portal, which will allow a user to compose, execute and analyze the results from an Earth system simulation. After authenticating themselves with the portal, a user will have access to a library of components that can model different aspects of the Earth system (for example, ocean, atmosphere) at different resolutions. The user constructs a composite application by selecting from these components (GENIE 2010, Vision).

This plug-and-play mode uses components and couplers like bricks. In principle, anybody could conduct an Earth system experiment. But these bricks are black boxes for users outside the modeller community, entailing the risk that results could be misinterpreted due to a lack of understanding. Nevertheless, this development democratizes the use of climate and Earth system models. This, in turn, will stimulate new user groups from other fields like economics and politics to apply these models in their work.

2.4.4 The IPCC Rhythm of Model Development and CMIP

The outlined developments of community-based cyberinfrastructures and new user groups are more or less associated with the work of the Intergovernmental Panel on Climate Change (IPCC). IPCC has become a leading driver of progress in climate modelling. Set up in 1989 by WMO and UNEP, the aim of IPCC is "to provide the governments of the world with a clear scientific view of what is happening to the world's climate" (IPCC 2010, History), in the words of the UN General Assembly Resolution 43/53 of 6 December 1988. One of the major activities of IPCC is the coordination and release of the IPCC Assessment Reports, involving hundreds of scientists as Coordinating Lead Authors, Lead Authors and Review Editors. The Assessment Reports give a state-of-the-art overview of climate and climate change science. Although there has been some critique of the work and procedures of the IPCC (see also Chap. 3 of this volume), from the perspective of climate modelling the IPCC has turned out to have a beneficial influence. In particular because the rhythm of the publication periods of the IPCC Assessment Reports (FAR 1990; SAR 1995; TAR 2001, AR4 2007, AR5 2014) have introduced a unique procedure for coordinated model development: Every 5–7 years a major part of the climate modelling community contributes to these Assessment Reports by delivering scenario results. A concerted cycle of model improvement, model testing and intercomparison, and production runs precedes these deliveries (Table 2.7).

The provisional timeline for the fifth IPCC Assessment Report, scheduled to be published at the end of 2014, lists September 2013 as completion date for the

Table 2.7

Intergovernmental Panel on Climate Change (IPCC). A co-sponsored program of the World Meteorological Organization (WMO) and the United Nations Environmental Programme (UNEP)

WGI	Working Group I: The Physical Science Basis
WGII	Working Group II: Impacts, Adaptation, Vulnerability
WGIII	Working Group III: Mitigation of Climate Change
TFI	Task Force on National Greenhouse Gas Inventories
TGICA	Task Group on Data and Scenario Support for Impacts and Climate Analysis
Reports	Assessment Reports (FAR 1990; SAR 1995; TAR 2001, AR5 2007, AR5 2014) Special Reports (e.g. Renewable Energy Sources and Climate Change Mitigation; Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation) Methodology Reports (e.g. IPCC Guidelines for National Greenhouse Gas Inventories) Development of New Scenarios (AR 1990, SR 1994, SRES 2000, currently: RCPs)
AR5	
WG I Authors	258 Coordinating Lead Authors, Lead Authors and Review Editors from 44 countries (65% new CLAs, LAs, REs; 19% female)
WG II Authors	302 Coordinating Lead Authors, Lead Authors and Review Editors
WG III Authors	271 Coordinating Lead Authors, Lead Authors and Review Editors

Source: http://www.ipcc.ch/

contribution of Working Group I (see Table. 2.8). WGI is responsible for the physical science bases and the model-based predictions. This means that all models already had to be improved and tested for performing the required experiments in 2010. Global projections in the AR5 are based on the Coupled Model Intercomparison Phase 5 (CMIP5); thus a preliminary set of CMIP5 experiments was designed and discussed in 2007, until a community-wide consensus was reached in 2008. In 2009 a list of requested model outputs was developed, and the final set of CMIP5 experiments approved by the WCRP Working Group on Coupled Modelling. In 2010 the modelling groups participating in AR5 started their production runs for CMIP5, and in February 2011 the first model output became available to the climate science community for analysis. With the First Lead Author Meeting of WGI in November 2010 work on the AR5 started. The complete process of writing and discussing of WGI's contribution to AR5 will last until the WGI Summary for Policymaker (SPM) Approval Plenary meeting in September 2013 approves the SPM line by line. During this period numerous comments have to be considered and a response to each comment has to be provided by the lead authors (Petersen 2006).

From the perspective of climate modelling, the beneficial part of this process is the model intercomparison of CMIP. In the 1980s modelling was still characterized by distinct modelling groups analyzing only their own model output. In the mid-1990s the WCRP Working Group on Coupled Models began organizing global model intercomparison of coupled atmosphere-ocean models (AOGCM) based on standard scenarios and experiments. The Program for Climate Model Diagnosis and

Table 2.8

Timetable of WG I for the fifth IPCC Assessment Report (AR5)

CMIP5	
2007	Preliminary set of CMIP5 experiments discussed (WGCM meeting)
2008	Community-wide consensus reached on the complete, prioritized list of CMIP5 experiments
2009	List of requested model output developed
Sept. 2009	WGCM endorsed final set of CMIP5 experiments
2010	Modelling groups begin production runs and produce CMIP5 output
Feb. 2011	First model output available for analysis
31 July 2012	By this date papers must be submitted for publication to be eligible for assessment by WG1
15 March 2013	By this date papers cited by WG1 must be published or accepted with proof
WG I AR5	
8–11 Nov. 2010	First Lead Authors Meeting
18–22 July 2011	Second Lead Authors Meeting
16 Dec.–10 Feb. 2012	Expert Review of the First Order Draft
16–20 April 2012	Third Lead Authors Meeting
5 Oct.–30 Nov. 2012	Expert and Government Review of the Second Order Draft
14–19 Jan. 2013	Fourth Lead Authors Meeting
7 June–2 Aug. 2013	Final Government Distribution of the WGI AR5 SPM
13–14 Sept. 2013	Preparatory Meeting of WGI AR5 SPM/TS Writing Team & CLAs

Source: http://cmip-pcmdi.llnl.gov/cmip5/; http://www.ipcc.ch/

Intercomparison (PCMDI) collected and archived the model data and made them available to researchers outside the modelling community. Additional phases of the Coupled Model Intercomparison Project (CMIP) followed (CMIP2, CMIP2+), opening up the model output to analysis by a wider community. The planning for the third IPCC Assessment Report (TAR) put forward the wish that “not only must there be more lead time for the modeling groups to be able to marshal improved model versions and the requisite computing resources to participate, but there should also be time and capability for the model data to be analyzed by a larger group of researchers” (Meehl et al. 2007, p. 1,384). According to Gerald A. Meehl et al., CMIP3 conducted the largest international climate model experiment and multimodel analysis ever. Various experiments on climate change, climate commitment, idealized forcing and stabilization, climate sensitivity, and other topics have been performed by the AOGCMs (Table 2.9). The amount of data supplied to PCMDI from modelling groups was so extensive that conventional online data transfer became impractical and the modellers had to send in their data on disks. Seventeen modelling centers from 12 countries with 24 models participated in CMIP3, and more than 300 researchers registered for access to the multimodel dataset. Based on these data more than 200 analyses were submitted to peer-reviewed journals by spring 2004 in order to be assessed as part of AR4. The CMIP3 process inaugurated

> a new era in climate science research whereby researchers and students can obtain permission to access and analyze the AOGCM data. Such an open process has allowed hundreds of

Table 2.9

23 Coupled Atmosphere-Ocean Models (AOGCM) participating in CMIP3 and AR4

BCC-CM1	Beijing Climate Center, China
BCCR-BCM2.0	Bjerknes Centre for Climate Research, Norway
CCSM3	National Center for Atmospheric Research, USA
CGCM3.1 (T47)	Canadian Centre for Climate Modelling and Analysis
CGCM3.1 (T63)	Canadian Centre for Climate Modelling and Analysis
CNRM-CM3	Météo-France
CSIRO-MK3.0	CSIRO Atmospheric Research, Australia
ECHAM5/MPI-OM	Max Planck Institute (MPI) for Meteorology, Germany
ECHO-G	Meteorological Institute of the University of Bonn (Germany), Korea Meteorological Administration (Korea), and Model and Data Group Hamburg (Germany)
FGOALS-g1.0	Chinese Academy of Sciences
GFDL-CM2.0	Geophysical Fluid Dynamics Laboratory, USA
GFDL-CM2.1	Geophysical Fluid Dynamics Laboratory, USA
GISS-AOM	Goddard Institute for Space Studies, USA
GISS-EH	Goddard Institute for Space Studies, USA
GISS-ER	Goddard Institute for Space Studies, USA
INM-CM3.0	Institute for Numerical Mathematics, Russia
IPSL-CM4	Institut Pierre Simon Laplace, France
MIROC3.2 (hires)	Center for Climate System Research, National Institute for Environmental Studies and Frontier Research Center for Global Change, Japan
MIROC3.2 (medres)	Center for Climate System Research, National Institute for Environmental Studies and Frontier Research Center for Global Change, Japan
MRI-CGCM2.3.2	Meteorological Research Institute, Japan
PCM	National Center for Atmospheric Research, USA
UKMO-HadCM3	Hadley Centre for Climate Prediction and Research/Met Office, UK
UKMO-HadGEM	Hadley Centre for Climate Prediction and Research/Met Office, UK

Source: CMIP3 Climate Model Documentation http://www-pcmdi.llnl.gov

> scientists from around the world, many students, and researchers from developing countries, who had never before had such an opportunity, to analyze the model data and make significant contributions (Meehl et al. 2007, p. 1393).

The CMIP3 multi-model data set also allowed new metrics to be developed for model evaluation. It gave modellers comparative insights into their own model and the others, enhancing further improvements. Therefore, CMIP5 will also be an integral part of the fifth IPCC Assessment Report, as it is a "collaborative process in which the community has agreed on the type of simulations to be performed" (IPCC 2010, p. 16). The IPCC Expert Meeting on Assessing and Combining Multi Model Climate Projections, held in January 2010 in Boulder, Colorado, developed a *Good Practice Paper on Assessing and Combining Multi Model Climate Projections* for the community (IPCC 2010). Compared to CMIP3, "since participation in the IPCC process is important for modelling centers, the number of models and model versions is likely to increase in CMIP5" (IPCC 2010, p. 16). More than 20 modelling centers are expected to participate in CMIP5, contributing more than 1,000 terabytes of data. A diversity of models is expected. Some of the models will include biogeochemical cycles, gas-phase chemistry, aerosols, etc., others will not. This introduces the problem of comparability between the models, which not only differ in various aspects from each other, but also in their individual performance. This has stimulated an ongoing debate on weighting models. CMIP3 analysis has followed a 'one vote, one model' policy of equal weighting to create a multi-model mean (MMM). But there might be reasons for weighting models based on some measure of performance (optimum weighting) (Weigel et al. 2010; Räisänen et al. 2010).

> Recent studies have started to address these issues by proposing ways to weight or rank models, based on process evaluation, agreement with present day observations, past climate or observed trends. While there is agreement that 'the end of model democracy' may be near, there is no consensus on how such a model selection or weighting process could be agreed upon (IPCC 2010, p. 16).

However, model intercomparison on a worldwide scale has not only preluded a new era in climate science involving more researchers than ever in the conjoint process of obtaining substantial and community-assessed information for the IPCC Assessment Reports. It also provides the role model of using model output, besides observational and experimental data, to gain knowledge for other disciplines. And these advances are important, as projecting the future has become the desire of mankind.

2.5 Climate Projections and the Challenge of Uncertainty

When Jule Charney and colleagues published their report *Carbon Dioxide and Climate: A Scientific Assessment* in 1979, they concluded that

> if the CO_2 concentration of the atmosphere is indeed doubled and remains so long enough for the atmosphere and the intermediate layer of the ocean to attain approximate thermal equilibrium, our best estimate is that changes in global temperature to the order of 3°C will occur and that these will be accompanied by significant changes in regional climatic patterns (Charney et al. 1979, p. 17).

Based on the numerical study of climate sensitivity carried out through experiments using models developed by Syukuro Manabe et al. and James Hansen et al., these conclusions still hold, although the authors were fully aware that "we can never be sure that some badly estimated or totally overlooked effect may not vitiate our conclusions. We can only say that we have not been able to find such effects" (p. 17). The so-called Charney report marked a turning point. It led to a series of Congressional hearings in the US during the 1980s, which turned climate change into a public policy issue. After decades of research that has made forecasting algorithms meteorology's ultimate objective—for weather forecasting as well as for climate projections—the public now started to ask for reliable predictions (very likely projections) about climate change. Strictly speaking, however, scientific forecasting and climate projections do not have much in common. While the main purpose of scientific forecasting is to be promptly verified or falsified in order to support or to disable a hypothesis climate projections are made to be avoided, so that we never will be forced to verify them in the future. This paradox of ‘to-be-avoided projections’ leads to various problems in the interaction between science and the public, and limits the range of scientific arguments used as the bases for socio-political decisions.

2.5.1 Mankind’s Dream of Rational Forecasting

It was science itself that fed mankind’s dream of rational forecasting based on physical laws. The triumphant advance of numerical prediction, ever since Urbain Le Verrier numerically forecasted the existence of planet Neptune in 1846, motivated science to make increasing use of physical laws articulated by differential equations to extrapolate future states of a system in time and space. Such extrapolations were used to verify or falsify theories and hypotheses, for instance the hypothesis of the existence of planet Neptune. As the philosopher of science Karl Popper pointed out in his study *The Logic of Scientific Discovery*, an empirical scientist “constructs hypotheses, or systems of theories, and tests them against experience by observation and experiment” (Popper 1992, p. 2). In case of planet Neptune the astronomer Johann Galle successfully verified Le Verrier’s hypothesis by observation in a single night. He did exactly what Popper described in his book: he tested a single prediction which could be proved or disproved straightforwardly. Either planet Neptune could be observed or not, based on Le Verrier’s assumptions that disruptions in the orbit of planet Uranus could be caused by a planet which had yet to be discovered. Le Verrier had inferred the possible position of this unknown planet numerically and asked Galle to observe a certain area. If he had not been able to see the planet, Le Verrier’s hypothesis would have been assumed to be wrong, because it had been falsified by observation. But other reasons were conceivable, for instance, false calculations or insufficient telescope resolution. However, since Le Verrier’s day science has changed rapidly, attempting to extrapolate more advanced predictions for systems more complex than a single planet. The testability of such predictions has relied increasingly on sets of measurement data rather than on yes and no answers now that observation and experiment have been so extensively quantified.[40] One of the main achievements of nineteenth and twentieth-century science was to quantify observation and experiment by introducing advanced methods of detection and measurement, thus producing a growing amount of numbers. Based on these improved measurement methods and on powerful sets of equations expressing physical laws, nineteenth-century science

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[40] As long as a single assertion can be inferred from a theory and clearly tested by observation or experiment in order to validate or falsify the theory, prediction is a practical tool for science to test its knowledge basis. Based on this practicability, Popper differentiated two forms of predictions: ‘conditional scientific predictions’ (if X takes place, then Y will take place) and ‘unconditional scientific prophecies’ (Y will take place). The conditional prediction is the type used in rational forecasting applied to a system that changes over time.

proudly called itself an ‘exact science’ as it became a matter of values and numbers, and of measuring and computing, respectively. An exact science is capable of accurate quantitative expression, precise predictions, and rigorous methods of testing hypotheses. Nevertheless, the downside of exact science is that quantitative methods are subject to limits on precision and complexity: every measurement device operates within a range of accuracy and collects only local information, which is why data sets never depict a complete and precise picture of the state of a system. Furthermore, every calculation based on infinitesimal entities like differential equations is approximative, and the inference of precise predictions is limited to simple systems. The adjective ‘exact’ easily leads to exaggerated expectations of science’s ability to forecast rationally.

The idea of predictability has been rooted mainly in the progress of physics, ever since Isaac Newton and others postulated the laws of motion in the seventeenth century. These laws turned physics into a mechanistic approach based on the dogma of strong determinism, as Pierre de Laplace aptly articulated in 1820:

> We ought to regard the present state of the universe as the effect of its antecedent state and as the cause of the state that is to follow. An intelligence knowing all the forces acting in nature at a given instant, as well as the momentary positions of all things in the universe, would be able to comprehend in one single formula the motions of the largest bodies as well as the lightest atoms in the world, provided that its intellect were sufficiently powerful to subject all data to analysis; to it nothing would be uncertain, the future as well as the past would be present to its eyes. The perfection that the human mind has been able to give to astronomy affords but a feeble outline of such an intelligence. Discoveries in mechanics and geometry, coupled with those in universal gravitation, have brought the mind within reach of comprehending in the same analytical formula the past and the future state of the system of the world. All of the mind’s efforts in the search for truth tend to approximate the intelligence we have just imagined, although it will forever remain infinitely remote from such an intelligence (de Laplace 1951, Preface).

That science, and also meteorology as the physics of the atmosphere, is rooted in this tradition, can be read from Vilhelm Bjerknes’ seminal paper of 1904, in the introduction of rational solution for weather prediction considered from the viewpoints of mechanics and physics.

> If, as any scientifically thinking man believes, the later states of the atmosphere develop from the former according to physical laws, one will agree that the necessary and sufficient conditions for a rational solution of the problem of meteorological prediction are the following: 1. One has to know with sufficient accuracy the state of the atmosphere at a certain time. 2. One has to know with sufficient accuracy the laws according to which a certain state of the atmosphere develops from another (Bjerknes 2009, p. 663).

If both are known with sufficient accuracy, “to construct the pictures of the future states of the atmosphere from the current state of the atmosphere at a starting point” (p. 668) will be possible. Every forecasting algorithm (GCM) based on Bjerknes’ mechanical and physical concept follows this approach. This imitation of an intelligence to which nothing would be uncertain, neither the future nor the past, characterizes mankind’s dream of rational forecasting. But despite his trust in determinism, Bjerknes was aware that a complete diagnosis of the current state of the atmosphere is not feasible and that—given that his outlined mathematical model properly describes the laws governing the development of the atmosphere from one state to the next—a strictly analytical integration of the governing equations is out of the question.[41] “Furthermore”, he pointed out, “the major atmospheric processes are accompanied by a long list of side effects [. . .] The question is: to what extent are there side effects with considerable feedback effects on the development of atmospheric processes? The feedbacks evidently do exist” (p. 664). This enumeration of basic constraints—lack of complete diagnosis of the atmosphere, lack of an exact solution of the mathematical model, and lack of knowledge on relevant processes—harbours all possible sorts of uncertainty which challenge climate projection even today.

2.5.2 The Challenge of Uncertainty

As long as science is interested mainly in epistemological questions, trying to decode the mechanisms of relevant processes of a phenomenon, uncertainty is a tedious feature, but not a threatening one. But when science has to apply its knowledge, uncertainty becomes a provocation. In case of technical applications, a designed system can be fully engineered and adjusted to scientific theory as its level of freedom can be controlled and restricted, but in the case of nature this is impossible. Therefore, an application of climate change science has to take into account the conjuncture of complexity and uncertainty, which requires a new understanding of scientific prediction. This new understanding is currently shifting through the ongoing interaction of climate change science and policy. This understanding tries to include uncertainty and decision-making under uncertainty as integral parts of both human and scientific knowledge. On the one hand, it aims to reduce uncertainty in research on the climate system; on the other, it aims to assess known uncertainties and the possible consequences of different decisions, including inaction. This two-pronged approach to uncertainty characterizes climate change science and policy and has led to various developments. Over the course of the IPCC Assessment Reports, in particular, sources and sorts of uncertainties have been examined and a specific wording and classification has been developed. An extensive discussion of a typology of uncertainty is given by Arthur Petersen (Petersen 2006). He differentiates the location, nature, and range of uncertainty as well as the limits of recognized ignorance, methodological (un)reliability, and value diversity (see Table 2.10).

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[41] “As is well known, the calculation of the movement of three points that influence each other according to a law as simple as Newton’s already far exceeds the means of today’s mathematical analysis. There is evidently no hope of knowing the movements of all points of the atmosphere which are influenced by much more complicated interactions” (Bjerknes 2009, p. 665).

Table 2.10

Typology of uncertainty involved in modelling and simulation

Location of uncertainty	Uncertainty in models, input data, model implementation, and output interpretation.
Nature of uncertainty	Epistemic uncertainty (incompleteness and fallibility of knowledge), ontic uncertainty (due to the intrinsic character of a natural system), and a mix of both. e.g. unpredictability of long-term weather forecasts due to the limited knowledge of initial states as well as to the chaotic behaviour of weather based on its sensitive dependence on initial conditions.
Range of uncertainty	Statistical uncertainty (range of uncertainty expressed in statistical terms) based on two paradigms (frequentist and Bayesian statistics) and scenario uncertainty (range of uncertainty expressed in terms of plausibility often articulated as 'what, if' statements). Scenario uncertainty can transform into statistical uncertainty if more is known about relevant processes. Statistical and scenario uncertainty ranges can be expressed in terms of (in)exactness and (im)precision, or (un) reliability and (in)accuracy.
Recognized ignorance	Awareness of the limits of predictability and knowability expressed in terms of the subjective probability of a statement or its openness.
Methodological unreliability	Adequacy or inadequacy of methods used, e.g. quality of initial and boundary conditions, analysis methods, numerical algorithms, discretization, and qualitative peer review by best practice and standard references in the scientific community.
Value diversity	Value-laden choices of decisions, e.g. regarding the processing of data or concepts of modelling. The values can result from general and discipline-bound epistemic values as well as from socio-political and practical values. These values can bias the scope and robustness of the results and conclusions.

Source: Petersen 2006, pp. 49–64

It is worth mentioning that Petersen differentiates two notions of reliability: Firstly, reliability of a simulation according to its accurate results given for a specific domain. Secondly, reliability of a simulation related to its methodological quality (Petersen 2006, p. 55 et seq.). While the first notion of reliability refers to statistical and therefore quantifiable reliability, the second refers to methodological and qualitative reliability. An important aspect of the quantifiable reliability of a simulation is that it refers to the whole model (system level) and does not imply top-down reliability for each element of the model (component level). On the other hand, each component needs to be tested for certain circumstances and reliability has to built from the bottom up. From this—and the consideration of qualitative uncertainty, too—it follows that model evaluation consists of a number of tests, studies, and practices, all of which constitute the reliability of a model and its projections.

Although during the IPCC process a specific wording and classification of uncertainties have been developed, the consistency of wording within each working group did not apply across statements by the other working groups. While WGI (Physical Sciences Basis) dealt with uncertainties in climatic processes and probabilities, WGII (Impacts) focused on risks and confidence levels, and WGIII (Response Strategies)

Table 2.11

Levels of confidence and a likelihood scale by IPCC

Levels of confidence	**Degree of confidence in being correct**
Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance
Likelihood scale	**Likelihood of the occurrence/outcome**
Virtually certain	>99% probability of occurrence
Very likely	>90% probability
Likely	>66% probability
About as likely as not	33–66% probability
Unlikely	<33% probability
Very unlikely	<10% probability
Exceptionally unlikely	<1% probability

Source: IPCC 2005, pp. 3–4

adopted a common approach only during the process for AR4 (see Table 2.11). One reason for this diverse approach among the working groups is rooted in their different topics and methods, another result from the scale of the working groups and difficulties in coordinating heterogeneous communities, especially when thousands of scientists of various disciplines are involved without any authoritative management. Nevertheless, sources and sorts of uncertainty are divers and range between the causality of natural systems and the intentionality of human systems, as well as between objective and subjective perspectives (Swart et al. 2009).[42] Furthermore, quantitative statements based on observation and measurement must be translated into future natural effects and their relevance for mankind. The problem thereby is that the causality to be considered is neither simple nor unidirectional, but a complex feedback cycle of human activities triggering natural causalities, which, in turn, cause effects that require human reaction (mitigation, adaptation). An ongoing spiral of action and reaction, including inaction as a form of reaction, must be assessed in terms of more or less (un)certain predictions or projections. Therefore, the growing awareness of the importance of communicating uncertainty is also reflected in a more subtle wording of the terms ‘prediction’, ‘forecast’, ‘scenario’, and ‘projection’ (see Table 2.12). While the first IPCC Assessment Report generously used the term ‘prediction’, since the second report this term has been used with more care, with the authors instead referring to the concept of ‘projection’. Although there are no clear definitions of these terms, the notion of ‘prediction’ differs slightly from the notion of ‘projection’.

Following Dennis Bray’s and Hans von Storch’s analysis of the nomenclature of climate science, one can say that

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[42] Rob Swart et al. suggest a consistent vocabulary of confidence levels and probabilities across all working groups, special training for IPCC authors, a legitimate view of different approaches, and a supportive articulation of the nature and origins of uncertainties for the reader (Swart et al. 2009, p. 3 et seq.).

Table 2.12

Definitions of forecast/prediction, projection, and scenario by IPCC

Definition by IPCC	**AR4 WGI Glossary**
Climate prediction	A climate prediction or climate forecast is the result of an attempt to produce an estimate of the actual evolution of the climate in the future, for example, on seasonal, interannual or long-term timescales. Since the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature.
Climate projection	A projection of the climate system's response to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty.
Climate scenario	A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed explicitly to investigate the potential consequences of anthropogenic climate change, often serving as input for impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information, or instance about the currently observed climate. A climate change scenario is the difference between a climate scenario and the current climate.
Definition by IPCC	**AR4 WGII Glossary**
Climate prediction	A climate prediction or climate forecast is the result of an attempt to produce an estimate of the actual evolution of the climate in the future, e.g., on seasonal, interannual or long-term timescales.
Climate projection	The calculated response of the climate system to emissions or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based on simulations by climate models. Climate projections are distinguished from climate predictions, in that the former critically depend on the emissions/concentration/radiative forcing scenario used, and therefore on highly uncertain assumptions of future socio-economic and technological development.
Climate (change) scenario	A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships and assumptions of radiative forcing, typically constructed for explicit use as input for climate change impact models. A 'climate change scenario' is the difference between a climate scenario and the current climate.

Source: IPCC 2007a, p. 943; IPCC 2007b, p. 872

> 'prediction' conveys a sense of certainty while 'projection' is associated more with the possibility of something happening given a certain set of plausible, but not necessarily probable, circumstances. A prediction can be used to design specific response strategies, while a projection, or more precisely a series of projections, provides a range on which to consider a range of response strategies (Bray and von Storch 2009, p. 535).

The interesting aspect here is the difference between probability and plausibility. While probability is a quantitative measure of statistical uncertainty and can be used as displayed in the likelihood scale, plausibility refers to expert judgments in terms of confidence. It is no coincidence that WGI uses the likelihood scale, while WGII applies levels of confidence in their report. Bray and von Storch point out that the simulated climate development is determined by the initial state, by external forcing, and by the internal variability of the climate system. But the initial state's impact on the simulated development of climate disappears after a few weeks of simulated time, the initial soil conditions after a few years, and that of the upper ocean after a few decades. As "the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature" (IPCC 2007a, p. 943). However, the initial state's loss in impact, compared to the long-term relevance of the highly uncertain factor of external forcing, transforms the probabilistic nature of climate prediction into the mere plausibility of climate projections after a certain period, the length of which remains unknown. Thus, a short-term prediction (decadal forecast) gradually turns into a long-term projection (scenario simulation).

> In both cases, any statement about a 'probability' hinges on an assessment of the probability of the conditioning elements, namely, the initial state of the climate system and the forcing scenario. Here, a key difference emerges—the initial state is known within given bounds, while the forcing scenario is an educated guess, without an associated probability (Bray and von Storch 2009, p. 535).[43]

These educated guesses rely on possible scenarios of future emissions and human behaviour and therefore can result only in possible or plausible outcomes of scenario simulations, not in probable ones. However, the purpose of scenarios and scenario simulations is to raise 'what if' questions, and to gain an understanding of how specific processes and forcings push the future in different directions. Therefore, scenario simulations are defined as

> images of the future, or alternative futures. They are neither predictions nor forecasts. Rather, each scenario is one alternative image of how the future might unfold. A set of scenarios assists in the understanding of possible future developments of complex systems (Nakicenovic and Swart 2000, p. 62).

2.5.3 Climate Scenarios and Storylines

Scenario simulations are plausible and often simplified representations of the future climate and entail their own range of uncertainty (scenario uncertainty). Nevertheless,

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[43] Bray and von Storch conducted an analysis exploring "how climate scientists perceive the products of their efforts, as a *projection* or as a *prediction*" (Bray and von Storch 2009, p. 538). The interesting result of this analysis is that about two thirds of the 283 responses are cautious about their outcome, calling them projections, not predictions. However, there is still some confusion, with "approximately 29% of the respondents associating probable with projections and approximately 20% of the respondents associating possible with prediction" (Bray and von Storch 2009, p. 541).

scenario simulations are required to assess future possible pathways. In the context of the IPCC Assessment Reports, scenario development started in the late 1980s, with the SA90 scenario used in the first IPCC Assessment Report in 1990, followed in 1992 by a set of six scenarios (IS92a through f) for the second IPCC Assessment Report in 1995 (cf. Leggett et al. 1992; Pepper et al. 1992). For the third and fourth IPCC Assessment Reports in 2000 and 2007 a set of four storylines and forty scenarios was used, developed and published in 2000 by the *Special Report on Emission Scenarios* (Nakicenovic and Swart 2000; Girod et al. 2009). New scenarios, called Representative Concentration Pathways (RCP), have been developed for the fifth IPCC Assessment Report in 2014 (RCP Database 2010). Scenarios describe possible worlds of different economic, social and environmental conditions which result in different greenhouse gas futures—externally forcing the development of the climate system. The underlying assumptions of these scenarios are based on reports by major international bodies like the Organisation for Economic Co-operation and Development (OECD) and expert analyses. The major factors driving anthropogenic emissions and land-use are population growth, affluence, energy efficiency and the state of technology. However, the estimates of these factors involve great uncertainties. Therefore, long-term projections (scenario simulations) are very vague images of possible future developments.

The main driving factor is the growth of population, as it scales anthropogenic emissions and humans' impact on the climate and environment. Population growth is driven by the fertility rate, which is close to the replacement level in developed countries, but much higher in developing countries. Because the number of females of reproductive age controls fertility, there is some potential to predict short-term future population growth. Another important factor is mortality, which in many countries shows a decreasing trend due to improved hygiene and modern medicine. Population projections involve current age distributions, as well as economic and social developments. However, events such as wars, the post-World War II baby boom, AIDS and the recent rapidity of declining fertility in developing countries could not be foreseen. In quantitative terms, the world population reached 1 billion in 1804, 2 billion in 1927, 3 billion in 1960, 4 billion in 1974, and 5 billion in 1987, reaching the 6-billion level shortly before the millennium. Projections of future population assume a stabilization in the mid-twenty-first century. Projections range between 8 and almost 11 billion, with more recent estimates near the lower end. Recent estimates cannot be evaluated, but earlier estimates can be compared to the present-day population. The percentage errors of twelve UN forecasts of the world's population made between the years 1957–1998 and representative for the year 2000 range between 1.0 and 7.1% (Bongaarts and Bulatao 2000). This is an excellent agreement; however, errors are considerably larger on a regional scale and for longer time periods. Short-term projections benefit from the fact that most people alive at a given date are still alive three or four decades later. The most used estimates are those derived by the World Bank and the UN. The SRES scenarios used for the fourth IPCC Assessment Report employ published projections from the

International Institute for Applied Systems Analysis (IIASA) along with the UN's medium and long-range projections.

Another driving factor is economic wealth, as it is associated with high consumption of resources and high CO_2 emissions on the one hand, but also high technological standards, which reduce emissions per activity, on the other. Economic development is expressed in terms of Gross National Product (GNP). GNP is defined as the monetary equivalent of all products and services generated in a given economy in a given year. Although GNP is widely used, it does not reflect all aspects of human welfare and sustainability. Due to these inherent weaknesses of GNP, for the degree of economic development IPCC uses a simpler measure: per-capita income. The impact of future energy use will depend on fuel types and the implementation of efficient technologies. The global demand for energy of all forms is likely to increase significantly, even with substantial gains expected in efficiency. Population and GNP assumptions, along with structural and technological changes that affect energy efficiency and energy, drive the demand for energy services. Energy use per unit of economic activity, that is, energy intensity, reflects a whole range of structural, technological, and lifestyle factors (Nakicenovic and Swarts 2000). Future resource availability is a dynamic process, which is controlled by the total amount of hydrocarbon or uranium in the Earth's crust or of any other energy form; accessibility, the state of technology, cost and energy prices. Because estimates of all these factors are highly uncertain, IPCC develops low and high resource scenarios.

A working group led by Nebojsa Nakicenovic and Robert Swart, both editors of the SRES report, developed four different storylines, but no explicit judgments have been made as to their desirability or probability (see Table 2.13). The purpose of these storylines is to explore the uncertainties behind potential trends in global developments, as well as the key drivers that influence these. The construction of scenarios reflects political and economical activity or inactivity and takes place at the interface between science and politics. Scenarios link qualitative narratives on population growth, economic growth, and technological aspects, for instance concerning energy effects and land-use (storylines) with corresponding quantitative data and formalized mechanisms for each storyline. The output is the specification of future emissions of GHGs in quantitative terms.

The scenarios provide the information necessary to derive the emissions. To construct an emission inventory one needs to know the temporal evolution of the emission factors (how much of a chemical species is produced by a specific source per time unit), the number and geographical distribution of different emission sources or sectors, and the activity statistics. For the construction of inventories mathematical models are used. Most of the data are available on a national basis and are disaggregated to the model's grid. The SRES emissions inventories include data on the most important greenhouse gases: CO_2, methane, nitrous oxide, nitrogen oxides, carbon monoxide, non-methane volatile organic compounds, sulfur dioxide, chlorofluoro-carbons and hydrochlorofluorocarbons, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride. Carbon monoxide, nitrogen oxides, and organic

Table 2.13

Storylines of the Special Report on Emission Scenarios (SRES)	
A1	The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into four groups that describe alternative directions of technological change in the energy system.
A2	The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
B1	The B1 storyline and scenario family describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
B2	The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on the local and regional levels.

Source: Nakicenovic and Swart 2000, pp. 4, 5

compounds are used to calculate ozone concentrations.[44] The SRES scenarios for projected CO_2 emissions until 2100 range from 5% (scenario B1) to 90% (scenario A1FI). While B1 describes global, sustainable development, A1FI describes a global, fossil-fuel-intensive development. These scenarios lead to an estimated increase in the mean global temperature of 1.1–6.4°C by the end of this century. None of these scenarios take into account the possibility of countries implementing new, comprehensive measures or additional climate policy initiatives for reducing emissions of greenhouse gases. Therefore, the so-called 'post-SRES mitigation scenarios', developed by nine modelling teams worldwide, analyze the influence of mitigation strategies. The developed storylines were related to the four SRES storylines, taking into account the availability and dissemination of relevant knowledge on emissions and climate change, institutional, legal, and financial infrastructure to implement mitigation policies and measures, policies for generating innovation, and adequate consumer mechanisms.

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[44] Emissions inventories are developed not only for future scenarios, but also for the past. Inventories for IPCC range from the year 1860 to 2100. Emissions inventories covering the past are provided, for instance, by the Global Emissions Inventory Activity (GEIA) project (GEIA 2010).

2.5.4 Model Evaluation and Intercomparison

The difference between probability and plausibility, or between short-term prediction (decadal forecasts) and long-term projection (scenario simulation) refers not only to different types of uncertainty (statistical vs. scenario uncertainty), it also refers to different practices of evaluation. While it is rather difficult to assess the output of scenario simulations (mostly 'to-be-avoided projections'), it is common scientific practice to evaluate short-term predictions. However, confidence in the plausibility and possibility of future scenarios inevitably requires confidence in short-term predictions and in the underlying model. As models are only as good as the quality of their inputs and representations of processes, evaluation methods have been developed that establish confidence in modelling the climate system as a whole as well as in its sub-processes. Models are evaluated in data test-beds, which provide a measurement-based link between the quantities of model-input and model-output. Model biases include coding errors, inadequate numerical methods, imperfect or lacking process understanding, parameter uncertainties, and simplifications. To quantify a model's performance and to measure its improvements, metrics and score ranking methods have been developed. In the framework of internationally organized model intercomparisons, evaluation has been standardized over recent decades (see also Sect. 2.4).

The literature about climate models often uses terms like 'evaluation', 'validation', and 'verification' in an exchangeable way, but this is misleading. While the term 'evaluation' refers to the investigation of the adequacy of a model for a specific purpose, the concept of 'validation' is related to aspects of mathematics and coding. The model must be consistent and logic, the methods have to be applied correctly, meaning that no coding errors, inadequate numerical methods, or similar faults are allowed. Sometimes the term 'verification' is used. This term is misleading as complex systems are impossible to verify—they cannot be proven to be true—because knowledge about complex systems is always incomplete and observational data are not sufficient (Oreskes et al. 1994). The reason for this is the nature of models based on inductive reasoning. Inductive reasoning infers generalizations from a limited number of observations. Some of these generalizations are fundamental; others are valid only within a specific range. Scientists observe nature, try to understand how some phenomena work, and formulate a model that is able to predict the behaviour of a phenomenon in the future. The model is accepted to be true as long as a phenomenon follows the set of rules laid out in the model. In principle, if there is one observation showing that the model failed to predict future behaviour, it is proven to be incorrect. However, the falsification of complex models is not feasible because the multitude of variables whose temporal evolution is predicted can never match the observations exactly. Thus, general statements about the correctness or incorrectness of a model are not possible.

Therefore the only criterion for the quality of a model is that it agrees with observations and measurements to some extent. As knowledge about the climate comes from observations and theoretical considerations, climate models are a composite of both fundamental physics and semi-empirical approaches. The quality of climate models depends directly on knowledge about and the quality of the representation of the physical processes, many of which are not explicitly resolved or are poorly constrained by observations, but play a key role in the Earth system. For confidence in model projections, a profound understanding of the processes as well as an understanding of the behaviour of the climate as a system is required. Therefore, in order to assess model's performance not only the processes treated in climate models have to be tested (component level), but also the system's behaviour (system level), through simulations of past and present climate states and by comparing the results with observational data. Evaluation on the component level is based on isolating components and testing them independent of the complete model. Evaluation should unveil model biases, e.g., coding errors, inadequate numerical methods, imperfect or lacking process understanding, parameter uncertainties, and simplifications. Moreover, climate models undergo permanent development to enhance their temporal and spatial resolution with increasing computer capacity, or to add new, hitherto neglected processes, or to improve parameterizations by using better physically-based approaches and new observational data. Whenever a simulation is repeated by a new model version, the results will be different. Although the differences may be minor, the results of a model will never match the parameter values describing the system's behaviour exactly.

Nevertheless, the performance of a model is evaluated by comparing model results with observational data on past and present climate states. Whereas in the early times of climate modelling results were compared to field measurements, or meteorological fields analyzed by mere visual inspection and qualified subjectively by statements like ‘good agreement’, in the mean time statistical methods have been applied to assess the degree of agreement between model and observation in a more objective way. Performance metrics have been developed to measure the skill of climate models and to establish a set of standard metrics to measure the strengths and weaknesses of a given model. Of course, the choice of specific metrics is based on subjective decisions and has some influence on the model's ranking. A common method used to analyze whether two data sets are different is Student's *t*-test, comprised of the ratio of the signal to noise in the respective variables (Mearns 1997). The method tests whether two data sets are really different, and is used to decide whether model results differ significantly from observations or whether the differences are arbitrary. The method is also applied to compare the climates of two periods, e.g., pre-industrial and present-day, and to test whether they are significantly different.

Performance metrics are used to evaluate a model on the system level and on the component level. The ability of models to reproduce both a specific climate state and climate change anomalies are evaluated by comparing model output to observation—based on comparing either gridded model output with assimilated variables, or interpolated model output with field observations and remote sensing data. Models are tested for their ability to reproduce the present-day climate (nowcast) and to simulate the evolution of different climate states forced by changes in boundary conditions, for instance greenhouse gas concentrations. Models are also tested to predict past climates (hindcast). Furthermore, hindcasts of the recent past are performed to evaluate short-term processes taking place on timescales for which sufficient observations are available (the last 50 years), e.g., extreme value statistics. Characteristic output variables calculated by extreme value statistics include the length of dry spells (days with less than 0.1 mm precipitation), the annual maximum 5-day precipitation amount, the number of frost days or tropical days (maximum temperature higher than 30°C per year), and so on. As modern society is particularly susceptible to extreme events, like, for instance, hurricane Katrina in 2005 and the heat wave in Central Europe in 2003, changes in regional extreme values of temperature and precipitation are key for any adaptation measures. There is concern that extreme events may change in frequency and intensity in a warmer climate. However, predictions of extreme values vary substantially between the models, and uncertainties are significantly higher than for average values. Long-term experience with model evaluation has shown that the quality of the model is different for different variables. For instance, calculated temperature values are more reliable than those for precipitation, and confidence in average values is higher than in extreme values. Models simulate the temperature extremes, especially the warm extremes, reasonably well, but have serious deficiencies in simulating precipitation extremes.

On the component level, parameterization schemes are tested in isolation in box-models or column-models, and compared to in-situ measurements to study the behaviour of the scheme. In a further step, the scheme is tested in the framework of the whole system, e.g., within an atmosphere model, by switching the new scheme on and off. Finally the full climate system model is integrated. A fundamental problem in evaluating small-scale features and processes is the problem of scale. In-situ measurements take a value representative of a specific time period and location. But since measurements do not usually represent the scales of model grid-boxes, to make use of measurements for evaluation purposes the data must be upscaled or the model output downscaled. Upscaling measurements requires a profound understanding of how processes act on different temporal and spatial scales and is a non-trivial problem.

Vice versa, downscaling from general circulation models to regional effects also involves fundamental problems. Climate change on a regional scale is analyzed by applying Regional Climate Models (RCMs) of higher spatial resolution, which are driven by global model output or by observed meteorology. Model skills vary with region and season. Thus, no general statements about regional climate model performance can be made. For instance, although RCMs capture the geographical variation of temperature and precipitation for Europe better than global models, they tend to simulate conditions that are too dry and warm in southeastern Europe in summer. “Most but not all RCMs also overestimate the interannual variability of summer temperatures in southern and central Europe” (IPCC 2007a, p. 873). These regional biases between model simulation and observation are difficult to assess. E.g., the seasonal mean temperature bias in the northern Europe region varies between different models from –5°C to 3°C, and that in the southern Europe and Mediterranean region varies from –5°C to 6°C. The cold bias in northern Europe tends to increase towards the northeast, reaching –7°C in the northeast of European Russia in winter. The bias varies from model to model and from season to season, and is more substantial in some regions and in some models than in others. Nevertheless, if climate change simulations, which are differences between two simulations (one representing present-day conditions, one future conditions) are analyzed, the relative bias of the difference might be smaller than the absolute bias. This could be because the model bias is about the same in the two simulations, such that it disappears when the difference is calculated. However, the assumption that model biases are independent of the state of climate is speculative, because it is not clear how the biases in the model simulating present-day climate will develop in future scenarios.

To analyze the causes of disagreement between model and observations, and to assess the effects of different model approaches, model intercomparisons have been developed over the last decades. Within the framework of the IPCC assessments the Program for Climate Model Diagnosis and Intercomparison (PCMDI) was established in 1989 at the Lawrence Livermore National Laboratory in the US. Its aim is to support the assessments and to develop tools for evaluating climate models. PCMDI activities focus on model intercomparisons and the development of test-beds.[45] PCMDI provides facilities for the storage and distribution of terascale data sets from multiple coupled ocean–atmosphere GCM simulations of the present-day climate as well as climate change simulations. Model output from a large variety of models and experiments is collected, processed and distributed by PCMDI to the international community to facilitate comparisons to data and tests for consistency. However, not only the results of the simulations but also the model codes are made publicly available. The degree of standardization and transparency of the evaluation procedure of numerical climate models is unique in science.

An example of model intercomparison is given by Thomas Reichler and Jinsun Kim (Reichler and Kim 2008). Reichler and Kim raised the question as to how well coupled models simulate today's climate. They designed a measure to estimate model skills. First they calculated multiyear annual mean climatologies (1979–1999) from gridded fields of global models and observations. The database contains 14 variables including air temperature, air pressure, sea surface temperature and seawater salinity. Next, they calculated for each model and variable a normalized error variance by squaring the differences between simulated and observed climate at every grid-point, normalizing with the observed interannual

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[45] Model comparisons are also performed to test the system behaviour and to assess the ability of climate models to simulate the trends of the recent past (1860–2000) and past climate states. Model intercomparisons performed by PCMDI are the Atmospheric Model Intercomparison Project (AMIP), the Coupled Model Intercomparison Project (CMIP), the Seasonal Prediction Model Intercomparison Project (SMIP), and the Paleoclimate Modeling Intercomparison Project (PMIP). In addition, more than 40 international model intercomparisons have been arranged by different institutions to test the behaviour of sub-models or of specific aspects of climate models, and a great number of publications has emerged from these intercomparisons (see also Sect. 2.4).

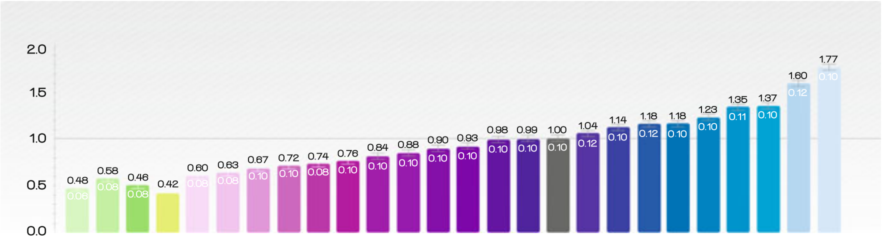

Fig. 2.6 Performance Index of 21 models Red rows denote models, the yellow row the model's median and green rows observations. Average PI is one, PIs smaller than one indicate better, PIs larger than one worse agreement
Source: Replotted by the authors from Thomas Reichler, personal communication 2006

variance on a grid-point basis, and averaging globally. A final model performance index (PI) was formed by taking the mean over all climate variables and normalizing it such that the average performing model has a PI of one. Figure 2.6 displays the performance index of the different models and a comparison to observational data not used in the comparison. Interestingly, the median model shows the best performance in all aspects.[46] The median model outperforms single models in almost all comparisons performed. This indicates that the model's errors are not biased, but well distributed around the observations. There is also no model that performs best in all aspects investigated. Interesting, for instance, is that the performance of a model to reproduce interannual variability is only weakly correlated with an index of mean climate performance (Gleckler et al. 2008). Thus a broad spectrum of climate processes and phenomena must be evaluated since the accurate simulation of one aspect of climate does not guarantee the accurate representation of other aspects. These findings suggest the use of multimodel and multiple model versions of median projections to advise policy, or the construction of a best model by weighting the various aspects of a multimodel ensemble according to their performance.

Another aspect of evaluation is model tuning. Climate models are tuned to achieve agreement with observations. The energy budget at the top of the atmosphere (TOA) controls the climate. Simulating these budgets correctly is a fundamental prerequisite for a realistic climate simulation. The budget includes the outgoing long-wave radiation and the solar radiation scattered back to space. In addition, satellite observations distinguish between clear-sky and cloudy-sky radiative budgets. Climate models are tuned to achieve agreement with the global and multiyear-averaged TOA radiative fluxes observed. Therefore the models are constrained to four parameters: the globally averaged outgoing long-wave radiation and the reflected short-wave radiation, for both clear-sky and cloudy-sky conditions. This means that parameter values are adjusted to generate good agreement with these four parameters. TOA fluxes are tuned to agree with satellite observations mainly via cloud parameters, as these are often

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[46] The median is the value which separates the upper half of a sample from the lower half. Here the median is calculated for any variable at any grid-point.

poorly constrained by observations. This tuning has to be repeated whenever the model code is changed, but the same tuning parameters are then used for simulations of the past, present and future climates. To find the right parameters for model tuning requires long-term experience and skill in running climate models. However, an agreement between the model and the observations of these four global averaged energy fluxes does not guarantee a correct spatial and temporal distribution of the various variables simulated by climate models. This can only be achieved by solid physics in the model.

With regard to model tuning in particular, a discussion has erupted as to whether data from measurements should be considered more trustworthy than those from model simulations. As outlined above, models never accurately match parameter values, no matter how well they have been tuned. However, neither do observations ever match ‘reality’ accurately. As our perception of reality is filtered by our senses as well as by each measurement tool, our knowledge about the real world inherently must include errors and inaccuracies. Only specific aspects that can be observed and measured are covered. Various measurement platforms such as weather stations, buoys, radiosondes, satellites and rockets record data continuously. The national weather services and the World Meteorological Organization collect and distribute global weather data. But observations deliver only an image of the current situation. To learn about past climates, tree rings, ice-core data, sediments and other so-called ‘proxy-data’ are analyzed. However, all of these data sets and observation systems generally have deficiencies in at least one of the key requirements: accuracy, resolution, or spatial and temporal coverage (see Table 2.14).

Furthermore, most modern measurement techniques do not measure the variable of interest directly, but derive the variables indirectly using mathematical algorithms or models that interpret the measurements. This trend has increased in recent decades. For instance, the state of the atmosphere is analyzed twice daily. This is the basis of any weather forecast. Measurements are provided by balloon-driven instruments, so-called radiosondes, which measure the vertical profiles of temperature, humidity, pressure, and wind direction and velocity. Additionally, satellites measure the spectral-band intensity of radiation scattered back or emitted from the ground, from the atmosphere or from clouds. Complex mathematical algorithms interpret these reflectances and derive meteorological parameters such as surface temperature fields and wind fields. Varying a weather forecast model to optimize the state of the climate, so that it agrees best with the model results and the observations, assimilates data from satellites and radiosondes. Such assimilation techniques also include estimates of the uncertainties or inaccuracies of the model and the measurement methods. Data assimilation combines measurements with the physical principles governing numerical models. This kind of model is also called a ‘data model’. Thus numerical models are evaluated by comparing the results of a ‘data model’ to ‘model data’.

As modelling usually seeks associations—by using data as input during a model initialization, by relying on data to constrain processes in modelling, and by applying data for the evaluation of results—, these uses of measurements as references in modelling work only if the data are more accurate than the expected accuracy of the model. Unfortunately, each measurement has some uncertainty

Table 2.14

Typology of data uncertainty for cloud and aerosol measurements

All data are samples	The spatial and temporal coverage is incomplete and there are often justified representation concerns for application to any other instance or location (e.g. local pollution or orography issues).
All data are as good as the instrumental capabilities	Space sensor examples include sensor degradation and pixel sizes that cannot resolve smaller-scale features. Or the in-situ sampling of atmospheric particles has to deal with artefacts of the measurement environment (e.g. particle break-up before sampling or water removal during analysis at warmer temperatures).
Many so-called data are model results	Models are often needed to translate a measured property into a 'useful product'. These models are based on simplifying algorithms and often need to apply a-priori assumptions to parameters and properties, which have a large impact on the resulting data. Good examples include the assumptions needed to calculate solar surface albedo and aerosol absorption in satellite measurements of aerosol traces based on perceived reflections of visible light.

Source: Stephan Kinne, personal communication 2008[47]

and advertised uncertainties are often smaller than the real ones. These real uncertainties can be so large that their use would not only fail to benefit modelling efforts, but could actually harm them. Moreover, some interactions between different variables and climate system compounds, and humans' impact on climate, although key to understanding the system's behaviour, cannot be observed, but only investigated by numerical models, like climate sensitivity. Results from this kind of model cannot be proven in principle, because observed climate changes are the result of a constellation of different forcings and the actual state of the climate.

2.6 Scientific Arguments for Socio-Political Decisions

Climate is change. It required more than 150 years of scientific work to establish this view against the traditional idea of 'klimata' as stable and static. The discovery of Ice Ages and the increasing awareness of the radiative imbalance of the

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[47] This classification was provided by the climate modeller and satellite data expert Stephan Kinne in a personal communication in 2008. He emphasized that accuracy is not an abstract problem. The accuracy necessarily depends on the problem investigated. Sometimes large uncertainty is acceptable, if qualitative pattern information is needed. Nonetheless, quantifying real uncertainty is extremely important. Modelling is better served by data on the real uncertainty range than averages. Close collaborations among data-groups as well as between data-groups and modelling-groups are needed to provide more accurate products, to establish the real uncertainties and to help prevent the misuse and misinterpretation of data.

atmosphere—widely discussed as the greenhouse effect—tremendously altered the idea of climate as well as the questions posed on this emerging concept of change. If climate is change, the relationship between climate and humans has to be taken into account. As long as climate is connected to stability, neither climate change nor human influence occur as relevant thoughts. But once mankind has become aware that climate is change, these changes are interpreted as causes of the rise and fall of civilizations as unearthed by archaeologists, as reasons for economic disasters, and as sources for improving or worsening people's life environment. Climate as change inextricably interconnects the idea of climate with mankind's cultural, social, and economic interests and, not surprisingly, leads to the awareness of the human influence on climate—exerted by six billion individuals.[48] Today's debates on anthropogenic climate change are reflecting this underlying basic shift that the idea of climate has undergone. This shift comes along with two major problems.

The first problem is that this awareness of the climate-man interconnection is not based on direct perception of causal interdependencies between mankind and a natural phenomenon. It is based on a statistical outcome called climate and usually defined as the averaged weather, or more narrowly as the globally averaged surface air temperature, over a period of at least 30 years—to follow the definition of the World Meteorological Society (WMO). In other words: Climate can not be experienced and directly measured in the way we perceive weather phenomena like rain, heat, and wind. What we 'experience' is the flickering of a curve with an averaged tendency towards higher globally averaged temperatures. Thus, the relatively new branch of climate change science and policy deals with an abstract, statistical phenomenon, which has to be retranslated into local and actual events. It also has to manage the difficult business of considering the change of change—the anthropogenic change of natural climate change.

The second problem is the need for reliable statements on future developments. It is no surprise that climate change and policy draw on the idea of projecting possible future changes of climate change in order to prevent them. But to prevent change from change and to project future scenarios are challenging tasks. For both tasks climate models are imperative scientific instruments. First, because only models allow the various reasons for climate change to be differentiated through the study of alternative scenarios and complex interdependencies. Second, because only models allow past and present information on climate change to be extrapolated into the future. Neither measurement nor experiments can do so. Therefore climate models constitute the basis for establishing how climate change science and policy are related. The problem thereby is that these scenarios are accompanied by vast uncertainties, and these uncertainties complicate the decision-making needed to shape socio-economical developments.

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[48] Wolfgang Lucht and Rajendra K. Pachauri refer to mankind's impact as the 'mental component of the Earth system' and an "uncontrolled coevolution of the mental, physical, and biological spheres [that] has increased over the last decades" (Lucht and Pachauri 2004, p. 343).

The question of what to do is therefore answered differently by different communities and individuals, and these answers have only partly to do with scientific arguments and simulated scenarios. As Mike Hulme showed in his study *Why We Disagree about Climate Change*, people's opinions concerning climate change depend on various 'myths of Nature', which assume nature to be 'capricious', 'tolerant', 'benign', or 'ephemeral' (Hulme 2009, p. 182 et seq.).[49] The capricious view understands climate as human-independent and fundamentally unpredictable, while the ephemeral view sees climate in a precarious and delicate state of balance. The benign view assesses climate as favourably inclined towards mankind, while the tolerant view understands climate as to some degree uncontrollable but resilient if suitably managed.[50] According to Hulme, these beliefs play an important role in peoples' attitude towards climate change, besides objective risk analysis, climate prediction, and expert judgment. The interesting aspect here is that all of these views reflect and one-sidedly over-interpret certain aspects of the behaviour of the climate system: its chaotic nature as capricious as well as ephemeral; its complex response as, hopefully, benign or at least tolerant. These beliefs dominate not only everyday philosophy on climate change, but also various scientific debates on and against climate change.

However, these opinions will not help in framing an appropriate response to climate change. One possible response is 'stability scenarios', which advertise the '2°C target'. The idea is to take efforts to limit the increase in global mean temperature to below 2°C during this century by halving CO_2 emissions by 2050 compared to 1990 (Meinshausen et al. 2009; Allen et al. 2009b; Washington et al. 2009; see also Chap. 4 of this volume and Table 2.15). Interestingly, the 2°C increase has been a robust result since the very first numerical experiments. Model-based computations deliver robust results for the low range of temperature increases, while they differ for high ranges. Therefore, it seems plausible to try to manage activities in order to have a fair chance to reach this target, although the 2°C target has been questioned by economists as infeasible, too expensive, and inappropriate (Randalls 2010), as it requires stabilization at 450 ppm CO_2-equivalent in the long term (ECF and PIK 2004; Graßl et al., 2003; Schellnhuber et al. 2006). However, the 2°C target based on robust results might be a better choice than a strategy that consists of a 'predict then act' paradigm, like the ones cost-benefit-analyses rely on in order to conceive optimal strategies. Such a paradigm could cost valuable time and money, especially since the range of 'optimal targets' varies in each study along with differences in value judgments and uncertainties about the costs of mitigation and damage (Hof et al. 2008).[51] For instance, William D. Nordhaus suggests an

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[49] Mike Hulme refers here to Mary Douglas' and Aaron Wildavsky's cultures of risk (Douglas and Wildavsky 1982).

[50] Perhaps the 'tolerant view' can be compared to the UNFCCC's 'precautionary principle', which advocates that it is better to be safe than sorry and therefore advises the reduction of carbon dioxide emissions "that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC 1992, Article 2).

[51] Andries F. Hof et al. studied the vast uncertainties and critical assumptions involved in cost-benefit analysis and conclude that the 'optimal targets', which range from 520 to 800 ppmv, are

Table 2.15

Information on carbon dioxide	
Pre-industrial	About 280 ppm by volume (ppmv)
2005	379 ppm, leading to a radiative forcing of +1.66 Wm^{-2} [±0.17]
2010	Approximately 390 ppmv
Doubled	560 ppmv (Basic assumption for climate sensitivity simulations, which causes a radiative forcing of 3.7 Wm^{-2} and could lead to an increase in mean global temperature of approximately 3°C [±1])[a]
2° target	Stabilization scenarios of about 450 ppmv CO_2-equivalent in the long term.
1995–2005	Growth rate of CO_2 in the atmosphere was 1.9 ppm $year^{-1}$ and CO_2 radiative forcing increased by 20%.

[a] "Without any feedbacks, a doubling of CO_2 (which amounts to a forcing of 3.7 Wm^{-2}) would result in 1°C global warming, which is easy to calculate and is undisputed. The remaining uncertainty is due entirely to feedbacks in the system, namely, the water vapor feedback, the ice-albedo feedback, the cloud feedback, and the lapse rate feedback. [. . .] Current state-of-the-art climate models span a range of 2.6–4.1°C, most clustering around 3°C" (Rahmstorf 2008, p. 38).
Sources: Rahmstorf 2008; IPCC 2007a, Chap. 2; Schellnhuber et al. 2006

economically optimal 800–850 ppm CO_2-equivalent that would result in a 3.4°C temperature increase; others suggest a 650 ppm CO_2-equivalent (Nordhaus 2007; Tol 2002). The Stern Report favours a cost-benefit analysis which advises stabilizing greenhouse gas emissions at about 450–550 ppm CO_2-equivalent (Stern 2007). "It is one of the few cost-benefit analyses on climate change that favours early emission reductions" (Hof et al. 2008, p. 412). In contrast to those 'optimal strategies',[52] practical strategies based on stability scenarios like the 2°C target could be a better practice for decision-making under uncertainty, as it offers a political anchor for mitigation policy—especially if it is translated into a 'lower than 550 ppmv' or more specifically a '450 ppmv' target.

Another possible practice is risk assessment to identify critical thresholds in natural and social systems. But identifying and predicting such thresholds is extremely difficult (Groffman et al. 2006). Even small changes, e.g., in temperature, can induce threshold changes, and these threshold changes can come suddenly and unforeseeably (Hare and Mantua 2000; Allen 2007).

> "Thresholds pose perhaps the greatest challenge currently facing climate change scientists. There is clear evidence that climate change has the potential to increase threshold changes in a wide range of ecosystems, but the basic and practical science necessary to predict and manage these changes is not well developed. [. . .] In addition, climate change interacts with other natural processes to produce threshold changes" (Fagre and Charles 2009, p. 11).

Furthermore, disturbance mechanisms that shape the environment, e.g., fires, can themselves be altered by climate change. Facing events caused by abrupt

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caused by differences in value judgments and uncertainties about the cost of mitigation and damage (Hof et al. 2008).

[52] Optimal for whom? The problem is that some regions are more vulnerable to global climate change than others.

threshold changes certainly belongs to the worst-case scenarios of climate change, dramatic enough for even Hollywood screenplays. Whether abrupt events will increase beyond the 2° limit—some literature refers to an increase of more than 2° as 'dangerous'—can not be assessed, but it seems plausible that an increase of 4° will cause more changes than 2° or 1° as we fuel the 'air mass circulation engine', called climate, with more energy.

As the EMF22 International Scenarios, based on ten integrated assessment models, have recently shown, on the one hand,

> "stabilizing the global climate will require a very different world than the one we live in today"; on the other, "regardless of the target, the global costs of achieving any long term climate-related target will be higher without comprehensive action, and they may be higher not just for the initial entrants but also for those that join along the way" (Clarke et al. 2009, p. S80).

In a way climate change science and policy seems to be trapped between Scylla and Charybdis. Avoiding climate change entails approaching the danger of economic calamity, and vice versa. This is not entirely true, as recent studies have shown that the 2°C target might cost on the order of 1% of Gross Domestic Product (see also Chap. 4 of this volume). However, if mankind is unable to decide how to frame an appropriate response to climate change, nature will decide for both—environmental and economic calamities—as the economy is inextricably interconnected with the climate.

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Chapter 3
Climate Simulation, Uncertainty, and Policy Advice – The Case of the IPCC

Arthur C. Petersen

3.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) is a body of the United Nations established in 1988 which has the responsibility to provide policy-relevant assessments of knowledge pertaining to climate change. While the IPCC does not advise on which climate policies should be agreed upon by the world's nations, it does provide succinct Summaries for Policymakers (SPMs) on the state of knowledge on the causes and effects of human-induced climate change, on mitigation of the causes and on adaptation to the effects. If we are interested in how climate-simulation uncertainty is dealt with in policy advice, the IPCC is a prime location for study.

The subject of climate change is imbued with scientific dissensus as to precisely what is happening, and will happen, with the climate. Part of this dissensus is related to the large uncertainties associated with climate simulation (see this volume; see also Petersen 2006a, b). Furthermore, there is disagreement on the appropriate political response vis-à-vis anthropogenic climate change (e.g., To what extent do we want to limit anthropogenic interference with the climate system? What should we do to mitigate the likely causes of climate change? To what extent should we prepare to adapt to it?). Perceptions of the climate-change risk vary widely both across the globe and within societies. Thus, the uncertainties are large – with climate simulation being a significant contributor to these uncertainties – and the stakes are high. This puts the problem of anthropogenic climate change in the category of policy problems that are in need of a 'post-normal' problem-solving strategy (Funtowicz and Ravetz 1993; Petersen 2006a; van der Sluijs et al. 2008).

The stakes are indeed high. Some key players in the economy feel their existence threatened by calls for drastic reductions of CO_2 emissions. By 2030 the macro-economic costs for multi-gas mitigation, consistent with emission trajectories towards

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stabilization between 445 and 710 ppm CO_2-eq, are estimated at between a 3% decrease of global Gross Domestic Product (GDP) and a small increase in GDP, compared to the baseline figure (IPCC 2007c, p. 11). Over the period 2007–2030 this amounts to a maximum reduction of the GDP growth rate by 0.13% points/year (that is, a small but still significant fraction of the projected average yearly GDP growth rates of 2–3%). Note that some regions and sectors (obviously those involved in the oil and coal industry) will bear a particularly large share of these economic costs, while some other sectors, such as agriculture outside of the tropics, will – at least initially and with some adaptation – benefit from climate change; furthermore, the global costs of mitigation may be much higher if economically inefficient policies are pursued. The stakes are also high for those who, through the projected climate change, risk damage to themselves or to things they value. For instance, some ecosystems are projected to become irreversibly damaged, species will become extinct, some developing small-island states risk disappearance with continued sea-level rise, food production may suffer in many areas, et cetera (IPCC 2007b). And finally, the stakes are high for those players who see business opportunities for more environmentally friendly technology.

Given that the climate-change debate takes place in the highly polarized setting sketched above, how do scientists advise policy-makers and politicians and inform society at large about their scientific findings? Before answering that question we must ask what roles scientists can play vis-à-vis policy-makers and politicians. Roger Pielke distinguishes between four idealized roles scientists may choose from: the roles of Pure Scientist (who seeks only the truth without considering the practical implications of his/her research), Science Arbiter (who seeks to focus on issues that can unequivocally be resolved by science), Issue Advocate (who seeks to advance particular interests using his/her expert status), or Honest Broker of Policy Alternatives (Pielke 2007). The latter role requires more explanation. For policy problems with large scientific uncertainties and high societal stakes, Matthijs Hisschemöller et al. characterize the role of science in such a type of ‘unstructured’ policy problem as that of ‘problem recognizer’ (Hisschemöller et al. 2001). The authority of scientists who take on this role can be assumed to reside in the scientists’ ability to assess and communicate uncertainty and analyze the different values and perspectives on the problem: that is by being an Honest Broker.

In practice, we find scientists taking on each of these four roles in the climate change debate. The media often feature Issue Advocates who are either pro or against climate policy measures, but who argue so on the basis of their reading of climate-simulation uncertainty (either reading that uncertainty as being low or high) instead of being explicit about their underlying values. In the public debate on possible measures to curb CO_2 emissions, critics of the proposed policy measures typically refer to uncertainties in climate simulation. They argue that there is no empirical evidence of the problem (“we don’t see human-induced global warming happening yet”) and that reliable prediction of climate far into the future (e.g., the year 2100) is not possible. As many of the critics currently admit that the earth’s surface has warmed by about 0.5°C over the last 50 years, the alleged lack of evidence is basically a negative assessment of the quality of climate simulation.

After all, it is only by combining the observations in an explanatory (= theoretical) model that one can attribute the observed changes to human influence rather than to natural fluctuations. From a philosophical point of view the critics certainly seem to have a case. Questioning the reliability of climate simulations is legitimate. Hence the uncertainties involved in climate simulation have taken on a central role in the 'sound science' debate (see e.g., Petersen 2006b, Chap. 4) and to date a significant part of the political discussion on climate change has focused on the relationship between models and data (Edwards 1999).

This chapter studies how scientists may play the role of Honest Broker, that is, responsibly assess and communicate climate-change knowledge under conditions of polarized political debate and severe scientific uncertainty. The Intergovernmental Panel on Climate Change (IPCC) is analyzed as a 'boundary organization' between science and politics that by virtue of its rules and ways of proceeding in the production of assessments of climate change has produced sophisticated and balanced assessments of climate-simulation uncertainty and played the role of Honest Broker.

In particular, this chapter takes a closer look at the IPCC review process by means of a case study on the assessment of the human contribution to climate change in the Third Assessment Report (IPCC 2001a, which concluded that most of the recent warming is "likely" to be caused by anthropogenic greenhouse gases). That assessment report constituted a significant change from the qualitative statement of the Second Assessment Report ("the balance of evidence suggests a discernible human influence on global climate") to a probabilistic expression. The Fourth Assessment Report (IPCC 2007a) continued in the same probabilistic framework when it increased the assessed likelihood from "likely" (>66% chance) to "very likely" (>90% chance). By taking a close look into where these probabilistic expressions come from and how they are discussed in the IPCC, we can obtain insight into how climate-simulation uncertainty is dealt with in policy advice.

3.2 The IPCC as a Boundary Organization Between Science and Politics

In the 1980s, climate scientists were very much involved in raising international political awareness for the human-induced global warming problem. This heightened awareness led to strong incentives provided by the international political community for the international scientific assessments of global warming. Meteorological and climate research – considered as a separate activity from policy advising – had already been internationalized in the 1950s. Large-scale scientific cooperation through international research programs had started with the International Geophysical Year in 1957/1958.Thirty years later, in 1988, public attention for the global warming issue sharply increased in many countries (Social Learning Group 2001). That same year, at the end of the Cold War, many countries decided to cooperate on scientific climate-policy advising within the framework of the United Nations. For that purpose a new international organization was established: the 'Intergovernmental Panel on Climate Change' (IPCC), formally a daughter organization of both the World Meteorological Organization and the United Nations Environment Programme.

The IPCC can be described as a 'boundary organization' between science and politics (Guston 2001; Miller 2001). The success of the IPCC can be measured as the degree to which this boundary organization between science and policy is able both to bring climate science to policy in a way that policy-makers consider legitimate and retain legitimacy in the scientific domain. What is meant by the term 'boundary organization' here? David Guston defines 'boundary organizations' as organizations that meet the following three criteria:

> first, they provide the opportunity and sometimes the incentives for the creation and use of boundary objects and standardized packages; second, they involve the participation of actors from both sides of the boundary as well as professionals who serve a mediating role; third, they exist at the frontier of the two relatively different social worlds of politics and science, but they have distinct lines of accountability to each (Guston 2001, pp. 400, 401).

'Boundary objects' are conceptual or material objects sitting between two different social worlds, such as science and policy, and they can be used by individuals within each for specific purposes without losing their own identity (Star and Griesemer 1989). An example is 'climate sensitivity' (the sensitivity of climate to perturbation by greenhouse gases – defined as the temperature change resulting from a doubling of the CO_2 concentration – that can be determined using climate data and climate simulation). Climate modellers use the concept of 'climate sensitivity' as a benchmark for comparing their models. Climate modellers who use simple models often use the 'climate sensitivity' simulated by more complex models as a model parameter. And for policy-makers and advisers, 'climate sensitivity' provides a 'window' into the world of climate modelling (van der Sluijs et al. 1998, p. 310). Surprisingly, given the large uncertainties associated with determining 'climate sensitivity', the uncertainty range has remained constant at 1.5–4.5°C since the first assessment of climate sensitivity, by the U.S. National Academy of Sciences in 1979. As Jeron van der Sluijs et al. show, many different interpretations have been given to this range, both statistical and non-statistical (scenario or 'what-if') interpretations, which prompted them to call this boundary object an 'anchoring device' and study the social causes of retaining the consensus range of 1.5–4.5°C (van der Sluijs et al. 1998). 'Standardized packages' are more broadly defined than 'boundary objects'. They "consist of scientific theories and a standardized set of technologies or procedures and as a concept handle both collective work across divergent social worlds and 'fact stabilization'" (Fujimura 1992). In the context of climate change, standardized packages can be found in the conceptualization of climate change and the establishment of a thriving line of climate research in coordination with climate policy-making.

An alternative definition of 'boundary organizations' is provided by Clark Miller, who pleads that, especially in the study of the boundary between science and politics at the international level, we should not focus on structure but on process and dynamics. According to Miller, boundary organizations are organizations that take part in 'hybrid management', with 'hybrids' being

> social constructs that contain both scientific and political elements, often sufficiently intertwined to render separation a practical impossibility. They can include conceptual or material artifacts (e.g., the climate system or a nuclear power plant), techniques or practices (e.g., methods for attributing greenhouse gas emissions to particular countries), or organizations (e.g., the SBSTA [scientific and technological body of the climate convention, acp] or the Intergovernmental Panel on Climate Change) (Miller 2001, p. 480).

Hybrid management activities are not necessarily limited to work carried out in boundary organizations.

It seems that the connection between climate science and policy has successfully been made by the IPCC. One can think, first of all, of the 1992 United Nations Framework Convention on Climate Change (UNFCCC), the 1997 Kyoto Protocol, the 2001 Bonn Agreement and the 2007 Bali Action Plan. Reaching those agreements was indeed facilitated by the first, second, third and fourth IPCC assessment reports, respectively. These reports – and their consequences – also led to the 2007 Nobel Peace Prize. The first report (1990) had confirmed that scientists thought that climate change may pose a serious risk, though much was still uncertain (e.g., whether the observed warming could be attributed to human influences) and had proposed ingredients for the climate-change convention. The second report (finalized in 1995) concluded that "the balance of evidence suggests a discernible human influence on global climate" (IPCC 1995, SPM, p. 4),[1] implying that the evidence for human influence had increased. The third report (2001) gave an even stronger message that "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities" (IPCC 2001a, SPM, p. 10) and the fourth report (2007) again strengthened the message by raising the likelihood that humans have caused most of the recent warming to 90% ("very likely"). Since all governments accept the IPCC reports and approve the Summaries for Policymakers line by line, the authority of IPCC reports is acknowledged at meetings of the Framework Convention. Furthermore, the IPCC has proved to be responsive to requests for more tailored advice by the convention. Thus, worldwide, IPCC reports are used directly in the policy-making process. Even countries with governments that are sceptical about the Kyoto Protocol accept the full IPCC reports, albeit often reluctantly, as authoritative.

The policy relevance of the IPCC is thus ensured by its ties to the climate convention and by it being an intergovernmental body. In fact, the reason for establishing the IPCC in 1988 was the need perceived at the end of the 1980s for an international agreement on the issue of global warming (Agrawala 1998). Since some governments were not yet convinced that there was enough scientific evidence for the problem to justify actions, an intergovernmental (not just international) body was created to provide an assessment of all available knowledge on the

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[1] In references to IPCC reports, aside from the page number in the whole report, the part of the report is also included: e.g., SPM = Summary for Policymakers.

issue that subsequently could not be discredited during the negotiation of actions. In fact, one could hypothesize that the IPCC has been so successful because the problem addressed was already considered relevant and consensual legitimation for climate policies was precisely what was sought for. This view would entail that the IPCC fulfilled a role not as problem recognizer in an unstructured problem context, but as problem solver for a structured problem (acting as a Science Arbiter). However, even though some governments would like to treat the problem of climate change in this way, the large uncertainties attached to many of the findings of the IPCC and the reality of the different interests of countries in intergovernmental negotiations, give rise to another hypothesis. It may have been, in particular, the assessment and communication of uncertainties, and the consequent careful phrasing of the conclusions in the assessments by the IPCC that gave rise to its authority in policy-making circles.

The ties of the IPCC with political processes aimed at climate action have remained strong ever since its inception, although the link has gradually become less direct. With the first comprehensive assessment, released in 1990, the IPCC provided direct input to the policy process. For example, the 1990 report explicitly discussed possible ingredients for a climate convention. After the convention had gained momentum in 1995, the Subsidiary Body for Scientific and Technological Advice (SBSTA) took over the discussion of matters closely related to the convention. This convention body now is the intermediary between the IPCC and the convention and has good working relations with the IPCC.

After the Third Assessment Report (TAR) was completed in 2001, the SBSTA defined its role vis-à-vis the IPCC as a forum to discuss the political impact of the IPCC conclusions in the context of the climate convention, e.g., the definition of 'dangerous anthropogenic interference with the climate system' (referring to Article 2 of the UNFCCC) and, related to that, necessary future commitments (that is, emission reductions). The IPCC has made it very clear over the years that the answers to such political questions, although they must be scientifically informed, basically involve value judgements. The first sentence of the TAR Synthesis report, for instance, reads:

> Natural, technical, and social sciences can provide essential information and evidence needed for decisions on what constitutes 'dangerous anthropogenic interference with the climate system'. At the same time, such decisions are value judgments determined through socio-political processes, taking into account considerations such as development, equity, and sustainability, as well as uncertainties and risk (IPCC 2001b, SPM, p. 1).

In order to ensure that the "essential information and evidence needed for decisions" is indeed delivered to the climate convention, the SBSTA guides the IPCC in taking up policy-relevant questions, for instance by commissioning Special Reports or Technical Papers from the IPCC, or by having governments submit 'policy-relevant scientific questions' to be addressed by the IPCC.

The IPCC thus tries to maintain legitimacy in the eyes of governments. Apart from the linkage to policy-making, another factor that determines the success of a boundary organization is the degree to which the organization is perceived by scientists to give an adequate representation of the science. In this respect, the credibility of the IPCC is quite high. IPCC reports are regularly used as standard works of reference for climate science and the key uncertainties identified often guide priority setting for research. Still, criticism is voiced in parts of the scientific community about the direct interaction between scientists and policy-makers in the production of the Summaries for Policymakers of IPCC reports. Although the number of scientists critical of the IPCC seems to have been declining over the years, some vocal critics still remain. These critics usually accept the main reports as being of a high scientific quality, but disqualify the Summaries for Policymakers as being "too political". Some of these critics themselves hold the political view that climate measures should not be installed and from their point of view the IPCC is considered to be too successful in its interaction with policy-makers but unsuccessful in terms of remaining faithful to science. Since concerns about the reliability of climate models are legitimate (e.g., Petersen 2006b), such criticisms warrant a closer look into the assessment of simulation uncertainty by the IPCC, and specifically into the writing of the Summaries for Policymakers. This investigation is taken up in the remainder of this chapter.

Over the years, the IPCC has increasingly paid attention to uncertainties (Swart et al. 2009). This can be explained by procedural shifts and changed participation in the production of the IPCC assessments (Shackley and Skodvin 1995). More generally, the role of procedures, especially those concerning the review of IPCC reports, is important in structuring the science–policy interaction that takes place through the IPCC (Skodvin 2000). The IPCC is a boundary organization that was specifically designed for the purpose of this interaction and that has subsequently evolved in practice to further improve on the structuring of the interaction.

Still, in the IPCC process, political and epistemic motives can be found to be intertwined, sometimes leading to the suppression of uncertainty communication. The IPCC process is inevitably a politicized one due to the formal ties to the climate convention, but since in the IPCC proceedings one tries to adhere to rules of procedure, the number of times the politicization is allowed to surface is minimized. Simon Shackley et al. hypothesized that the public expression of 'intra-peer community differences' was subdued due to the presence of greenhouse sceptics in society, who are typically very vocal critics of the IPCC (Shackley et al. 1999). Shackley et al. ironically observed that there seemed to be an agreement between some of the IPCC lead authors and the sceptics on the political consequences of putting more emphasis on uncertainties in the summaries of the reports. They advised the IPCC to accept politicization as a given and "to find ways to communicate informed agreement and disagreement, and informed judgements concerning levels of confidence in knowledge claims, as well as divulging the processes by which assumptions are formed and disagreements resolved" (Shackley et al. 1999, p. 448). The solution suggested by Shackley and co-authors was that the scientists involved should abandon the idea that communicating uncertainties inevitably leads to disbelief and policy inaction. Of course, in reality uncertainties are often politicized, but the ideal that I, with Shackley et al., wish to uphold is that the different perspectives on uncertainty can be made more explicit and can themselves become part of societal debate.

It appears that through regular revisions of both the scope of the reports and the rules of procedure, the IPCC has adjusted to external criticism. Many social scientists have published negative evaluations of how the early IPCC had treated critics of both the scientific claims and the policy proposals put forward by the IPCC (as mentioned above, until 1990 the IPCC had the task of making policy proposals; from 1990 onwards this task was taken over by other bodies). Furthermore, some scientists criticize the IPCC for allowing direct interaction between scientists and policy-makers in the production of the Summaries for Policymakers of IPCC reports. In order to be successful as a boundary organization, however, such an interaction is definitely needed. The boundary between science and politics clearly needs continuous maintenance. As David Guston writes:

> The success of a boundary organization is determined by principals [a term from principal agent theory, acp] on either side of the boundary. . . . The success of the organization in performing [the] tasks [of pleasing both sides] can be taken as the stability of the boundary, while in practice the boundary continues to be negotiated at the lowest level and the greatest nuance within the confines of the organization (Guston 2001, p. 401).

The question then becomes what safeguards have been built into the IPCC procedures (both formal and informal) for retaining a certain level of "stability of the boundary". In the subsequent sections, first the IPCC review process is analyzed and sceptical criticism of this process, as it occurred in the Third Assessment Report, is investigated. Next, the negotiations "at the lowest level and the greatest nuance" are pictured and interpreted with respect to the SPM formulation concerning the likelihood of human-induced warming. The purpose of the latter analysis is to study closely a crucial aspect of the final report related to problematic aspects of the uncertainty vocabulary of the latest IPCC reports and its impact on the communication of climate-simulation uncertainty.

3.3 The IPCC Review Process

The IPCC has always paid a significant amount of attention to the quality of its review process. Compared to the traditional peer-review process for journal articles, the peer-review process for IPCC reports is vastly larger in scale and much more sophisticated in procedure. Some numbers related to the Working Group I (WG I) contribution to the Third Assessment Report (TAR), titled *Climate Change 2001: The Scientific Basis* (IPCC 2001a), may give an impression of the amount of work involved in the production of IPCC reports.[2] The 14 chapters of the TAR WG

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[2] The procedures and actual way of proceeding for the Fourth Assessment Report (AR4), finalized in 2007, were identical as compared with the Third Assessment Report (TAR). This claim partially derives from personal observation by the author, who attended both the TAR and AR4 plenaries (in respectively Shanghai and Paris) in which the WG I SPMs were approved. Since the specific case studied in this chapter refers to the TAR, the dates and numbers given here pertain to that report.

I report were written by 122 lead authors and 515 contributing authors, who had started their writing in July 1998. One and a half years later, in January 2001, when the final versions of the chapters were accepted at the IPCC WG I plenary session in Shanghai, four revisions had been made of drafts of the chapters. The review rounds involved 420 experts and 100 governments. At the plenary session in Shanghai, the Summary for Policymakers (SPM) of the report was approved line by line by the governments in 4 days. The approval of the SPM went hand in hand with the final revision of the chapters: where the final wordings of the SPM differed from the text contained within the chapters, the precise wording of the chapters was revised accordingly for reasons of consistency.

The review comments on both the chapters and the SPM were forwarded to the lead authors, who came together for lead author meetings, consisting of lead author plenaries and chapter meetings. The lead authors were asked to write down explicitly what was done with each comment received. It is important to note here that, since the quality of the review process is not guaranteed by simply involving a large quantity of people, we have to look at the quality of the review comments that were submitted. In fact, many of the comments turned out to be of a quality similar to good article review comments.

Review editors then checked whether all review comments had received a fair treatment. An important task for the review editors was to guide the lead authors in their treatment of genuine scientific controversies. The role of review editor was newly added in the IPCC procedures after the Second Assessment Report (SAR). In the first and second assessment reports, a similar role was played by the working group Bureaux (consisting of elected officials, mostly scientists, who manage the working groups) and Technical Support Units (TSUs, consisting of staff members assisting the production of working-group reports). After the completion of the SAR commentators had observed that more explicit rules of procedure were needed, while recognizing that the IPCC should not become a "science-stifling, inflexible bureaucracy" (Edwards and Schneider 2001, p. 228). There is a tension between scientific informality and the adherence to formal rules of procedure:

> One of the IPCC's most important features is its openness and inclusivity; balancing this against scientific informality will require constant vigilance, and perhaps a reconsideration of the formal review process (Edwards and Schneider 2001, p. 228).

Through the new procedural rules, the editorial role was explicitly defined, enhancing the transparency of the review process. Review editors were asked before the plenary sessions whether they had ensured that "all substantive expert and government review comments" had been "afforded appropriate consideration" and that "genuine controversies" had been "reflected adequately in the text of the Report" (IPCC Procedures). For all 14 chapters of the WG I report all review editors (two per chapter) responded positively to these questions. A further innovation that increased the transparency of the process was the possibility for all participating reviewers to obtain all review comments and the comments by the lead authors on these comments through e-mail from the TSUs.

Although the editors of the TAR WG I report had hoped that the report would become less voluminous than the SAR WG I report (which had contained 572 pages), the authors did not succeed in keeping it short. The whole report became 944 pages long. This happened despite the fact that the report's chapters, following IPCC's TAR Decision Paper of 1997, primarily assessed information published since 1995, the year that the SAR had been finalized. The 14 chapters comprise most of the 700 pages or so of the TAR WG I report. The growth in volume of the chapters was primarily related to the sheer increase in the number of scientific publications dealing with the issue of climate change. All the information contained in the individual chapters (which each have an Executive Summary) was summarized into one SPM of 17 pages (i.e., about 2% of the total volume occupied by the chapters).

Given the politicization of the global warming issue, it is understandable that much of the criticism of the IPCC has been directed at the SPMs, specifically at the way these are reviewed at final plenary sessions, where governments have to approve the SPM text, tables and figures in detail, that is, line by line. In principle, IPCC plenary sessions operate by consensus. Therefore, everything is done to ensure that all governments can agree with the SPM. Since governments have different political agendas, they also hold different views on what constitutes a proper 'balance' (a word used very often during plenary sessions) between the amount of space devoted to positive claims (concerning what we know about climate change) and the amount of space devoted to negative claims (concerning the uncertainties that remain). Given this context, it is interesting to see how one of the co-chairs of WG I introduced the governmental approval process in Shanghai (each working group has two co-chairs: one from a developed and one from a developing country; the TAR WG I co-chairs were Sir John Houghton from the U.K. and Prof. Ding Yihui from China)[3]:

> The IPCC provides a scientific assessment; therefore all proposals for changes in the SPM must be related to scientific accuracy, scientific balance, clarity of message, understandability to policy-makers and relevance to policy. The procedure is – based on the October text [Final Draft, October 2000] – to proceed bullet by bullet or sentence by sentence. The proposals for change by the lead authors, in response to government comments, are then considered. New proposals for wording changes can be made by the delegates. These proposals are checked with the lead authors for accuracy, balance, and consistency with the chapters. If possible, the plenary should reach agreement on the new text, otherwise the text will be referred to either a small group to construct new draft wording among agreed lines, or to an open contact group to work with the lead authors to resolve issues and construct a new draft text. If the agreed SPM text implies changes in the technical summary or the chapters, lead authors will make the necessary changes and present these to the plenary towards the end of the meeting (IPCC WG I Co-Chair, plenary session, Shanghai, January 2001).

Thus the co-chair made clear which five normative criteria are allowed to play an explicit role during the meeting. Any proposal for changes in the text – also if they

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[3] The quotes from the TAR plenary session are the author's own transcripts.

were politically motivated – should thus be cast in terms of 'scientific accuracy', 'scientific balance', 'clarity of message', 'understandability to policy-makers' and 'relevance to policy'. Furthermore, the important role of the lead authors came to the fore: although it is formally the governments that decide on the text, they are not free to make whatever changes they want.

After this introduction by the co-chair one government raised its flag and was given the floor. This government expressed its particular concern that the lead authors would have too much influence on the final text by being allowed to apply criteria such as balance themselves. According to this country the governments were responsible for the text, and not the lead authors. Furthermore, the country was afraid the plenary in practice would not discuss the Final Draft (October 2000) but would instead discuss the new 'Shanghai Draft' prepared by the lead authors just before the meeting. Since countries had submitted their comments on the basis of the Final Draft and had prepared to work with those comments, it would be too difficult for the countries to work with a new draft which, on the one hand, most countries had not yet read and, on the other hand, contained quite substantial changes. The co-chair at this point tried to steer the meeting away from politicization:

> This is a scientific meeting, consisting of a scientific debate, where, of course, governments should decide on their positions. The lead authors are here to help us. The starting point shall be the October text, which will be projected on the screen; the Shanghai Draft is only intended to be of help. Regarding the criterion of balance, it is a scientific balance that should be strived for, not a political balance (IPCC WG I Co-Chair, plenary session, Shanghai, January 2001).

Through such rituals, which are part and parcel of most IPCC plenary sessions, the criteria regulating the changes that can be made to the text are made explicit and thereby given extra force. Later during the meeting references were often made to the criteria mentioned at the beginning of the session. Actually, in practice, the plenary session did not use the Final Draft instead of the Shanghai Draft, even though it had agreed to do so. Apparently most countries agreed with the lead authors that it was more efficient to start the discussion from the latest version produced by the lead authors. The country that had first made the objection preferred not to push the issue.

Since the aim of the IPCC is to produce reports that are credible not only among scientists and governments but also within society at large, representatives of non-governmental organizations are admitted to IPCC sessions as observers, and experts from all organizations that represent interested or affected parties are invited to participate in the review process. The TSUs have considerable freedom to circulate the drafts widely for review. The following experts are eligible (and actively approached) to participate (IPCC Procedures):

> Experts who have significant expertise and/or publications in particular areas covered by the Report.
>
> Experts nominated by governments as Coordinating Lead Authors, Lead Authors, contributing authors or expert reviewers as included in lists maintained by the IPCC Secretariat.
>
> Expert reviewers nominated by appropriate organizations.

It is the ‘appropriate organizations’ category which makes it possible for TSUs to really open up the IPCC review process. The WG I TSU considered this category to include at least every organization that expressed an interest. For instance, in the TAR WG I review comments one can find comments from special-interest organizations (including fossil fuel lobbies and environmental organizations). Some of the stakeholders, notably those representing the interests of fossil fuel industries and oil-exporting countries (but also several independent sceptics – typically asked to be involved for their expertise), have repeatedly claimed that their views were not seriously considered in the IPCC reports. It is true that special-interest organizations do not co-decide on the text and in general observers are not even allowed to speak at the plenary sessions. However, their viewpoints, as expressed through the expert review rounds, are seriously considered by the authors, and through the review-editor mechanisms checks are included on the way lead authors handle their comments.

The IPCC review process adds another layer to the traditional peer review that takes place in scientific practice. Peer review is a necessary ingredient in the evaluation of simulation models (Petersen 2006b, Chap. 3). The IPCC review process provides for a significant second review mechanism and helps lead authors to arrive at an even better grasp of the limitations of climate simulation models. The assessment of uncertainties, for example as carried out by the IPCC, will necessarily be a cooperative enterprise – both among individual lead authors and among lead authors and reviewers. Still, it is hard for the IPCC to do much ‘better’ than the scientific community. Given that the reflexivity in climate science on model-structure uncertainty is relatively low (Petersen 2006a, Chap. 6), there is obviously room for improvement of IPCC’s communication of uncertainty (see also Swart et al. 2009).

3.4 Sceptical Criticism of the IPCC Review Process

Several prominent climate sceptics have challenged the integrity of the IPCC review process. They typically give examples of where they think the process has gone wrong. Here I analyze the criticism of MIT meteorologist Richard Lindzen on the production of the TAR SPM, as a typical exemplar. In 1998 Lindzen was made part of the IPCC process as an IPCC TAR WG I lead author (of the chapter on “Physical Climate Processes and Feedbacks”; this chapter had one co-ordinating lead author, Thomas Stocker, and ten lead authors). Although Lindzen was generally satisfied with the way the full report was produced, he strongly criticized the production and review process of the SPM. He testified before the U.S. Senate Commerce Committee on 1 May 2001 that many questions relevant to climate change could not yet be answered by scientists and that the SPM of the TAR WG I report was not an adequate reflection of the full report. Lindzen sees himself as playing a functional role as a greenhouse sceptic. In an interview he admitted that while in the early years of the IPCC he felt it was a “moral obligation” to voice his sceptical opinions, "now it is more a matter of being stuck with a role" (*Scientific American*, November 2001).

Most scientists would agree with Lindzen that the claims made by the IPCC will not be the definitive say on the issue of climate change. This is why the IPCC in the TAR has introduced in its vocabulary a gradual scale for expert confidence judgments, which makes it possible to include an assessment of the quality of climate models in the conclusions derived from these models – albeit in probabilistic terms. Trying to capture controversies on the quality of models in 'consensus' judgments is tricky, of course, since the expert who thinks that the models are certainly wrong, would not agree on a statement that 'there is a 10–33% chance that the models are wrong' – even if such a statement is intended to explicitly take his minority viewpoint into account. The central target of Lindzen's criticism is the published version of the detection and attribution conclusion in the WG I SPM:

> In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely7 to have been due to the increase in greenhouse gas concentrations (IPCC 2001a, SPM, p. 10).

Here "likely", according to the corresponding footnote 7, is to be read as a 66–90% chance (defined in the footnote as a "judgmental estimate of confidence") that the statement is true. Lindzen is quite sure about the fact that the models are wrong and he does not trust the lead authors' judgment.

Since Lindzen has been very closely involved with the IPCC, his criticisms merit a more detailed investigation, especially since his criticisms are related to the assessment of climate-simulation uncertainty. In his testimony before the Senate, Lindzen made three claims about the SPM:

1. the SPM distorts the underlying science (which is adequately represented by the chapters);
2. the SPM was "written by representatives from governments, NGOs and business";
3. the SPM was significantly modified at the plenary session in Shanghai.

The first claim is related to the "misrepresentation," according to Lindzen, of computer-model uncertainty in the SPM. An example is the qualification contained in the attribution statement just quoted (a claim that is "likely" true, according to the SPM). Lindzen had not been involved in writing the SPM and he pointed out in his testimony that only a fraction of the lead authors had been members of the core writing team. He did not add, however, that the full writing team consisted of about 60 lead authors (i.e., about half of the lead authors were involved in the drafting). The SPM representation of his own chapter was taken by Lindzen to demonstrate his case. He claimed that the whole chapter was summarized, inadequately, by the following sentence:

> Understanding of climate processes and their incorporation in climate models have improved, including water vapour, sea-ice dynamics, and ocean heat transport (IPCC TAR WG I SPM, p. 9).

Lindzen's problem with this conclusion cannot be that it does not come from the chapter, since these "improvements" were indeed all mentioned in the chapter's Executive Summary. Furthermore, some caveats related to this statement were put in an introductory SPM sentence immediately above the quoted conclusion:

> [Complex physically-based climate] models cannot yet simulate all aspects of climate (e.g., they still cannot account fully for the observed trend in the surface-troposphere temperature difference since 1979) and there are particular uncertainties associated with clouds and their interaction with radiation and aerosols (IPCC TAR WG I SPM, p. 9).

Thus, Lindzen's claim that there is only one sentence dedicated to his chapter in the SPM is not true. My contention is that Lindzen was not satisfied with the phrase "there are particular uncertainties associated with clouds and their interaction with radiation and aerosols". He might have preferred that the following statement was transferred from the Executive Summary of his chapter to the SPM:

> The physical basis of the cloud parameterizations included into the models has also been greatly improved. However, this increased physical veracity has not reduced the uncertainty attached to cloud feedbacks: even the sign of this feedback remains unknown (IPCC TAR WG I 2001, Chapter 7, p. 419).

Apparently, in the face of space constraints, the lead authors who drafted the SPM had decided not to include these statements in the SPM. Here again the issue of 'balance' surfaces. The IPCC could have decided to include these statements and leave other statements out. It is debatable whether the fact that this did not happen must be regarded as a serious misrepresentation of science (that is, a more serious misrepresentation than any summary inevitably is).

Lindzen's second claim, that the SPM was written by non-scientific outsiders, is not true, in the sense that governments can make proposals for textual changes, but the lead authors have to agree on those changes. Indeed, the SPM drafting team (consisting only of participating scientists) paid serious attention to all comments received from experts (including experts from NGOs and business lobbies) and governments, as monitored by the review editors. As shown above, there were five criteria guiding the SPM writing process: scientific accuracy, scientific balance, clarity of message, understandability to policy-makers and relevance to policy. During the plenary session in Shanghai only the different government delegations (but not the observers, as noted earlier) could make comments on the text. Depending on lead authors' responses, texts were changed or left unchanged. Usually the interventions were of such a nature that the lead authors did not have a problem with the suggested changes, that is, they agreed specifically that the suggestions were not at odds with the criteria of scientific accuracy and scientific balance, and the changes were deemed consistent with the chapters. Sometimes the plenary was not able to reach consensus, either because the lead authors did not agree with a suggestion or because governments disagreed among themselves. Since the IPCC has to work under the procedural rule of decision-making by consensus, the task of coming up with a text that was agreeable to all (including the lead authors) could in those cases be delegated to a contact group, chaired by one or more countries or by a member of the working group Bureau. One of the pieces of text that was given to a contact group was the concluding statement on attribution criticized by Lindzen. This relates to Lindzen's final claim.

Lindzen's third claim is that the SPM draft was significantly modified in Shanghai. Although he did not explicitly say so, he apparently thought that the quality of the text had deteriorated because of the modifications. However, in his testimony Lindzen, had made an erroneous comparison. He compared the Second Draft (April 2000) instead of the Final Draft (October 2000) to the published version, which made the change look larger than it actually was. In order to evaluate Lindzen's claim I will here list the four latest versions of the paragraph (Table 3.1).

So what has actually happened to this paragraph? The main changes in the step from Second Draft to Final Draft were the introduction of the word "likely" (incorporating both a statistical estimate of internal climate variability and an assessment of climate-model uncertainty) and the deletion of the first two sentences (they actually appeared elsewhere in the same section). The third sentence of the Second Draft became the first sentence of the Final Draft (in a more precise

Table 3.1

Drafts of the third IPCC assessment report published in 2001

Second draft (April 2000)	*From the body of evidence since IPCC (1996), we conclude that there has been a* ***discernible*** *human influence on global climate.* Studies are beginning to separate the contributions to observed climate change attributable to individual external influences, both anthropogenic and natural. This work suggests that anthropogenic greenhouse gases are a substantial contributor to the observed warming, especially over the past years. However, the accuracy of these estimates continues to be limited by uncertainties in estimates of internal variability, natural and anthropogenic forcing, and the climate response to external forcing (emphasis added in bold)
Final draft (October 2000)	It is likely that increasing concentrations of anthropogenic greenhouse gases have contributed **substantially** to the observed warming over the last 50 years. Nevertheless, the accuracy of estimates of the magnitude of anthropogenic warming, and particularly of the influence of the individual external factors, continues to be limited by uncertainties in estimates of internal variability, natural and anthropogenic radiative factors, in particular the forcing by anthropogenic aerosols, and the climate response to those factors (emphasis added in bold)
Shanghai draft (January 2001)	The precision of estimates of the contribution from individual factors to recent climate change continues to be limited by uncertainties in internal variability, natural and anthropogenic forcing, in particular that by anthropogenic aerosols, and the estimated climate response. *Despite these uncertainties, it is likely that increasing concentrations of anthropogenic greenhouse gases have contributed* ***substantially*** *to the observed warming over the last 50 years* (emphasis added in bold)
Approved version (January 2001)	In the light of new evidence and taking into account the remaining uncertainties, **most** of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations (emphasis added in bold)

Source: IPCC

formulation). The following draft, the Shanghai Draft, is similar to the Final Draft except for the order of the two sentences. Finally, two changes were made during the Shanghai meeting: “substantial” was changed into “most” and the specification of the four sources of uncertainty was removed. The phrase “remaining uncertainties” now refers to what is stated in the introductory text of the section, namely that “many of the sources of uncertainty identified in the SAR still remain to some degree” (IPCC 2001a, SPM, p. 10). What happened during the Shanghai meeting was that several governments were opposed to the word “substantially”, which was therefore later replaced by “most” in a contact group meeting (for a detailed account of this meeting see Petersen 2006b, Appendix).

It must be clear by now that I do not agree with Lindzen’s negative evaluation of the review process for the SPM. Still, the detection and attribution section of the Final Draft version of the SPM was substantially changed before the Shanghai meeting and some significant changes were not made in response to government comments. An example of a sentence that was not in the SPM of the Final Draft and not even in the Executive Summary of Chapter is the following

> Most of these studies find that, over the last 50 years, the estimated rate and magnitude of warming due to increasing concentrations of greenhouse Assessments of climate-simulation uncertainty for policy advice gases alone are comparable with, or larger than, the observed warming (IPCC 2001a, SPM, p. 10).

This sentence constituted the basis for one of the most important conclusions of the IPCC 2001 report that “there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities” (IPCC 2001a, SPM, p. 10). To be sure, these statements were backed by a sentence in the chapter text itself (and by the underlying science), but – that is the point that must be made here – they were formulated by the lead authors late in the process. As prescribed by IPCC procedure, the Executive Summary of Chapter 12 was changed at the Plenary Session in Shanghai to make it consistent again with the SPM, and this change was presented to the plenary at the end of its session.

3.5 Negotiating the Wording of the Summary for Policymakers

Uncertainties are not objectively given. Experts typically have diverging opinions about how uncertain a given statement is. Furthermore, actors that have a stake in the way uncertainties are assessed and communicated by the IPCC will try to influence the formulation of the Summary for Policymakers. The positive conclusions communicated by the IPCC are taken by the governments and experts involved to be ‘robust’, given the assessment of uncertainties. The phrase ‘robust conclusion’ is defined by the IPCC as one that holds “under a variety of approaches, methods, models, and assumptions and . . . [is] expected to be relatively unaffected by uncertainties” (IPCC 2001b, SPM, p. 19). According to the IPCC, one of the prime examples of a robust conclusion is that “most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations”. In this example we can see that one way to ensure robustness of a conclusion is to explicitly include a qualifier within the positive statement, based on an assessment of the uncertainties involved. Here, by adding the word “likely” (and specifying what is precisely meant) the conclusion just mentioned became robust, according to the lead authors’ judgement.

As is shown in Petersen (2006b, Chap. 6), the main conclusion of the TAR on the attribution of climate change to human influences only implicitly reflects the collective expert judgment on the methodological reliability of climate-simulation results. The collective assessment processes as done within the IPCC in principle provide a unique institutionalized opportunity to try to reach consensus on the models’ methodological reliability and its impact on the formulation of the main attribution statements. However, this opportunity was not fully exploited – neither in the TAR analyzed here nor in the AR4 –, partly because the IPCC is lacking a typology of uncertainty, which – if suitably chosen – would allow one to unequivocally communicate the methodological reliability of climate simulation. Still, in the production of the TAR the issue of methodological reliability was addressed by the lead authors, and different model approaches were compared and confronted with each other – thus bringing elements of ‘expert judgement’ to the assessment. Furthermore, the possibility that all models have similar flaws was seriously considered.[4]

When the IPCC came together in Shanghai in January 2001, the robust conclusion mentioned above on ‘detection and attribution’ could not be quickly agreed upon in the plenary meeting. There were obviously political agendas behind the attempts at obstruction by one country in particular, Saudi Arabia. The argument that was used by this country was that the word “substantial” could not be adequately translated into its own language, an official UN language. When subsequently a delegate of France – without a similar political agenda – claimed that the translation was also problematic for his language (another official UN language), the chair decided to relegate the issue to a contact-group meeting. The (anonymized) proceedings of this contact-group meeting can be found in Petersen (2006b, Appendix), interspersed with my hypothetical analysis of what people were thinking when they were acting. Political agendas clearly play a role for countries in their attempts at reformulating conclusions; but these political agendas are able to force changes in the text only by referring to scientific issues or to problems with the clarity of the language. In this case, one country, which did have a political agenda to downplay the issue of climate change, first used the argument of clarity in the plenary session (with the translation of “substantial” purportedly being unclear) and subsequently made an issue in the contact group of the way the lead authors’ assessment of computer-model uncertainty was

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[4] This seems to have been less so in the production of the AR4. One sign of this was that the Final Draft SPM of the AR4 characterized the probability in AR4 statements as the “assessed likelihood of an outcome or a result”. Only after plenary intervention by the Netherlands, this phrase was altered to read “assessed likelihood, **using expert judgement**, of an outcome or a result” (emphasis added).

inadequately conveyed by the word “substantial”. In my judgement, since the IPCC does not clearly distinguish between statistical uncertainty and methodological unreliability in its formulation of robust conclusions, it was difficult for this country to separately raise the issue of the methodological reliability of models. Still, its interventions led to a significant change in the text, as can be read in the proceedings.

The proceedings of the contact-group meeting give an interesting glimpse into the functioning of the IPCC as a boundary organization between science and politics. From these proceedings we can conclude that political motives leading to the use of methodological arguments can be effective in changing the text of the SPM. Most observers present in Shanghai had failed to recognize that the country originally raising the objection wished to put a quantitative modelling statement in the conclusion of the detection and attribution section of the Summary for Policymakers of the IPCC WG I TAR, with a clear reference to that fact that it was ‘only’ a modelling statement, in order for the country to be able to downplay the conclusion. The end result was probably not what the country really wanted. However, the lead authors had in the end accommodated the change as genuinely reflecting the contents of the underlying chapter.

It was the difficulty of assessing and communicating the methodological reliability of climate models, as compared with their statistical uncertainty, that caused the lead authors to pause when asked to use a relatively strong modelling statement from the body of the detection and attribution section in the conclusion. Since the word “likely” did not appear in this modelling statement, it even disappeared from view for a moment. The discussion in the contact group – more broadly, the quality of the IPCC TAR report (and also the AR4 report) – could have been facilitated by explicitly referring to the distinction between statistical uncertainty and methodological (un)reliability as two different sorts of uncertainty. Of course, this would not have directly solved the country’s problem with the use of computer simulation in climate science. There could still have been discussion about the methodological reliability of models and the appropriate way to communicate this reliability. But at least the discussion would have focused on the appropriate sort of uncertainty, that is, on the methodological quality of models, as such instead of lumping together two sorts of uncertainty.

3.6 Conclusion

IPCC assessments are social constructs that contain both scientific and political elements. The IPCC’s success depends on its ability to connect to both climate science and climate policy. The generally-voiced criticism that the IPCC is not open enough to ‘sceptics’ is largely untrue. The IPCC procedures ensure inclusivity and ‘sceptics’ do have influence on the formulation of the reports. However, the IPCC could be much more reflexive on its procedures and ways to deal with dissensus. All in all, I would not characterize the IPCC reports as constituting the ‘scientific consensus' on climate change, but instead as 'policy-relevant assessments acknowledging uncertainty'. There is still room for further improvement of IPCC's communication of uncertainty, as was seen in the analysis of the wording of the attribution statement in the IPCC's Third Assessment Report. A similar conclusion applies to the Fourth Assessment Report.

The problem that the lead authors of the detection and attribution statements in the IPCC Third Assessment Report ran into with respect to uncertainty communication can be understood from the way IPCC WG I had implemented the IPCC guidance on uncertainty communication. In the preparation of the TAR, a strong demand for a more systematic approach to uncertainties was identified and the subsequent discussion led to a so-called cross-cutting 'Guidance Paper' on uncertainties (Moss and Schneider 2000). In that guidance paper, Moss and Schneider proposed that authors should use a probabilistic scale that expresses Bayesian confidence estimates about claims in five categories: very low confidence (0–5%), low confidence (5–33%), medium confidence (33–67%), high confidence (67–95%) and very high confidence (95–100%). As a supplement to this scale, writing teams could explain their choice of category for particular claims by making use of four qualitative uncertainty expressions: 'well established', 'established but incomplete', 'competing explanations' and 'speculative'. In WG I, however, the scale proposed by Moss and Schneider was changed into a likelihood scale which was not unequivocally defined as a Bayesian scale. For the statements on climate observations, the scale was used as a purely frequentist scale. For the modelling statements, for instance the attribution statement extensively discussed in this chapter, the scale represented a hybrid of frequentist and Bayesian statistics. First, a frequentist estimate was made of the chance that most of the observed warming was attributable to human influences (resulting in the "very likely" category, a more than 90% chance). Subsequently, an informal Bayesian updating was performed on the basis of judgements on the methodological reliability of the models, and the likelihood category "likely" (66–90%) was chosen. The reason for WG I to propose its own scale was that the IPCC guidance materials for the TAR lacked advice on how to represent frequentist statistical claims.

More recently, in the preparation of the IPCC Fourth Assessment Report (which appeared in 2007), the situation of having two separate probability scales within the IPCC was judged to be confusing and additional guidance was prepared. The problem that I have identified in this chapter has not been solved, however. In fact it has become worse, since lead authors are now encouraged to use only one of two scales (confidence or likelihood), without having the option to use the qualitative terminology as a supplement to these scales, as was originally proposed. Now, this qualitative terminology can only be used as a substitute, in case no probabilistic statements can be made. However, I advise the IPCC to find some standardized way to qualify its quantitative statistical statements. At the very least the reasons for the choice of a likelihood category should be made transparent, which was not the case in either the TAR or the AR4.

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Chapter 4
Dealing with Uncertainty – From Climate Research to Integrated Assessment of Policy Options

Hermann Held

4.1 Introduction

'Uncertainty' has accompanied the debate on global warming since its onset. It started out as a shadow-like follower of alarming climate projections, nastily pointing to the limitations of climate science. Often enough it has served vested interest. But this very terminus also acted like a vaccination that successively immunised climate science against over-confidence in modelling results and helped climate scientists to distil the solidly established from the poorly known. Consequently, key statements by the 2007 Intergovernmental Panel on Climate Change (IPCC) report are given in uncertainty-acknowledging formulations. For the future, 'uncertainty' will provide a conceptual cornerstone when humankind may ask science for the systemic validity of potential societal solutions – validity, or even optimality, that is robust under uncertainty.

Over the past decades, science has accumulated evidence for a causal link of anthropogenic greenhouse gas emissions and rising global mean temperature (GMT) to such an extent, that 2007 the IPCC proclaimed 'Most of the observed increase in globally averaged temperatures since the mid-twentieth century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations'. Thereby one of the key features displayed by climate models, referring to past and present temperature rise, was found valid, adding also trust to climate models' statements that refer to the future. The latter is what ultimately matters for society, as the present century may witness a GMT rise by an order of magnitude larger than the 0.8°C (compared to the 'standard' GMT value before the onset of industrial revolution) that have already materialised.

Now an increasing fraction of society judges the geo-physical phenomenon 'global warming' as a 'climate problem' (in that sense socially construct it), along two strains of argument. The first is the more important the larger the

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uncertainty in the causal link from GMT rise to climate damages, the second, the smaller that uncertainty is in the sense that additional damages are reported in positive terms. According to the first, further increase of GMT as it is projected if no global warming mitigation policy was implemented, very likely would assume values unprecedented for more than 50 millions of years. Given that humankind's oldest institutions hold a proven life-time of thousands rather than millions of years, this is seen as a violation of the 'precautionary principle' (as e.g., formulated by the European Commission 2000). Steering a system into a regime so much beyond the horizon of historic experience would only be justifiable – according to the precautionary principle – if a much better mechanistic understanding of the system could be obtained. Quite the contrary, the second strain looks at the still rather scattered knowledge of the positively known consequences of GMT rise (for an overview, see IPCC 2007b), such as increasing GMT-induced physical damages due to extreme weather events, large-scale ecosystem disruptions, economic losses, or triggering of 'tipping elements', i.e., crossing of sub-continental-scale thresholds in response to GMT rise.

Both strains of argument represent strategically different attitudes on how to take decisions under uncertainty: While the second sets climate damages that are not positively reported to zero, the first assumes the worst-case for situations of incomplete system understanding. In a sense, the precautionary view is that of a 'climate-impact-pessimist', the second, traditionally assumed in climate economists' analyses that of a 'climate-impact-optimist'. Which view to assume represents a crucial normative issue that – as such – cannot be decided science-immanently, but rather by society only. However there are two configurations in which society could get around that decision: (1) if science reduced impact uncertainty so much that society's risk attitude became irrelevant, (2) if responses were suggested that were both acceptable and invariant under that risk attitude. As developed below, (2) could be activated in part rather swiftly, while in the long run (1) may become relevant.

Although the climate problem has been prominently ventilated in the societal discourse since the 1980s, it is only since a couple of years that significant global warming mitigation targets are officially supported on a broader basis. At the Conference of the Parties 2010 in Cancún, the so called '2°-target' was adopted – the proclaimed goal to jointly strive for international frameworks that help keeping GMT rise below 2°C compared to preindustrial values. The rationale behind this target is a mix of both strains of arguments mentioned above. Why has been society's response that delayed? According to Ottmar Edenhofer et al. as well to Held and Edenhofer a key reason had been that the main stream of climate economics found it 'socially optimal' to reduce greenhouse gas emissions not now but rather in the middle of this century (Edenhofer et al. 2005; Held and Edenhofer 2008; Nordhaus 1994; Nordhaus and Boyer 2000). According to such cost benefit analysis, climate damages are weighted against the costs to mitigate greenhouse gas emissions. Damages from global warming were valued relatively low, while transforming the energy system towards a low-carbon path was seen as rather welfare-reducing.

Only recently and just in-time for the IPCC-AR4 report in 2007, climate economics developed the attitude that cost-lowering effects of directed investment ('induced technological change') had been underestimated in the past. A new suite of numerical experiments revealed that the global economic losses (from switching the energy system) of observing the 2° target might be on the order of 1% GDP (Edenhofer et al. 2006; Stern 2007) which is regarded a tolerable number for most economists. This helped to open considerable the manoeuvring space for climate policy. However, in these analyses, the issue of uncertainty has been postponed for refined analyses: both, for the climate response to greenhouse gas forcing as well as for energy technology parameters, intermediate values were assumed, thereby analysing an 'averaged' system as a first, certainly crucial iteration. Yet a self-consistent relation to various risk-attitudes is still lacking, in particular, as several mitigation measures may also come with considerable risks in terms of energy security or environmental impact. Therefore, a complete analysis on the 'optimal' solution of the climate problem with respect to various risk attitudes is still to come.

Hereby it is assumed that policy-relevant science aiming at societal solutions should be neutral with respect to normative settings, including risk attitudes. Ideally, such science should develop solution pathways for any of the major attitudes that can be found in society (in case a solution can be found). The key role of science is to explicitly separate the possible from the (systemically) impossible (e.g., from solutions that would violate energy or mass conservation laws). It would thereby open normative choices before politics that are all systemically valid, hence functional.

In the following, key steps towards such an 'complete' analysis are outlined. We begin with the struggle on GMT projections that have dominated climate research over the last decade. We give a summary on how these uncertainties are internalised in latest economic optimisation analyses. We then focus on one particular impact category of GMT rise, namely the triggering of tipping elements in the climate system. In particular it is discussed how data assimilation schemes might be further developed in order to reduce uncertainty on the proximity to a threshold. Finally we discuss some rather abstract, yet potentially fundamentally important developments in the foundations of statistics that may prove crucial for the adequate representation of risk attitudes prevalent in society.

4.2 Uncertainty in GMT Projections

In the 1990s, the discussion was dominated by a debate on whether global warming existed and if so, whether it was anthropogenically caused. The answer was non-trivial, as the increasing warming signal was just about to contrast against the background of natural climate fluctuations. As the main tool of analysis, the so called 'optimal fingerprinting' statistic strived at an optimised signal-to-noise ratio 'spatio-temporal warming signal' vs. 'natural fluctuations in the climate system'. The observed trend was linearly regressed with patterns from CO_2, SO_2, and other radiative forcing agents, under a metric derived from long-term natural fluctuations. It could be shown that the observed twentieth century temperature record appears rather unlikely within a climate system unforced by anthropogenic emissions (‘detection’), and the CO_2 pattern could explain the difference of observation and unforced climate to the largest extent (‘attribution’). These statistical tests are model-independent (‘let the data speak for themselves’) in the sense that the response amplitude $CO_2 \rightarrow$ temperature is inferred from the data. They led to the statistically founded claims of observed anthropogenically induced global warming. However, the methods are semi-empirical only: while they absorb the observed temperature record, they still rely on model output in terms of patterns and natural variability that is not questioned.

An alternative strain of research asks for future warming and the uncertainty of it, given a certain CO_2 forcing scenario. A key stylised quantity that encapsulates a large fraction of that uncertainty, is the climate sensitivity, the long-term temperature rise for doubling of the pre-industrial CO_2 concentration. IPCC-AR3 (IPCC 2001) specified its error bar as 1.5–4.5°C. That statement was informed by the uncertainty spanned by the properties of the dozen state-of-the-art climate models, available at that time. It was criticised for not representing the intra-model uncertainty. The latter can be traced back to so-called parameterisations that must be employed in any climate model for substituting sub-scale processes that cannot be numerically represented. Ideally, any of those parameters can be determined by comparison with observational or higher-resolution modelling data for that specific physical process. However, considerable overall uncertainty would result in case any parameter combination possible would be considered, implying almost-null-information on climate projections. Two structural elements were therefore introduced. First, often modelling experts specified parameter values at the boundaries less likely than those in the centre of parameter intervals. Bayesian statistics – in contrast to classical statistics – requires specification of such Bayesian priors. Second, one may request that any model version made-up by a specific parameter combination, must reproduce the climate history ‘sufficiently well’ – and ‘how well’ it does can be acknowledged by Bayesian updating in principle. In terms of climate projections, one would acknowledge the more statistical weight to a model version, the better it is able to reproduce the historical record and the higher it had been ranked by the model expert prior to model-data intercomparison.

Bayes’ formula states that the probability of a certain parameter combination a, $P(a)$, is proportional to the prior probability of a times the conditional probability for the observational data, assuming a (i.e., ‘how well the model version ‘a’ would have predicted the observation’):

$$P_{\text{posteriori}}(a) \propto P_{\text{priori}} \cdot P(\text{obs}|a).$$

Given the observation, $L(a)\colon = P(\text{obs}|a)$ is called likelihood of a. The likelihood is the statistical means to objectively rank different climate model parameter values of a, given the historical record of climate observations. One can show (e.g., Berger, 1985) that the Bayesian posterior allows for the optimal betting strategy, if the Bayesian prior had adequately represented the betting strategy prior to the additional data. Bayes’ formula extracts the maximum amount of information from data. (Some intuition for Bayes’ formula can be obtained when considering the special case of Gaussian prior and likelihood: the posterior mean is then the precision-weighted average of prior and likelihood mean, whereby 'precision' is the inverse variance; the more informative the new data are the more the likelihood mean will influence the posterior mean).

This Bayesian strategy was followed in the aftermath of IPCC-AR3 to better inform IPCC-AR4 (IPCC 2007a) on climate sensitivity. A numerical approximation of Bayes' formula requires on the order of 100–100,000 realisations of parameter combinations, if ~10 key model parameters should be addressed by the uncertainty analysis. Computational costs preclude taking such a sample for the most advanced climate models–for general circulation models (GCM). Therefore in general, GCM uncertainty analyses have been restricted to projects of distributed computing (see climateprediction.net). The main 'work horses' have thus been climate (or Earth system) models of intermediate complexity (EMICs) that allow to compute N-ensembles of climate sensitivity within an order of magnitude of N-hours, feasible on present-day super computers. The idea behind using EMICs as substitutes for GCMs is that they still contain enough physics to stay informative, on the other hand are flexible enough that by parameter-detuning one 'sweeps over the whole spectrum of GCMs'. The first Bayesian EMIC uncertainty studies of that kind were conducted by Chris Forest et al. and Reto Knutti et al. (Forest et al. 2002; Knutti et al. 2002). Both ranked model versions by Bayesian updating with twentieth century climate data. They revealed posterior probability density distributions for climate sensitivity rather fat-taled at the upper end. Accordingly, the upper end of 95% percentiles on climate sensitivity was found roughly twice the IPCC-AR3 upper end for climate sensitivity. Subsequent studies along such a scheme did not significantly alter the picture (for an overview, see IPCC 2007a).

This was exactly what critics of 'extensive uncertainty analysis' had warned of: openly addressing all input uncertainties would result in almost 'non-informative' output statements of such modelling exercises. At this instance, some rather subjective, general thoughts on function and nature of science might be in order. Science should clearly communicate the 'known' and the 'unknown'. To be able to do so, however, a certain topic within science needs to be consolidated to such an extent that it is possible to distinguish something 'well-known' from something 'less-well known'. 'Knowledge on uncertainty is always more uncertain than knowledge on the primary issue (Victor Brovkin, 2000, private communication).' In the course of IPCC-AR3, it became obvious that CS was a key uncertain property, much more uncertain, e.g., than the radiative forcing exerted by CO_2. Therefore it then made sense to explicitly analyse the range and a ranking for represent possible realisations of CS. One had to state that the upper limit of CS remained rather poorly confined, at least as long only data from the twentieth century were employed. This implied the rather uncomfortable scenario of a large long-term GMT rise even if humankind were able to limit CO_2 concentrations somewhere at present-day levels – which in itself is regarded an unrealistically strict mitigation target.

The latter statement holds only under the assumption that we further abstain from directly modifying the Earth's radiative balance by so-called 'geo-engineering schemes' (Keith 2000; see also Chap. 7 of this volume). Interestingly, a minimum values for climate sensitivity around 1–1.5°C were found very likely, hence adding weight to the thesis of anthropogenically induced global warming.

The question arose whether it was possible to back-reduce climate sensitivity uncertainty on objective grounds. Three possible ways are followed or planned in the scientific community. The first, the 'king's way', leads to improving the representation of physical processes, mainly through enhanced resolution of 'cloud physics', i.e., bringing coarse-grained climate models even closer to the fundamentals of physics equations. In that vein, according to a fundamental hypothesis of climate modelling, finally all climate models should converge in their projections. However, computational power may increase too slowly in order to let climate research deliver the desired quantity of climate sensitivity in time for the 'post-Kyoto bargaining process' on reduction targets. A second strain of research attempts to extract more information from twentieth century observational record in absorbing the temperature signal in higher resolution terms (Knutti et al. 2006). A third makes use of the much larger signal-to-noise ratio 'GMT vs. CO_2 concentration' in the last glacial interglacial transition as against the twentieth century temperature record. While GMT rise since pre-industrial times is just 0.8°C, the glacial-interglacial transition implied 4–6°C (Schneider von Deimling et al. 2006a, b). However, the latter approach would lead to false projections if the temperature/CO_2 ratio from the transition were simply assumed to hold for the future. Due to changing large-scale ocean dynamics as well as other boundary conditions we have reasons to believe that the glacial displayed a different GMT/CO_2 relation than modern-day climate. However, common wisdom in climate research assumes that statistical properties of smaller-scale processes, represented by climate model parameters, stayed rather unaffected by the glacial-interglacial transition. The key idea by Thomas Schneider von Deimling et al. was therefore to link the knowledge from that transition with future climate dynamics in a dynamically self-consistent way: as one of the few climate models, the Climate and Biosphere Model (CLIMBER2) of the Potsdam Institute for Climate Impact Research (Petoukhov et al. 2000; Ganopolski et al. 2001) lets both the glacial as well as the present-day climate emerge if CO_2 (as well as land-ice, dust, and insolation) are prescribed. One now requires that any combination of uncertain parameters must lead to both a glacial as well as a modern-day climate 'compatible' with observations. The model structure itself ensures dynamic consistency. Schneider von Deimling et al. could show that by requesting agreement of CLIMBER2 with paleo data would back-reduce CS uncertainty roughly to the interval given by IPCC-AR3. The latter implied a reduction of uncertainty by a factor of 2, when measured in terms of 5–95% quantiles.

Satisfyingly, that result appeared robust against choice of region (tropical Atlantic vs. East Antarctica) and temperature proxy. A similar approach was followed by James Annan et al. (Annan et al. 2005), leading to a non-overlapping interval for CS. For that reason IPCC-AR4 displayed those results, however with leaving open how to value any of these contributions. While the author of this article tends to trust more in the CS interval derived from CLIMBER2, for a number of rather technical reasons, it must be stressed that the discrepancy is subject to ongoing research and will hopefully be resolved until IPCC-AR5. What these pieces of research have shown, however, is the potential power of absorbing paleo data into climate models for further constraining climate projections. The author expects that this approach will lead to a whole new branch of GCM modelling that is capable of linking paleo information to the future.

4.3 Estimating the Proximity to Thresholds

While the general public starts to become rather aware of potential increase in future extreme weather probabilities, relatively little attention has been paid to so called tipping elements, sub-continental-scale regions that may respond over-proportionally to GMT rise, once a certain GMT threshold has been crossed. Examples out of the dozen of suspects discussed by Timothy Lenton et al. are the Artic sea ice and the Greenland ice sheet (Lenton et al. 2008). Once enough altitude of the ice sheet would have been lost, fresh snow would melt immediately, as lower altitude comes with higher regional temperature, hence the complete collapse would be unavoidable. The latter would imply an additional long-term sea level rise of about 7 m.

While ice sheets tipping involves a thermodynamic phase transition, a certain subset of tipping elements relates to dynamic bifurcations: although the ocean waters would not change their thermodynamic state of aggregation (i.e., ‘liquid’ as against ‘frozen’ or ‘gaseous’) when GMT rose a couple of °C, its dynamics could do so nevertheless. A prevalent hypothesis, backed by a series of spatially explicit ocean models, claims that GMT-rise-triggered enhanced freshwater input into the Northern Atlantic could lead to the collapse or at least abrupt weakening of the northern branch of the Northern Atlantic thermohaline circulation. Ocean models vastly diverge on whether such a threshold exists and how close we currently are to it. Uncertainty in that respect is much larger than on GMT projections. The reason is that the relevant processes cannot be directly compared to observations, but are indirectly inferred from the model in fitting it to certain mean properties of the present-day climate.

For that reason it appeared meaningful to relate model and data with respect to a system’s property that is much closer to the ‘heart of a bifurcation’: the force that restores small excursions in a stable system, vanishes at a threshold, in fact, making the threshold appear. The weaker that restoring force, the closer the threshold, and the longer a perturbation prevails. The key idea is now to infer that mean restoring time scale from the historical record of the system. The related statistical procedure, i.e., lag-1 autocorrelation (Wiesenfeld 1985) was generalised to spatially extended systems (‘degenerate fingerprinting’) and applied to the CLIMBER2 ocean (Held and Kleinen 2004). They found that within the set of vastly differing CLIMBER2 versions displaying all sorts of distances towards the bifurcation, up to an order of magnitude in precision could be obtained from that approach. Ironically, that statistic makes use of the noise of the system, while one generation of climate researchers before had tried to ‘optimally get rid of noise’ by ‘optimal fingerprinting’ (Hasselmann 1993), also called ‘BLUE estimating’ (Allen and Tett 1999), when trying to detect a trend in the observational temperature record. This clearly shows the necessity to optimise a classical test for the question at hand (‘trend detection’ vs. ‘threshold detection’), a decision not necessary when using Bayesian statistics.

A variant of the new threshold statistic was then tested in the hindcast mode – would it detect past thresholds in retrospect? Vasilis Dakos et al. showed for half a dozen paleo transitions that this may in fact be the case (Dakos et al. 2008). Future research must now clearly reveal under what circumstances an ‘early warning system’ for thresholds could be developed that way.

4.4 Extracting Response Time Scales

But that new statistic may not only be beneficial in cases of thresholds. The concept of extracting a system-immanent response time scale is of much more general interest. Constraining future GMT projections by the twentieth century GMT record is confounded by the following effect: the so far observed warming could either be explained by a small CS in combination with a fast responding climate, or a large CS in combination with a slowly responding climate. If the climate’s main response time scale could be reconstructed (e.g., from the last 10,000 years of ocean parameters, to be mapped from new ocean paleo sediments), then this would allow to discriminate between the two cases. This in turn would drastically reduce GMT projection uncertainty. Again, new (to the climate community) statistical-dynamical approaches can help to better project the future, without having to ever increase model resolution.

In analogy to determining CS, further approaches of different sort are followed. The climate response time scale is in part determined by the ocean heat uptake which can be measured, and is done so with increasing accuracy. In a competing approach, Alexander Lorenz et al. exploited the fact that ocean diffusivities, key uncertain system properties that strongly make-up ocean heat uptake, also indirectly co-determine appearance and length of the so-called ‘8 k-event’ (Lorenz et al. 2007). From the paleo-reconstructed 8 k-event Lorenz et al. narrowed-down then the ‘compatible’ set of CLIMBER2 parameter combinations which in turn reduced uncertainty in climate response time scale by a factor of 2. This analysis was contingent on certain assumptions on freshwater fluxes that triggered the 8 k-event. Nevertheless this stylised analysis demonstrated (like for CS) the remarkable information content that in principle can be found in paleo data, reflecting a certain dynamical feature of the climate system, in informing the future.

4.5 Climate Projection Statistics as a Philosophical Battlefield

The ‘fingerprinting analysis’ that linked the observational record to CO_2 forcing, represents a classical statistic, thereby following the main statistical strain within natural science. Classical statistics accept or reject a certain hypothesis for a given confidence level, observed noisy data and a stochastic model (likelihood function) of the process that is supposed to have generated those data. In case the model contains uncertain parameters a, this principle can be reformulated as error bars on a, i.e., an interval of confidence for a. Within the fingerprinting analysis, this was done for the influence factor 'CO_2' → 'temperature'. It revealed that '$a = 0$' ('no influence') was not contained in the 95%-level interval of confidence. This line of argument formed the statistical basis for 'anthropogenically induced global warming'.

Intervals of confidence ('error bars') represent a long-standing tradition in natural science. It is required that experimental data match theoretical predictions for 68% ('1-sigma')-intervals of confidence within experimental physics, or the (in an identical situation larger) 95% (2-sigma)-intervals in most life science applications. There is no obvious mechanism how to select the level of confidence or the statistic (a 'statistic' is by definition the mapping that reduces the complexity of the data set to one or a hand full of 'crucial' numbers). The sheer fact that physics and life science were 'successful' with their choices justifies those choices in retrospect. For the case of fingerprinting the test was decisive at the 95% level, a level, that is commonly regarded as 'large' and 'close to 100%'. For any set of data, one can push up that level so close to 100%, that the test becomes in-decisive. It is left to the cultural tradition of a nation and humankind as a whole whether one should act upon which level. Given that human society tends to act already at much lower 'levels of evidence' for a proclaimed danger, a positive 95%-fingerprinting test not implausibly was seen as a reason to press for mitigation measures by many climate scientists and NGOs.

These days climate models are consolidated to such an extent that instead of testing whether there was anthropogenic influence, direct projecting the future is of main interest, including regional consequences. Hereby it is uncertain, what climate model is the most adequate one, and in what parameter setting. Classical testing was popular within fingerprinting because for that setting a compact, well-established statistic existed (due to the linearity of the set-up). However, the mapping from model parameters onto model output in rather non-linear, hence, to ensure efficiency, new, rather opaque classical tests would have to be developed, contingent on the set of models under consideration.

In comparison to that it appeared rather straightforward to test output robustness by randomly testing model output for competing parameter combinations (Monte Carlo analysis, or more sophisticated variants such as Latin Hypercube). This procedure can be given a statistical interpretation: numerically, a Bayesian prior was made-up. In well-thought numerical experiments, the density of numerical shots in 'parameter-space' were in-line with expert judgements on those parameters. When relating model output and observational record, numerical approximations of a Bayesian posterior were obtained thereby. For cases in which experts were in principle willing to bet in accordance with their prior estimate, and society assume those experts as informed and trustworthy enough that such subjective estimate is taken into account, that Bayesian procedure is the optimal way to represent posterior knowledge in the light of new data (here: the observational record constraining the model versions), in particular, when it comes to making decisions under uncertainty.

However, often it can be questioned whether experts are really that well-informed and would bet in accordance with their prior. This immanent feature of Bayesian statistics, to include a subjective prior judgement, has been seen as the main drawback of Bayesian statistics in cases of poor prior knowledge. Bayesianism has developed two major strains to deal with that challenge: Firstly, 'objective Bayesianism' and secondly, 'robust statistics' and the closely related 'imprecise probabilities'. Objective Bayesianism suggests to represent rather poor prior knowledge by a 'non-informative' prior, i.e., a uniform distribution. However this approach runs twofold into trouble. First, it triggers 'Bertrand's paradox' (Rosenkrantz 1977). Assume, no prior knowledge existed on uncertain parameter a, and that knowledge were modelled by a uniform distribution. Then also no knowledge exists on any non-linear derivative of a, e.g., $b{:} = a*a$. However, conservation of probability measure maps the uniform probability distribution onto a non-uniform distribution for b, hence we have generated knowledge on b out of nothing. In this situation, David Frame et al. suggested to require a uniform distribution in the model output of interest instead (Frame et al. 2005). However, the author found the prescription ill-posed in case of more than one uncertain parameter. Meanwhile, this suggestion to save objective Bayesianism is off the table, yet has induced repercussions within the climate community for several years.

Objective Bayesianism has also been challenged on empirical grounds. Daniel Ellsberg's famous experiment showed that in cases of poor prior knowledge, subjects did not bet in accordance with a uniform distribution, but rather with a collection of distributions (Ellsberg 1961).

This observation co-triggered a new branch of uncertainty representation, imprecise probabilities (Walley 1991). They represent a smooth transition between the two extreme cases of assuming a probability distribution on the one hand, or an interval with no further preference within that interval, on the other hand. They may be the adequate way to represent the existing prior knowledge, and utilising them for climate projections represents an expanding branch of science right now (Kriegler and Held 2005; Tomassini et al. 2007). As a result, output uncertainties tend to be larger than when using standard ('precise') probabilities.

Also that rather recent approach may not be the 'King's way', as rather bizarre effects occur, when Bayesian updating such imprecise measures. First, Bayes' rule must explicitly be generalised, and several versions are under discussion. The most prominent and conservative one ('generalised Bayes rule', Walley 1991) allows for the phenomenon of 'dilation': we know in advance that no matter what we observe, we will be more uncertain than before. Competing rules that confine dilation display other counter-intuitive features (Held 2007; Held et al. 2008; weighted or maximum likelihood updating and quantile-filtered updating can violate a desirable monotoneicity feature between observation and posterior).

In the end, no statistic may ever fulfil all properties at once that may appear desirable. Only by including some sort of cultural theory it can be decided which kind of statistical approach is most in accordance with a society's actual preference order. Then it could be decided in a more stringent way, which of the conflicting desirable properties should be sacrificed in a given application. The attempt to resolve the century-long battle 'Bayesians' vs. 'frequentists' (supporters of classical statistics) within the statistical community may prove therefore an ill-posed approach. However, within a pragmatic view it is important to recognise that whatever statistical approach was followed, massive global warming was predicted in case of further unmitigated greenhouse gas emissions.

4.6 Deriving Sustainable Solutions Under Uncertainty

The ultimate challenge humankind faces right now is not to understand the climate system and project into the future, but to figure out what action would be 'most desirable', given considerable residual uncertainty in both the climate as well as the techno-economical system. Hereby it should be noted that 'inaction' in terms of climate policy represents also one version action, not innocent at all, namely further 3–5-folding annual greenhouse gas emissions by 2100.

At present, climate economics seems to have sorted out a robust kernel of low-cost mitigation option mixes that could achieve rather ambitious mitigation targets (Edenhofer et al. 2006). Those analyses were still performed in the deterministic paradigm, and a new suite of analyses has to be expected: how much to invest when into solar, wind, carbon capture storage (CCS), the related infrastructures, under uncertainty and anticipated learning on uncertain system parameters. Climate uncertainty will be reduced in the vein of better research on climate dynamics, and over the course of time. Technology uncertainty will easiest be reduced by 'simply' implementing the new technology on ever-larger scales. Held et al. (2009) have shown that including climate uncertainty in economic optimisation presses for even earlier mitigation, involving 10–30-folding of global annual investments into renewable energy sources one to two decades earlier.

Those numerically challenging, yet conceptually comparatively rather straightforward implementations need to be nested in a more general ranking of options in terms of their potential side-effects, not yet monetarised. Almost all options – solar thermal so far seeming the only exception – come with severe potential or proven side-effects. Over the last years, the speculative option 'geo-engineering' enters the debate. The reason for that is vested interest on the one hand that tries to add new options that would reduce the public pressure on phasing out fossil fuels, and climate environmentalists on the other hand that fear, conventional mitigation options may be insufficient or may come too late to address the severe climate problem.

Geo-engineering is by definition a conscious, planetary-scale intervention in order to counter-balance an undesired side-effect of a previous action (such as greenhouse-gas emission). Schemes like putting up giant reflectors at the L1-point to dim sunlight reaching Earth, or doping the lower stratosphere by SO_2 emissions, inducing reflectivity-enhancing aerosols, would result in a reduced radiative influx and hence would cool the planet. (Note that both options do not solve the 'Second

CO_2-problem': ocean acidification.) Most scientists rank such options as secondary compared to directly cut greenhouse gas emissions. With respect to the climate system it is argued that the climate system reacts 'non-linearly', implying that responses can be over-proportional and rather surprising. Accordingly, adding another action on planetary scale (after having already elevated CO_2 concentration) would imply just another layer of risk for unintended side-effects that then would further have to be mitigated (if ever possible), thereby leading to a quasi-infinite regress of human interventions. Such a regress has been called 'risk-spiral' (Jochen Jaeger, 2000, private communication) in analogy to competing in the arms race of the cold war.

In the end, science can be helpful in providing 'transdisciplinary information': information of 'if-then' character, linking controls decision makers really have at hand (e.g., policy instruments on emission control), to normatively relevant variables (e.g., economic gains or losses, or factual damages). Science must abstain for giving explicit or hidden normative prescriptions. It rather should open choices for politics in terms of scientifically sound, self-consistent options. The choices may be normatively involved. But it is the privilege as well as the burden of politicians to make informed choices, not of science. How to deal with uncertainty represents a normative choice as well. Science can reflect risk attitudes of society in deriving solutions of the climate problem that internalise the societal risk attitude. Science should abstain, however, from masking choices on risk attitudes by encapsulating them in certain statistical approaches, without further communication.

For that reason we will witness a rebirth of the philosophy of science. The pressure to distinguish the known, the systemic, the 'objective', from the normative, still often entangled in scientific, particularly in socio-economic, approaches, has never been larger than now, when it comes to negotiate the best climate policy for our future.

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Chapter 5
Uncertainty in Climate Policy – Impacts on Market Mechanisms

Alex Vasa and Axel Michaelowa

5.1 Introduction

In terms of geological shifts in climate, climate policy is a very young field. However, during the last two decades it has developed at a rapid pace. In 1987, the Brundtland Report first used the concept of sustainable development, followed in 1988 by the first meeting of the Intergovernmental Panel on Climate Change (IPCC) in Toronto. The establishment of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 marked the birth of global climate policy.[1] For the first time in history governments of almost all nations gathered to discuss the effects and consequences of and measures to be taken against global warming and agreed on the principle of "common but differentiated responsibilities".[2] The first decade of climate policy culminated in 1997 in the signing of the Kyoto Protocol, in which industrialized countries (37 so-called "Annex B countries"), agreed to reduce anthropogenic emissions of six greenhouse gases (GHGs) by 5.2% below 1990 levels during the Kyoto commitment period, 2008–2012 (Article 3, UNFCCC 1997).[3] At the same time, developing countries, agreed to provide GHG inventory reports. As abatement of a ton of CO_2 eq. is equally

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[1] The UNFCCC was signed May 9th, 1992 as part of the UN Conference on Development and Environment (UNCED) in Rio de Janeiro and entered into force March, 1994. By early 2008, 192 nations have ratified the UNFCCC, while 154 nations had signed the UNFCCC in 1992 in Rio de Janeiro.

[2] This was done by differentiating countries into "Annex I", i.e., industrialized countries and "Non-Annex I", i.e., developing countries.

[3] GHGs covered under the Kyoto Protocol are carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and Sulphur hexafluoride (SF_6). All GHGs can be restated in terms of CO_2-equivalent (CO_2 eq.) by multiplying their

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effective for the global climate irrespective of the location of abatement, according to economic theory emissions should be reduced where the marginal cost of abatement is lowest (Dales 1968; Coase 1960). To reduce costs of compliance for Annex B countries, four flexible market mechanisms have been introduced to increase the efficiency of emission reduction opportunities by global trading:

- Target reallocation (Bubble) (Article 4)[4];
- Joint Implementation-JI (Article 6);
- Clean Development Mechanism – CDM (Article 12); and
- International Emissions Trading – IET (Article 17).[5]

International Emissions Trading (IET) allows governments of countries with commitments to sell unused shares of their emissions budgets, so called Assigned Amount Units (AAUs), to other countries that want to use more AAUs than they have been assigned in the Kyoto Protocol. The second mechanism, Joint Implementation (JI), permits the generation of emissions credits through emission reduction projects in an Annex-I country. These credits can be used by the acquiring (Annex B) country to fulfil its Kyoto commitments; an equivalent amount has to be deducted from the emissions budget of the country hosting the projects to avoid double counting (Michaelowa 1995; Metz 1995; Geres and Michaelowa 2002). The Clean Development Mechanism (CDM) allows projects that reduce emissions in non-Annex I countries that do not have an emissions budget to generate emission credits that can be used by countries that have commitments. Finally, the CDM is the only instrument of the Kyoto Protocol that started before 2008. CDM credits, so-called Certified Emission Reductions (CERs), can be generated from 2000 onwards if early and serious consideration of the CDM in the planning of the project can be proven (Michaelowa et al. 2007). Due to the fact that all actors involved in CDM projects have an incentive to overstate emission reductions, there is a detailed body of rules whose implementation is checked through independent audits. A cornerstone of the rules is the principle of additionality, i.e., that a CDM project would not have happened without the CER incentive.[6]

The Kyoto Mechanisms are the most innovative feature of the Kyoto Protocol and therefore particularly prone to impacts of uncertainty regarding general stability of climate policies, rules for mechanism implementation and performance of projects under the project-based mechanisms. We focus on the CDM to illustrate the effect of those uncertainties. First, we identify sources of uncertainty at the policy, project and institutional level. We then look at their impact on the Kyoto market as a whole and

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quantity in tons with the 100 year global warming potential (GWP) of the respective greenhouse gas. Until October 2008, the Kyoto Protocol had been ratified by 182 countries.

[4] This mechanism, although often omitted in the list of flexible mechanisms, is used by the European Union to achieve the emission targets as a group rather than as individual countries.

[5] There is a wealth of abbreviations in the Kyoto carbon market. For convenience, the most frequently used terms can be found in the Annex to this paper.

[6] The most recent version of the "Tool for the demonstration and assessment of Additionality" has been approved by EB 39 in its fifth version.

provide recommendations for improvement. Section 5.2 deals with uncertainty in international climate policy and domestic climate policy of large players, especially regarding the lifetime of the Kyoto Protocol regime and domestic incentives for use of certified emission reductions. Section 5.3 gives a brief overview of the current CDM market and introduces the effect of real and perceived policy uncertainties on CER prices. Furthermore, the quality and performance of CDM projects, both of which are major determinants driving the environmental integrity and effectiveness of the mechanism are analyzed as an additional factor. Performance of the CDM in general and of specific project types in particular can give substantial price signals as some domestic climate policy instruments only accept certain types of CERs. Section 5.4 assesses external and internal actors in the Kyoto system and analyses how these actors influence the price of carbon. Moreover, this section makes recommendations to enhance transparency and regulatory stability. Section 5.5 concludes the chapter.

5.2 Uncertainty in International Climate Policy

The key uncertainty on the international level is whether an international regime is applicable and binding, and for how long it lasts. The Kyoto Protocol initiated the "period orientation" of climate policy. The Kyoto commitment period runs from 2008 to 2012. For the time leading to and including this period, market participants, governments and institutions have a certain degree of planning security. The 5 year interval was chosen on the basis that a usual business cycle needs about the same time to complete. It is intuitive that the length of climate regime period is positively correlated with planning certainty for market participants. The 15 year time-span from the drafting of the Kyoto Protocol until the end of the first commitment period in 2012 was believed to be an adequate investment horizon for businesses. But nobody expected the uncertainty of entry into force – for an interval of 7 years between 1997 and the final ratification by Russia[7] in November 2004, it was not clear if the Kyoto Protocol were ever to enter into force.[8] The long waiting period for entry into force was due to the unwillingness of the US to ratify the Protocol, which then gave Russia a de facto veto power. Thus, even if decisions have already been taken on the international level, domestic interest groups and political interests of big emitters have considerable impact on the implementation of the international climate policy regime (for Russia see Michaelowa and Koch 2002; Burtraw et al. 2001).[9]

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[7] The ratification by the Russian Federation was required to fulfil the condition that more than 55% of CO_2 emissions from Annex-I countries are included in the ratifying group (Article 25, KP). This was due to the refusal of the US to ratify, as the US was responsible for 36% of the emissions.

[8] Interestingly, 39 CDM projects were submitted before Russia's ratification, showing that some market actors were willing to take up the Kyoto risk.

[9] Axel Michaelowa and Tobias Koch examine Russia's possible reasons, including interest group rent seeking and Duma power issues, for not having ratified the protocol despite generous counting of sinks (and doubling of these sinks in Marrakech) and allocation of "hot air" permits (Michaelowa and Koch 2002 pp. 563). Alain Bernard et al. show in their paper using computable general

As the Kyoto Protocol only lasts until 2012, the current uncertainty due to the lack of a post-2012 climate policy regime increasingly becomes similar to the situation before the Russian ratification. The “Bali Action Plan” foresaw that a final treaty would be finished during the 15th Conference of the Parties (COP-15) 2009 in Copenhagen but this was not achieved. The key issue is stringency of emission targets. The Bali Action Plan contained a target corridor of 25-40% emissions reduction by 2020 for industrialized countries. The EU has proposed a 30% reduction target for itself if other industrialized countries embark on similar commitments. The Copenhagen Accord and the recent Cancun Agreement provide a framework for bottom-up country pledges by industrialized countries and advanced developing countries but no legally binding commitments.

If market participants expect that the post-2012 Copenhagen treaty is weak in terms of emission reduction commitments, they have little incentive to engage in “early” action now and thus delay emission reducing investments. If on the other side actors expect stringent and enforceable emission targets, emitters have incentives for domestic reductions and purchasing emission reduction credits from the Kyoto Mechanisms.

Similarly, big players such as the European Union have a large influence not only during the negotiations of the regime but also on setting incentives for the carbon market. The EU set up the only really large domestic policy with a concrete incentive for the Kyoto Mechanisms – the European Union Emissions Trading Scheme (EU ETS), which started operating in 2005 and which has been linked to CDM and JI. In 2009, over 6 billion EU allowances (EUAs) were traded at a turnover of 89 € billion (Kossoy and Ambrosi 2010). In part II, we will discuss the key role of the emission allowance price for the pricing of certified emission reductions. In this context, a recent decision by the EU to severely restrain CER imports has had a negative influence on the CER price. The EU is clearly aware of its key role in the Kyoto Market and willing to use this as a negotiation tool. This increases uncertainty in the market, as the market is “taken hostage” of political interests. As the Kyoto Mechanisms and the resulting carbon market have entirely been established by government intervention, political decisions can in principle create new demand and similarly take away demand with a stroke of a pen (Michaelowa 1998). For an analysis of the impacts of interest groups on such decisions see part III. A nice example of the impact of interest groups on policy decisions with a heavy impact on the carbon market can be seen in the US. Until 2001 there was considerable interest by US businesses in the carbon market and the Kyoto Mechanisms, which essentially had been included in the Kyoto Protocol on the request of the United States.[10] However, when President Bush refused ratification, US businesses specializing in the carbon market lost momentum

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equilibrium models how Russia faces a trade-off to maximise their revenue from emission permits versus the revenue from fossil energy exports (Bernard et al. 2003).

[10] The positive experience gained by the US through the SO_2 emissions trading regime, established through the Acid Rain Programme of the Clean Air Act in 1990, should not be underestimated here.

and eventually European providers took the lead. As the few US businesses remaining active focused on domestic offsets only, they see the CDM as a competitor and therefore oppose it. At the same time, as European investors and carbon-related businesses have already made substantial investments in the CDM market that would be worthless if the CDM was abolished they want to keep the system as it is.[11]

The aspect of uncertainty about the future post-2012, even though the current CDM market is blooming, leads to a saw-tooth curve of uncertainty in which uncertainty about the potential follow-up post-2012 regime increases when approaching the end date of a period, without another follow-up treaty being decided. Similarly, uncertainty decreases when approaching the start date of a new period as more information enters the market and expectations are formed. This uncertainty is reflected in the volatility of the price for carbon. An optimal solution for the above problem is a series of commitment periods with established progress checks each period to give the right incentives to abate and invest also during the period rather than only at the beginning or the end. Given that climate treaties are international legal constructs in nature, sanctions, arbitration and other real enforcement mechanisms have to be in place to secure compliance. Also trade issues, involving competitive concerns of countries with and countries without strict environmental regulation have to be dealt with at the international level. Although enforcement and trade is beyond the scope of this text, it is interesting to note that a credible and working enforcement mechanism is a necessary condition for a good climate treaty and is able to diminish uncertainty about the environmental impact of the treaty.[12] Ultimately, the uncertainty about the concrete policy framework affects the price and volatility of carbon commodities, which is discussed in the following part after a brief introduction in the carbon market.

5.3 The State of the Carbon Market and the Influence of Real and Perceived Uncertainties on Prices of Carbon

5.3.1 The Regulatory Framework of the Carbon Market

At the highest level the Conference of the Parties and the Meeting of the Parties (COP/MOP) shape current and expectations about future climate policy, but does only have legally binding power where the treaty has conferred such authority. The meetings take place once a year and give important signals for market participants. However, also decisions not taken or delayed by the COP/MOP can impact the

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[11] Currently, the discussion focuses on reforming the clean development mechanism, especially the CDM institutions and the approval system. However, consensus among carbon-related businesses is to maintain the CDM as a tool to reduce greenhouse gases.

[12] A good enforcement mechanism ensures that the environmental integrity of the treaty is ensured.

Table 5.1

Carbon commodities specified by the Kyoto Protocol	
Assigned Amount Units (AAUs)	When the allocation of AAUs was decided in the negotiations leading to the Kyoto Protocol, Russia and Ukraine and countries of Eastern Europe got emission targets comparable to OECD countries. However, the economic transition and the related closure of heavy industries which occurred during the 1990s led to emissions decreases of 40–70%. The overall surplus of these countries, the so-called hot air is estimated at 5–7 billion t CO_2 eq. Its initial purpose was to provide the US with an easy way to reach its Kyoto target by agreeing on a bulk transfer of "hot air". This bargain did not work and the "hot air" is about twice to three times as large as the combined demand of all OECD countries. Thus, theoretically, the CDM market could be eliminated overnight as the "hot air" can always sell at a lower price than CDM project developers. However, the countries in transition lost several years in setting up the institutions for selling AAUs, while OECD governments were reluctant to buy "hot air" due to expected opposition from non-governmental organizations. This might change towards the end of the commitment period once governments face the need to comply and do not have the budget to buy expensive CERs.
Emission Reduction Units (ERUs) under Joint Implementation (JI)	JI suffered from a late start of the institutions on the UN level and host country problems similar to those encountered for assigned amount unit trades.
Certified Emission Credits (CERs) under the Clean Development Mechanism (CDM)	The CDM has the twin objective to reduce emissions and to contribute to sustainable development (SD) of the country in which the project is implemented.

Joint Implementation projects can generate ERUs from 2008 onwards
Source: UNFCCC

market severely, depending on the respective issue. In the Kyoto Protocol, COP/MOP specified three distinct carbon commodities[13] (Table 5.1):

A complex array of institutions has been set up after 2001 to guarantee the twin objective of environmental integrity and sustainable development of the CDM. At the core, the CDM Executive Board (EB) decides about the technical rules and the registration and issuance of CERs for CDM projects.[14] Over time, the EB has created a number of supporting panels,[15] including the Meth Panel, the Small-Scale

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[13] Verified or Voluntary Emission Reductions (VERs), which belong to the voluntary market, are not part of the Kyoto compliance market. We will only look at the Kyoto market.

[14] The CDM Executive Board is following the guidelines decided by the Conference and Meeting of the Parties (COP/MOP) and is fully accountable to COP/MOP (3/CMP.1, Annex, paragraph 5).

[15] The CDM AP and the Meth Panel was established by EB 3; the A/R WG at EB 14 (Annex 8); the SSC WG following Decision 21/CP.8 in New Delhi, 2002 and the EB-RIT at EB 29. The Small Scale Panel had a short existence between April and August 2002, met three times and drafted simplified modalities and procedures for small scale projects.

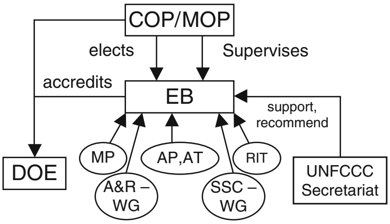

Fig. 5.1 CDM institutions
Source: Michaelowa et al. 2007

(SSC WG) and the Afforestation and Reforestation (A/R WG) working groups, the Registration and Issuance Team (RIT) and the Accreditation Panel (CDM AP), which provide technical expertise and prepare recommendations for the EB.[16] Since late 2006, a sizeable number of staff has been hired by the UNFCCC Secretariat to support the Executive Board's work. Over time, the rules for formal acceptance of projects under the clean development mechanism have been elaborated by these institutions. In addition, on the private side project developers, financial institutions, Designated Operational Entities (DOEs), Designated National Authorities and local governments depend and interact with the rules established by the EB.[17] A visual representation of the CDM institutions can be seen in Fig. 5.1 below.

Since 2001, the market for CERs has been constantly growing. The main driver has been that CERs can be sold into the EU Emissions Trading Scheme through the EU linking directive (2004/101/EC). The linking directive governs the imports of certified emission reductions and emission reduction units for compliance under the EU ETS; the import of AAUs is not allowed. Until late December 2010, 2,548 projects had been registered, 475 million CERs issued and 1.9 billion CERs are expected until 2012 from these projects. Furthermore, over three thousand more projects are in the pipeline.[18]

Despite this success, due to the multiple institutions and participants involved in the CDM project cycle, different degrees of uncertainty pervade the market. An initial uncertainty in the CDM market was whether so-called "unilateral" projects are allowed, i.e., projects that are fully financed and organized by an entity from a developing country. The decision of the CDM Executive Board in May 2005 to

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[16] The Kyoto market developed a whole array of new terms and abbreviations. A glossary of terms is attached at the end of this article for reference.

[17] Another challenge that can arise from such a multi-layer structure is the anti-commons problem, which means that certain players can delay progress if it is in their (rent-seeking) interest follow such a strategy. However, the rent-seeking argument loses some momentum as the governmentally established entities and their private counterparts are under high critical scrutiny by the public and the media (Buchanan and Yoon, 2002).

[18] In a recent report validators (so-called Designated Operational Entities - DOEs) have stated that more than 100 projects that are currently in the validation phase will never reach registration due to additionality reasons. However, the data remains confidential for reputational issues of the respective project developers, who handed in the project (Dornau 2008).

allow unilateral projects immediately triggered a strong inflow of projects. While previously only a handful of projects had been submitted every month, within 6 months 100 projects per month came in. This unexpected surge stretched the CDM institutions. Members of the EB had to check all the submitted projects themselves. As they put faith into the validators, only 6% of projects submitted for registration in 2005 were put under review and 1% rejected. Therefore, project developers expected that once a project is validated, it achieves registration. However, the EB set up a second layer of scrutiny in 2006, the Registration and Issuance Team whose experts check the validation report and Project Design Document (PDD) for conformity with CDM rules. In 2006, rejection rates increased to 3%. In 2007, the revenues from the administration fee paid to the EB allowed hiring of a substantial number of support staff, which does a third level check of documentation. In 2007, rejections jumped to 8% and they increased to 10% in 2008 and 2009. Uncertainty of project developers regarding registration of a project proposal has thus increased substantially.

The interaction of CDM institutions has an important impact on the investment and planning security of the system. This interaction will be assessed in Sect. 5.4 of this chapter.

5.3.2 *Pricing of Emission Credits*

Differences in perceived uncertainties generated differences in pricing of different greenhouse gas market units right from the beginning. We show this by some examples before starting a systematic discussion why prices have not yet converged. Before the Kyoto Protocol entered into force, prices for certified emission reductions from CDM projects reached only 3 $. When the European Union Emissions Trading Scheme was decided, the price for EU allowances established itself at a much higher level – initially 8 € and later up to 30 € as the EU ETS was seen as a stable source of demand. The acceptance of CERs in the ETS generated certainty about their use and an increase in price followed. The EU Commission's threshold for the use of Kyoto Mechanisms credits for compliance is unlikely to be binding, but has been used as an argument for a price discount of Kyoto credits compared to a EUA. For a long time, the lack of the International Transaction Log (ITL), which is required for transferring Kyoto units between registries of different countries has also been used as an argument for price differentiation between CERs and EUAs.

We see the following three conditions for price convergence of similar commodities: transparency of the market, homogeneity of the product, free and undisrupted trade, following Catrinus Jepma (Jepma 2007). The last two conditions are closely linked in case of the EU ETS and the CDM market: We discuss whether they are likely to emerge in the international greenhouse gas market.

In the EU ETS market the transparency of the market is dependent on the information about which installations in the market get how many allowances in which way and if the market has a surplus or a deficit of EU allowances. For example only after the verified and monitored emissions data of EU member states has been published for 2005, market participants realized that EUAs had been over-allocated (Buchner and Ellerman 2006). This led to a sudden price drop of allowances, from which they never recovered until the end of 2007.

In case of the CDM market, decisions taken by the institutions should be transparent and consistent. This is not always the case. For example, the "completeness check" of the documents submitted for registration of a CDM project by the UNFCCC Secretariat, in early 2008 took on average 2 months. Furthermore, in the first econometric analysis of Executive Board and Methodology Panel decisions, Flores Flues et al. find that the degree of transparency is higher for methodologies than for project approval/rejection (Flues et al. 2008). The authors find that EB membership of the country concerned in project decisions raised the chances of approval in the past. Although it might be helpful in reducing the rejection rate, it is opaque and not supported by any decision of the EB or the Conference of the Parties. On another note, cement blending projects that easily got registered in 2005 now are routinely rejected.

The market for certified emission reductions is characterized by different prices for CERs depending on the stage of the project and the type of contract. Since CERs are generally sold in forward contracts (so-called primary CERs), uncertainty about the creditworthiness of the seller and the buyer, the performance of the technology and the risk of rejection of the project influence the price quoted in a carbon contract. The allocation of these risks to the parties in the contract leads to price differences. The more advanced a project is in the cycle and the closer a project is to issuance by the Executive Board, the higher the CER price. Liabilities play a key role for risky contracts.[19]

Moreover, Axel Michaelowa et al. show that CDM performance regarding the number of CERs expected for delivery and the actual number issued is substantially different between project types. In an analysis of 203 projects, they also show that issuance success is between is 15% for geothermal projects and over 120% for N_2O projects (Michaelowa et al. 2008). More worrying is that also frequently applied project types such as hydro and biomass power plants have low issuance delivery rates in the range of 80–85%. Also issuance success differs between project developers, with the first large victim of the carbon market being the company AgCert, which specialized on methane recovery and flaring from pig manure. Its 27 projects so far had delivery rates of less than 20%. The increased awareness regarding the variety of risks – some analysts differentiate between over 70 types of risks – has led to an increased price differentiation according to risk allocation over time (Richardson 2008). Primary CERs with the volume risk fully on the buyer side traded around 3 € until early 2005 and 5 € from 2005. Primary CERs with a firm volume and monetary compensation for underdelivery started to get a premium

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[19] For a good analysis and an overview of how carbon contracts can be structured (see Streck and Freestone 2005, Chap. 20).

in 2005 which rose to 3 € in 2006 and 5 € in 2007. Guaranteed CERs, i.e., CER portfolios aggregated by financial institutions with a high credit rating, were available from the second half of 2007 and have traded at a discount of about 1 € to the price of issued CERs, so-called secondary CERs (Capoor and Ambrosi 2008). At the end of March 2008, IDEAcarbon started a weekly market survey with four categories (IDEAcarbon 2008). The lowest tier has the buyer taking methodology, validation, registration and volume risk and a 50% forward payment. In the second tier, the seller takes the methodology and validation risk. In the third tier, the seller takes the registration risk, while the buyer pays on delivery and in the fourth tier the seller takes the volume risk. The price range within each tier was higher than the average price difference between tiers, showing the influence of project type and host country risks.

The homogeneity of the carbon commodities and free undisrupted trade are related subjects in the carbon trading universe. In principle homogeneity is established by the EU linking directive. In general terms, EUAs and CERs allow its holder to emit 1 t of CO_2 eq. or to convert to such a right, respectively. In theory, CERs and EUAs should thus trade at the same price. However, it is notable that even issued CERs, for which no delivery risk exists, do trade at a discount to EUAs. A potential reason could be regulatory decisions, highlighted in Fig. 5.2, by the EU and the EB about the future of the Kyoto market. For example, the UNFCCC announcement in August 2007 that the ITL would become functional in November 2007 led to a substantial drop in the EUA-CER spread. Despite the timely fulfilment

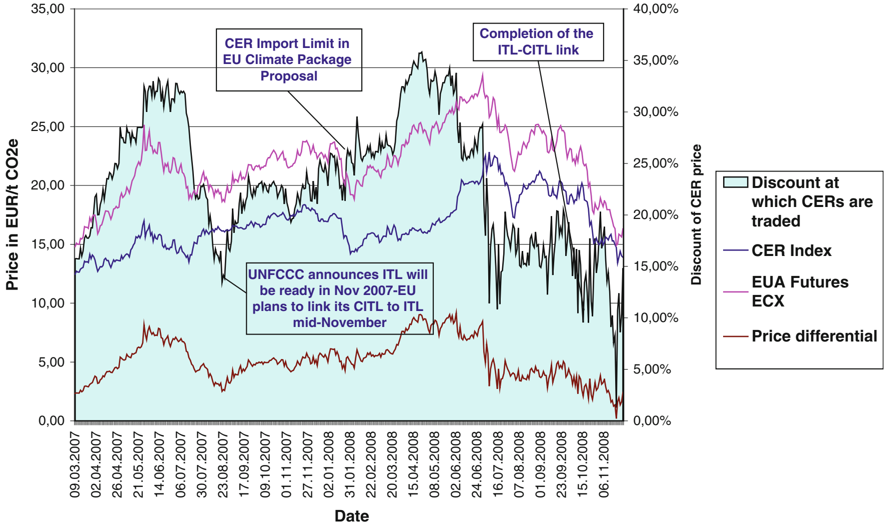

Fig. 5.2 EUA vs. CER prices in 2007–2008. The figure depicts the price of Dec 2008 EUA future contracts, secondary CERs and their price differential both in absolute and relative values. Prices for primary CERs are often confidential information and are thus currently not available on a large scale for analysis

Source: ECX (2008), Reuters (2008) and calculations by the authors of this promise, a registry-related problem remained until late 2008. All transactions of the EU ETS are registered in the CITL (Community Independent Transaction Log). Similarly, all international transactions in the Kyoto system, AAUs, ERUs and CERs are registered in the ITL. While linking the CITL and the ITL had been expected for no later than December 1st 2007, it took until mid-October 2008. This in turn meant that the free trading of EUAs in phase II was inhibited. Some countries, reacting to pressure from emitting interest groups, even refused to issue EUA to their installations before the ITL is linked to the CITL. At the same time, the missing link between the CITL and the ITL also meant that CERs generated by CDM projects could not be used for compliance in the EU ETS. Finally, in mid-October 2008 the ITL-CITL link has been completed. The linkage did lead to the expected decrease in EUA-CER spread as can be seen from the figure 5.2.

The subsequent arguments discuss reasons for volatility in EUAs and CERs and pricing differences between the two. Volatility in EU allowances stems from multiple factors, where the interaction of supply (the allocation of allowances) and demand (the emissions by covered installations) dictates the price. Moreover, the information and access of market information and expectations by market participants moves the market. As compared to phase I of the EU ETS (not shown in the figure) where an over-allocation of allowances led to a sudden collapse of the EUA price, phase II EUAs established a support line at around 20 €/t CO_2 eq. due to stringent decisions by the EU Commission that slashed most allocations. Only when it became clear in October 2008 that the financial crisis would lead to a decrease of heavy industry production, EUA prices fell substantially. Thus, expectations about future EUA demand drive the price. EUA prices fluctuate also in dependence of the amount of external credits that can be used for compliance. In phase II, the European Commission established an overall import limit of 1.4 billion t CO_2 eq. (EU Commission 2007). As the projected shortage in the EU ETS is about one billion t, this limit is not binding. In late January 2008, the Commission announced its intention not to allow any new imports beyond the limit for the time 2013–2020 if the overall EU reduction target was 20%. Only with a 30% target, 0.9 billion t could be imported. Figure 5.2 shows the sharp increase of the differential between EUAs and CERs after the Commission announcement. Whereas the limit of CER credits is an arbitrary decision, which is at risk of being influenced by interest groups, it should be communicated in a transparent manner to enhance certainty for stakeholders.

The announcement by EU Commission representative Slingenberg that certified emission reductions should be calculated according to very stringent benchmarks, thus leading to a “de facto discount of CERs” did not have an adverse effect on price of issued CERs and EUAs, which have increased in the same time period due to high fossil fuel prices (GTZ CDM 2008). However, it can cast a chill on the development of new CDM projects.

Pricing in CER forward contract can be set as a combination of a weighted average of various factors, such as the actual EUA price at the time of CER delivery, an indexed price over a pre-specified time period, a fixed price or various combinations of both (Streck and Freestone 2005). The impact of the choice of parameter can be striking: A contract specifying CER price in terms of phase I EUA price in December 2007 was settled at 0.03 €/CER, as the underlying EUA price had collapsed due to overallocation. Had the contract been determined in phase II EUAs, it would have had to be settled at 23 €.

The pricing of post-2012 credits is another complicating factor. CERs for projects extending beyond 2012 trade currently at a large discount compared to CERs expected to be issued within the Kyoto Protocol commitment period and not many entities buy such CERs. Large buyers such as the World Bank can influence the market by their price offers for post-2012 credits. Karan Capoor and Philippe Ambrosi claimed "uncertainty of compliance value as one aspect" to discount the value of post-2012 CERs and report prices of 2–4 € (Capoor and Ambrosi 2007). Such low offers by large buyers cast doubt on a credible commitment to a continuation of the current climate policy regime and are even dangerous for the system.

The huge pricing volatility, especially due to regulatory uncertainty, makes it difficult to secure a loan with the CER flows, especially if loan-providers expect the current system to be altered. Generally, the pricing of Kyoto credits depends on a multitude of issues involving energy prices, environmental regulation globally and domestically, risk perception and shifting, the behavior of large players and on decisions taken at the EU and UNFCCC level. At each stage uncertainties can arise if the information revealed and the transparency of the market is incomplete. In the following the interaction of key market participants will be examined in light of their influence on uncertainty in the market.

5.4 Interaction of Key Actors in the Kyoto/CDM Market and Their Influence and Challenges with Uncertainty

In the Kyoto market various actors influence, and are impacted by, uncertainty. External participants shape the rules of the market and internal participants act within the market. However in some instances, external participants, especially if they are large, can impose or change the rules after which they themselves will act.

5.4.1 External Market Actors

Governments are involved at the COP/MOP level, but also at the supranational and at the domestic level implementing supportive policies to reach the Kyoto targets. They can directly join or to refrain from the CDM market or link the CDM to domestic policies such as the EU ETS. The duration of the third EU ETS phase has been specified as 2013–2020 even before a post-2012 climate policy regime has been decided. The stringency of the third phase – and CER demand, if imports are allowed – depends on the degree of credibility/enforcement of the 20% energy efficiency improvement and 20% renewables targets for 2020. If companies with installations covered under the EU ETS replace them by renewable energy or reduce fossil electricity production due to a reduction in electricity demand, this leads to a reduction in demand for EUAs and CERs.

A counteracting effect is the learning effect in the production of renewables equipment, which increases as more of this equipment is demanded and installed. Moreover, through economies of scale this can also make technology more accessible to CDM project hosts and thus lead to an increase in the supply of credits.

Host governments of CDM projects can influence the functioning of the carbon market by giving project developers and external investors legal, investment and political security and assuring low or no barriers to technological transfer (Ellis and Kamel 2007). Investors demand lower risk-adjusted returns and are more willing to invest in countries where their investments are protected by legally enforceable contracts and regulations. The political and regulatory stability across electoral cycles of host countries is an important issue for all investments including the CDM. Investors and project developers have to be assured that country specific rules impacting the CDM project are not changed retroactively. Similarly, many CDM projects require technology imports. Host countries, which are at the same time producers or even exporters of the respective technology might be inclined to protect their domestic market. These host countries are in the difficult position to reduce barriers for incoming technology or to give in to domestic interest groups.

Not only on the demand side, governments of large countries can influence the working of the market substantially by their regulatory decisions. For instance, China has set a price floor for CERs.[20] The level of the floor is arbitrary and injects volatility into the market if the decision is not transparent and communicated accordingly. In theory, the effect of a price floor is that if the price floor is below the actual price of CERs, the floor is not binding and is a "safety net" for project developers, which are able to calculate with the price floor as the "worst case" scenario. If the price floor is exactly the price observed in the market, nothing happens. If the price floor is above the market price, supply of CERs exceeds demand, which would, in the absence of the floor, theoretically lead to a price decrease to the equilibrium level. However, the expected effect is that project developers are discouraged from producing CERs for which there is no demand. This is of course only possible if no other CER suppliers can enter the market, i.e., it requires control of a sufficient share of CER demand. Thus, price floors set unilaterally by governments of major CER suppliers are an important incentive signal for project developers and investors.

Non-governmental organizations – both in host and industrialized countries – can oppose CDM projects due to attainment property rights of persons and communities in host countries. The displacement of people, and their income-generating activities

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[20] China is very supportive of its CDM project developers, e.g., by providing a standard electricity grid emissions factor and introducing a maximum consultant fee for PDD development. On the other hand, the Chinese government utilizes China's market power to tax CER revenues, e.g., HFC-23 by 65%, as long as this does not adversely impact China's market position.

by CDM projects is not in line with non-governmental organizations' interpretation of sustainable development. Project developers ignoring the awareness-raising power of non-governmental organizations might face unwelcome surprises, as already seen in the context of CDM projects in the palm oil sector. These projects have difficulties to find buyers for their CERs.

The unpredictability and interaction of decisions taken at the government level of Annex B countries increase the general uncertainty level for the Kyoto mechanisms. Decisions taken at the domestic level but having an impact on the global functioning of the market, should be communicated clearly and in a transparent manner, and carefully implemented as large player can have severe impacts on the market.

5.4.2 Internal Actors

Project developers, as the name suggest, plan and develop projects. They are extremely vulnerable to uncertainty in the market. Many projects have expected crediting life cycles from 7 to 21 years, well exceeding the Kyoto commitment period ending in 2012. Thus, project developers need to assure a stream of CER flows that enables them to finance the respective project. This situation has a harmful effect on the additionality of projects: Since project developers cannot calculate with streams of CER cash-inflows post-2012, or at least can currently not be assured a high enough price of CERs, additional projects are crowded-out by non-additional projects. Even if the EB and its panels are able to sort out non-additional projects, it increases the transaction costs of the system. The shift in preference by project developers to non-additional projects depends on the risk aversion and the possibility to take risk on the balance sheet of project developers (see also Lütken and Michaelowa 2008, for incentives of financiers). Large players have an advantage in comparison to smaller players, as it can be assumed that the former project portfolio is more diversified and exposure is smaller in comparison to the latter, all else equal.

Buyers and sellers naturally have opposite incentives. Buyers want to buy at a low price and sellers are looking to sell at a high price. Sellers, such as project developers in unilateral CDM or other project partners in multilateral CDM, can engage already early during the CDM project cycle in the sales of CERs. By selling CER forwards, sellers can minimize their risk, but receive a lower price for their CERs. Buyers in such a transaction receive a low price but carry specific risks such as delivery, technology and regulatory risk.

As buyers can buy carbon credits for various reasons such as immediate compliance, future compliance, and pressure from institutional and private shareholders,[21] also the exposure of a contract not fulfilled is different in the above cases. It can be assumed that exposure is highest for transactions used for immediate compliance and lower for transactions to please shareholder demands of reputational image of

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[21] The threat of environmental litigation can also be an incentive for firms to engage in purchasing CERs (Streck and Freestone 2005).

one's company. Stock listed companies not complying with a regulation can be punished both by the regulator and the shareholder.

In theory, company buyers under a compliance obligation should compare the price of the compliance tool to the cost of installing alternative cleaner production or energy generating technology. However, faith of the companies in long-term binding climate policy instruments remains limited. Electricity utilities continue to invest in coal-fired plants, which have an estimated life time of 30–40 years. This is well beyond the reach of current global and domestic climate policy. Therefore, it seems that utilities have substantial doubt in the seriousness and credibility of climate policy and continue with investments that do not deviate substantially from business-as-usual practices.[22] A widely touted alternative for coal-fired plants is to implement carbon capture and storage (CCS) for new plants or as a retrofit for old ones. The technology is currently still in the testing phase, however, already now energy providers are lobbying for subsidies to install CCS. Without subsidies, CCS-equipped plants are expected to be more expensive than alternative renewable energy sources. CCS could influence the CDM market if it gets cheap enough to be competitive at the future CER price or if widespread use of CCS in industrialized countries reduces power plant emissions and the CER demand.

A third party, intermediaries and traders, are linking buyers and sellers and help to make the market more efficient since intermediaries are able to gather more information than rational individual participants would do on their own. With this information intermediaries can time and structure the trades of carbon credits according to the market setting, and at the same time hedge themselves against risks in the market place. Traders have various income streams. They gain through arbitrage with the price differential between EUAs and CERs, through a long (short) position in a bullish (bearish) market and through the commission fee. More competition in the market for intermediaries and traders induces higher informational efficiency of the market. Therefore, promoting a stable and healthy intermediary market reduces uncertainty. At the same time experience from securities and corporate markets has shown that market manipulations and accounting scandals can lead to a sudden downturn of the market.[23] A careful regulation of trading, market principles and optimized informational requirements decreases the volatility of the market and the risk of a sudden collapse.

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[22] Energy providers have profited substantially during phase I of the EU ETS by free allocation of allowances by passing through the opportunity cost of allowances to consumers and other businesses. This has amounted by conservative estimates to about € 8–10 billion (Sijm et al. 2006; Cramton and Kerr 2002; Hepburn et al. 2006; Neuhoff et al. 2006). Therefore, for 2013–2020 full auctioning for allowances to energy providers was envisaged before lobbying by East European states led to some exemptions. Auctioning gives a clear and credible signal to energy generators to change their investment behavior.

[23] The 2008 financial crisis was caused by the sub-prime crisis in which mortgage obligations had been restructured multiple times with the help of Special Purpose Vehicles (SPVs). The restructured product carried a better rating than its inherent risk level would suggest. As many CER transactions are structured with the help of SPVs, it is crucial for the credibility of the market to be assured of the quality and real risk of credits.

Validators and verifiers are responsible for the validation of projects and subsequently of monitoring actual emissions from CDM projects. Although the actual work is not requiring much personnel per se, it requires specific engineering and technological expertise and skills. Assuming a growing CDM market, in order to cope with the increasing demands of projects occurring worldwide, validators and verifiers should start to employ more personnel in the long-run. However, they do not do so because they fear that the CDM market might no longer exist after 2012. Here it seems that the market does not signal clearly that the demand of CDM-specialized personnel will grow in the long-term.

5.5 Conclusion and Final Remarks

Climate policies and the related markets suffer from the inherent uncertainty that is generated by political decisions. Market participants and governments did not know for a long time whether the Kyoto Protocol would actually enter into force and currently the continuation of the climate policy regime after 2012 is unclear. Moreover, uncertainty is generated through inconsistent application of rules by the institutions governing the market mechanisms, and random or opaque rule changes. Domestic and supranational regulation by big players such as the European Union can send both adverse and supporting signals to the market. Finally, there is an important uncertainty about the quality of mitigation projects and their actual performance, which influences the willingness of project developers and investors to undertake such investments. All these elements of uncertainty influence the carbon market price through changes in supply of and demand for emission credits.

In contrast to markets that trade a tangible commodity, markets for CERs can be created and destroyed with a stroke of a pen. This leads to extreme short-term orientation, rent seeking behaviour and high volatility in market prices. These negative effects can be reduced if climate policy decisions have a long-term nature with clear consequences of non-compliance. Moreover, the markets should be regulated in a transparent manner. A liquid market with many players and different expectations decreases volatility and thus increases “certainty”; it also generates a lobbying potential that will make it difficult to enact political decisions that negatively impact the market. An independent institution overseeing international climate policy, acting like a central bank could be a solution, yet currently is politically unimaginable.

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Chapter 6
Insuring Climate Change – Managing Political and Economic Uncertainties in Flood Management

Michael Huber

6.1 Introduction

Can climate change be insured? This question concerns experts and insurance managers since insurance was branded a prime tool to flexibly and productively deal with the effects of climate change (e.g., Kunreuther and Linneroth-Bayer 2003). Contrary to supporting advocates, social science and economic literature emphasizes rather the constraints to insuring natural hazards and problematizes the insurability of an ill-defined bundle of climate related hazards in general and the applicability of a formalized risk concept to climate change in particular.

Insuring climate change implies that not climate change as such, but only that the various effects of climate change can be insured by transforming them into a set of insurable risks.[1] However, although it is emphasized that various facets of climate change can be described in terms of risk, risk is a confusing term. Risk has often been operationalized as the product of the probability of the occurrence of an event and its potential damage. Nevertheless, the media claim both that climate change puts penguins and polar bears *at risk* that it causes flood-risks or storm-risks and that firms might risk climate-related law suits. Contrary to such an all-encompassing, but mainly heuristic concept of risks, it is assumed here that the applicability of the formalized risk concept is restricted by climate change being not a single event, but a bundle of partially unknown and unknowable effects that only through considerable efforts, e.g., complex simulation models, can be linked to the actual

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[1] The management of risk through insurance is an essential factor of trading since the fourteenth century (Luhmann 1993: p. 9). Only since the eighteenth century, insurance has been successfully introduced to deal with problems of health, family safety and property protection (Clark 1999). In the nineteenth century the roots of the modern social welfare state expanded the insurance idea to the collective system protecting the weak (Knights and Vurdubakis 1993). Only currently, insurance is perceived as a generic tool to manage individuals and collective risk (Baker and Simon 2002; Huber 2002).

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cause, rising carbon dioxide emissions. Even if comparing IPCC-scenarios over time unveils a steep learning curve, the difficulties remain in attributing accurate probabilities to events and damage costs. The causal relationship of climate change and societal or individual damage is constructed on an experimental basis rather than on practical experience, and can therefore always be challenged.

Apart from the unknowable effects of attributing probabilities, the fact that climate change undeniably causes disruption and damage is also a source of uncertainty as the same disruptive event may be beneficial for some and disadvantageous for others – and so reveals itself as a major source of potentially irresolvable conflicts. For example, while a warmer North Sea could be expected to damage fishery, it might turn out to be beneficiary to agriculture or tourism. It is less the factual accuracy of these examples but rather the implicit logic of cost-attribution that generates uncertainties. Bjorn Lomborg's praised book about the state of the world's environment, *The Sceptical Environmentalist* (Lomborg 2001), was fiercely criticized as it contained factual inaccuracies, but what was more problematic, it failed to recognize that the attribution of current costs and benefits defines a political battleground about future distributions rather than establishing a long-term consensus about how to deal with the effects of climate change. These conflicts are amplified by the impossibility of tracing the effects back to individual decisions and therefore it is equally impossible to hold people, organizations or countries liable for their climate-related decisions. Thus, it is not only difficult to capture events in term of risk, but it is a conflict-riddled process to consensually establish risks.

Another set of problem of insuring climate change may related to the technical constraints of insurability. It is worth noticing that the applicability of insurance to climate change depends not only on the ability to transform events into risks but also on economic, political and sometimes even moral conditions. As far as the economic theory is concerned, insurability is a highly formalized concept related to the 'Law of Great Number', meaning that events are insurable if they occur in great number, are well-defined and each event has a moderate impact; besides, they need to be independent from individual decisions. Natural hazards related to climate change do not have all those characteristics. Although being beyond individual decisions, climate change is a bundle of unknowable and well-known events that are characterized by previously unimaginable damage[2] and by an increasing frequency of occurrence. Although events such as draughts, floods, storms or challenges to the agricultural production are well-known, their more frequent occurrence inhibits rather than permits calculability and hence insurability (compare Beck 1999).

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[2] For example, in the 1990s the maximum impact of natural hazards such as floods, earthquakes or storms were estimated to be below € 680 million (Kunreuther 1997, p. 7). In 1992, already Hurricane Andrew caused insured costs € 10–€13.5 billion. However, it was estimated that had the storm taken another route, costs would have raised up to € 34–€ 55 billion (Klein and Kleindorfer 1999, p. 6). The summer floods of 2007 in the UK cost insurance firms € 5 billon, the 2002 flood in Germany accumulated to insured costs € 10 billion. For all cases it has to be noted that insured costs cover only about half of the caused damage.

Consequently, both the risk concept and the concept of insurability are problematic in the context of managing climate change and it appears that at a conceptual level insuring climate change is impossible. However, practice shows a different picture as many climate related risks are insured. From a sociological perspective this would indicate that climate risks are socially constructed. This 'social construction' would be a fundamentally naïve idea – as social processes are necessarily shaped by social factors –, if it would not be able to identify the *mechanisms* and the *constraints* to the process. Therefore, this paper demonstrates how the concepts of *risk* and *insurability* are interpreted to adapt and balance conceptual features with societal needs and economic interests. Section 6.2 outlines some general considerations about the highly value-loaded field of insurability and the need to negotiate about its local conditions. Section 6.3 reviews some national flood regimes arguing that there are good, but not necessarily economic reasons to insure or not insure floods. It shows rather how secondary criteria are introduced, challenging the fundamental certainty of objective and standardized risk and climate modelling (see also Sect. 6.4). In sum, the paper shows how formalized methods are flexibilised making them applicable to unknown events as well. Although relying on empirical evidence from flood insurance, the concluding discussion suggests that this is a more generic feature of managing climate risks.

6.2 The Insurability of Natural Hazards

In modern societies, expectations about insurability span from confidence that (practically) all events can be insured to the concern that fewer and fewer risks are insurable. Thus, the potential role of insurance is heavily debated. For example, Richard Ericson et al. assumed total insurability due to the universal applicability of risk, only somewhat constrained by economic factors (Ericson et al. 2003; Ericson and Doyle 2004). Contrary to this viewpoint, Ulrich Beck emphasized the weakening of the methodological fundament of risk management due to 'doubt, lack of legitimacy and an eroded scientific rationality' (Beck 1992, p. 102) and he concludes a decline in insurability. In particular, the compensation of *new* risks like climate change is prohibitive to insurance as "it makes no sense to insure against the worst-case ramifications of the global spiral of threat" (Beck 1999, p. 142).

These differences can be explained by conceptual choices but also by expectations about the adaptability of political institutions to new situations. Beck focuses on a standardized risk assessment emphasizing the incapacity to adapt to new situations. Ericson et al. stress the contextual and negotiated conditions of risk management, i.e., economic and political conditions, income distribution, market structures, regulations, predictions about the level of exposure and assessments of a society's vulnerability. As the need for flexibility characterizes insurance decisions more than the fear of insufficient adaptability, the market leader in reinsurance, Swiss Re, outlined its criteria of insurability of floods introducing institutional factors as central argument (SwissRe 1998) (Table 6.1).

Table 6.1

Criteria of insurability of floods by Swiss Re	
Mutuality	A large number of people who are at risk must combine to form a risk community
Need	When the anticipated event occurs, it must place the insured in a situation of financial need
Accessibility	The expected loss burden must be assessable
Randomness	The time at which the insured event occurs must not be unpredictable and the occurrence itself must be independent of the will of the insured
Economic viability	The community organized by the insured persons must be able to cover its future, loss-related financial needs on a planned basis
Similarity of threat	The insured community must be exposed to the same threat and the occurrence of the anticipated event must give rise to the need for funds in the same way for all concerned

Source: SwissRe 1998, p. 7

These six criteria go beyond the formalized concept of insurability. Taking 'economic viability' I can point to the need of a sufficiently large and prosperous insurance-population. Thus, societies must be wealthy before insurance coverage can be provided for rarely occurring events. Consequently, economic viability points to the problem of *adverse selection* as the willingness to invest into coverage for natural hazards is limited even in prosperous but exposed areas. Even more so, if the hazards are considered too remote to take long-term precautions. Only few would purchase coverage under those circumstances (Kunreuther 1978; Palm 1995; NAO 2000). More precisely, if at all, only high-risk persons will purchase insurance, while groups with average exposure to risks or lower will refrain from it. Consequently, the efficient spreading of risks is impeded "with the result that absent countervailing efforts by administrators, insurance pools can be expected to contain a disproportionate percentage of high-risk individuals" (Baker 2003, p. 259). Thus, as the economic conditions do not suffice, other considerations and aspects become more significant trying to contain adverse selection. The solutions, however, may vary a great deal. For example, property owners can be legally forced to purchase flood insurance, attractive programs and campaigns may be designed to attract attention to the problem or insurance coverage may be nationalized. In the next section, these and other solutions are reviewed for flooding. They all indicate the institutional ingenuity of modern societies and illustrate thereby some of the social mechanisms to adapt the problem to society's capabilities (and not the other way round!).

6.3 The Varying Insurability of Floods

Natural hazards are insured in some countries and not in others. More interestingly, sometimes they are insured, although considered uninsurable and some times they are not insured, although considered insurable. In short, we can distinguish four options of the *insurability/insurance* relation mirroring the conformity or incongruence of assessment and practice (see Table 6.2).

Table 6.2

The insurability of insured events – schematic overview

Natural hazards		Insured	
		Yes	**No**
Insurable	**Yes**	Insured (3.1.)	Lost opportunity (3.2.)
	No	Ambiguity (3.3.)	Uninsured (3.2.)

To outline some of the lessons to be learned, let me start with the evident cases and some of the striking institutional differences (see also Faure and Harlief 2006a).

6.3.1 Insurable, Hence Insured

Even if insurable floods are insured, the institutional context of the insurance may vary considerably. For example, the UK established a (largely) *private* insurance regime while in France it is state-centred, public, even if operated by private firms.

In the UK we find one of the few, if not the only working private insurance setting to protect against flooding (more detailled: Huber 2004a). It emerged after the devastating floods of 1953 and was set up, where the state provided comprehensive flood prevention measures, while insurance covered all costs (Crichton 2002, Salthouse 2002). Instead of a contractual agreement, the parties established a Gentlemen's Agreement which codified a division of responsibility between the state, providing flood defences, and the insurance companies, compensating in the case of flooding. The insurance industry gave the "guarantee to government that for residential properties it would not refuse to offer flood insurance for any residential property, no matter what the risk. It further agreed that the additional premium rate would not exceed 0.5% on the sum insured" (Crichton 2002, 127; emphasis added). This seems to be a comprehensive scheme. However, there is space for interpreting what risks are covered. While Crichton claimed that coverage would be fully guaranteed (*no matter what the risk*), pointed John Salthouse to a more restrictive interpretation of insurance coverage. "Insurers and Government agreed in the late 1950s *that only in exceptional circumstances where continual, regular flooding was unavoidable*, would insurers consider withholding cover or apply especially loaded terms to reflect the higher risk" (Salthouse 2002, p. 71, emphasis added). The 'exceptional circumstances' are one category to adapt the insurance scheme to climate change. Another one are the in-build dynamics of the setting. The scheme established a reliable market penetration, thus overcoming adverse selection by linking coverage to mortgage. All lenders have to purchase coverage; hence the market penetration in the UK is estimated to be between 75% and 95%.[3] However, this system works with

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[3] The upper bound marks the penetration in the group of mortgage takers; the lower bound reflects that coverage is only obligatory for bank customers. Hence, a growing group of property owners without mortgage is no longer obliged to purchase flood insurance.

declining success as the increasingly lax behaviour (or *moral hazard*) of insurance firms, the state as well as the insured undermined an efficient flood management. The state tends to withdraw from responsibility as "insurance firms accept the financial responsibility for flood risks. The Government offloads responsibility for flood damage to the insurance industry" (The Economist 17.11.2001, p. 34; also ABI 2000). Hence, flood protection management is systematically underfunded. However, also the house-owners hardly invested into protective measures, as their damage was paid regardless exposure or size. Insurance firms did not react to these challenges – and therefore fostered the lax behaviour of the State and house owners – as long as a certain threshold is not transgressed. Climate change altered the situation, but led to minor adjustments of the regime only (e.g., Huber and Amodu 2006, p. 292 et seq.; Huber 2004b).

In France, flooding is insured as well. However, the institutional setting differs considerably from the UK as the state directly demands insurance coverage of all housing properties. Moreover, the state controls it as insurer-of-last-resort and defines the event, i.e., decides when 'overflow' is turning into a 'flood'. Although the system is run by private firms and appears robust (Cannarsa et al. 2006), it represents a working, but public version of insuring climate risks. Due to its economic and legitimatory robustness provided by the state it was not reformed after climate change gained importance at the political level and in the public debate.

6.3.2 *Not Insured, but Insurable*

Numerous countries do not insure natural hazards. We can distinguish two major reasons for the lack of insurance: prevalently, it is the lack of resources, but sometimes it may be higher morality.

In most countries, natural hazards are not insured as the potential insurance population is financially unable to purchase coverage. Most striking examples are Third World countries where despite the hazards regularly devastating large zones of highly populated areas, insurance is unavailable. Hungary can be mentioned as it is one of the few transitory countries where the traditional state-based flood protection has been substituted by a private insurance scheme – with the effect that most people are not covered against floods (Vari et al. 2003).

The case of banning insurance due to moral reasons is exceptional. However, in the Netherlands the non-availability of flood insurance was explained not by scarcity, but by moral arguments (criticized in Faure and Harlief 2006b). Floods are considered uninsurable and private flood insurance has been legally banned as the impact of floods on the country with about two-thirds of its surface below sea-level is more devastating than in 'normal' countries. Hence, it was considered essential to protect all citizens, irrespective of their economic and social capabilities to help themselves. The Dutch system relies on high standards of social responsibility and solidarity that have their roots in historical experiences. Free-riding and other unintended (and unwanted) effects of a private flood management system are avoided – at high costs. As a consequence, a very elaborate system of flood protection and prevention has been developed.[4]

6.3.3 *Ambiguity: Insured, yet Uninsurable*

In the USA floods are considered uninsurable. In difference to European countries, the USA has ample historical experience with the private insurance of natural hazards that ended with the insolvency of insurance firms (Meier 1988, p. 51 et seq.). Reacting to these failures, the state strictly regulated insurance industry and established a federal flood insurance scheme that tightly coupled prevention and compensation. Although insurance is an adaptive strategy, prevention plays the central role in the US-case: The flood insurance scheme provides coverage for individual assets only if communities beforehand accepted to participate in a flood prevention scheme. Prevention takes the leading function in flood protection. Kenneth J. Meier noted: "The National Flood Insurance Program became as much a land-use regulatory program as it was an insurance program" (Meier 1988, p. 117). Moreover, the state acts as insurer-of-last-resort. Here the problem of adverse selection is dealt with by regulatory openness and – differently to the UK and France – by a scheme conditional on minimal regulatory standards.

6.3.4 *Discussion*

Sketching the basic features of these insurance regimes, I drew attention to a range of institutional interpretations of insurability. They seem each to prioritize one of the pressing insurance problems, either adverse selection or moral hazard or either public or private solutions. The 'costs' are evident: While it can be expected that in the USA highly exposed areas and properties will fail to be covered, in the Netherlands people who do not live on flood plains pay for futile coverage. Now, both of these extreme solutions are state-run public insurance regimes. The (predominantly) private insurance regimes are also faced with the problem how to balance the demands of a maximal insurance population and of economic justice. The English example however indicated that reduced moral hazard implies a declining insurance density and a broadening of the insurance population. It triggers lax behaviour. There is another important factor of the institutional variations, namely the degree of state-dependency, ranging from state control as in France or the USA to the most privately oriented insurance scheme in the UK or Hungary. It allows

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[4] Recently, this decision has been overruled by the European Union's decision to allow for market competition in the field of financial services, hence also insurance (Faure and Harlief 2006b).

distinguishing regimes along the question who pays the price; either the public through e.g., taxes or private property owners that are never exposed to floods.

The brief sketch indicates that and how these factors shape insurability more than economic decisions and it suggests that the answer to the initial question if climate change can be insured, depends on the political, moral and historical conditions and, on the institutional setting. When Beck believed the institutional adaptability to be negligible, this outline suggested the reverse view that institutions are flexible enough to manage even uninsurable risks. Thus, the position of Richard Ericson et al. seems to have greater explanatory force and to go one step further (Ericson et al. 2003), I suggest that use of predictive tools such as risk further flexibilizes the management of natural hazards and improves the adaptation of climate related events to societal needs in the context of insurance; other tools may have similar effects on the risk management.

6.4 Risk

When hazards are cast as risks, insurances can better price unwanted effects and thus send a clear message to organizations and individuals about the ranking of risks and the predictability of the future. Risk is the key concept of insurance and normally conceptualized as a standardized decision tool that multiplies the probability of the occurrence of event *e* with the damage inflicted

$$\mathrm{R}\ (\mathrm{e}) = \mathrm{P}\ (\mathrm{e}) \times \mathrm{D}\ (\mathrm{e})$$

(Gratt 1987). In practice however, this formal simplicity cannot be sustained. For example, Paul Sayers et al. explicate a basic indifference of the risk formula to distinct events when they comment their formal definition of risk: “Intuitively it may be assumed that risks with the same numerical value have equal ‘significance’ but this is often not the case. [. . .] Low probability/high consequence events are treated very differently to high probability/low consequence events” (Sayers et al. 2002, p. 12).[5] Risk records cannot manage these differences and therefore need risk managers additional criteria to distinguish ‘relevant’ from ‘less relevant risks’.

One example of this selection process can be found in the Australian standards for risk management. Among other things, these standards request a general orientation of risk management to a “single organization, working within an environment where risks are often industry- and even location-specific” (Jones et al. 2001, p. 295). This view seems too restrictive as the practical guidelines emphasize the need to “recognize that multi-organizational nature of emergency

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[5] Low probability/high impact risks are mainly dealt with by politics (or not at all), while high probability/modest impact events are interpreted as a task for insurance.

management and the diverse and external to the organization nature of the risks, which must be addressed" (Jones et al. 2001, p. 295). We learn that what is developed of bureaucratic necessity at one level may be softened and flexibilized at a second, more practical level. This two-level-approach allows for containing practical difficulties and to cope with the less accurate predictions and less reliable assessments provided from first level assessment. To proceed more systematically, we follow insurance firms when they managing climate change have to cope with the three elements of risk: the event, the probability of its occurrence and its expected damage.

When actors refer in the context of insurance to flood, it is assumed that the event is well-defined. However, clarity is difficult to obtain. Historically, floods were perceived as divine punishment. In Noah and the Ark, God flooded the entire globe as punishment for wickedness. Modern science neutralized this divine model and conceived flood as natural events without immediate significance, intent, meaning or plan. Floods are now considered to be caused by natural cycles of rainfall patterns, tides or other random events. The scientific narrative decoupled floods from intentional interventions. The common ground of all flood definitions is best illustrated by the Concise Oxford Dictionary's explanation of flood as "an over-flowing or influx of water beyond the normal confines esp. over land". In other words, flood means 'too much water'. However, such a definition lacks usability in a political or economic context. For insurance purposes, floods are significant events only when they can be linked to unintended and measurable, negative, effects. Even if the yearly flood of the Nile is a flood in the ordinary understanding, it is not for insurance purposes, because its effects are generally benign and their occurrence can be predicted quite precisely. For insurance purposes relevant floods are damaging, unwanted with an uncertain, irregular frequency. To manage flood risks, how does insurance transforms the natural event of 'too much water' into a man-made disaster? The definition of flood risks is qualified through institutional constraints, legal obligations and liabilities, references to political frameworks and to indicators of societal vulnerability. Thus, our understanding of floods depends largely on what happens after the event. For instance, in the legal context, floods are defined by three compensation indicators: size of damage, number of cases and frequency. Those indicators are interpreted quite distinctly. For example, the Belgium government defined a flood as causing at least € 1.200.000 of damage which implies that the average amount per family must be at least € 5.200 and by the affirmation that a similar disaster will occur only every 20 years (Durand 2006). In the USA a flood is defined as water damage to two or more neighbouring properties. Compared to the British definition where floods ought to happen only once every 75 years (Crichton 2007) or to the Netherlands where flood protection allows for such events to occur only once every 200 years, the Belgian flood frequency sets a low standard for flood protection and a low threshold for compensation (overview in Faure and Harlief 2006a). However, not only can an event be shaped according to managerial needs, but also the concept of risk itself is up for practical adaptations.

These additional risk-criteria vary over time and across space. As flooding triggers emergency aid, compensation payments and liability claims, it has not only to be defined unequivocally but also in such a way that organizations and institutions are able to decide whether they should intervene or not. For example, the US Federal Emergency Management Agency (FEMA) specified ‘floods’ as the worst controllable accident that needs to be avoided: “A dam failure is usually the result of neglect, poor design, or structural damage caused by a major event such as an earthquake. When a dam fails, a gigantic quantity of water is suddenly let loose downstream, destroying anything in its path” (FEMA 2009). ‘Too much water’ is connected with a technical breakdown and floods can therefore be blamed on maintenance or regulations and compensation issues end up in court or in the political arena as they have an address for claims. However, the main risk is not flooding anymore, but the failure to prepare against its trigger, dam failure. Similarly, the UK Environment Agency defined flooding as “inundation by river or sea water whether *caused by inadequate or slow drainage or by breaches or overtopping of banks and defences*” (EA 1997; emphasis added). The insufficient protective measures burden regulatory actors with the responsibility of managing flood, not as a natural hazard but as a socio-technical event. Controlling protective measures such as dams or land-use, the required robustness of assets become the focus of flood-risk management.

If it is not private firms, as in the British example, but public actors that predominantly manage flood risks, they may follow a similar strategy, but develop a different set of criteria. For example, in a summary report of a Franco-German action-plan for flood protection from the mid-1990s (Action Plan 2002), floods were linked to the growing urbanization, settlements on flood plains and interferences with the watercourse and water balance. Hence, flood was qualified by the vulnerability of social systems and by protective measures rather than by the exposure of individual assets.

But veiled modifications of the very concept of risk may increase flexibility as well. In a publication of the Association of British Insurers (Crichton 1999), the traditional risk notion is substituted by a *risk triangle* linking *hazard*, a combination of the frequency and severity of an event, with *vulnerability*, indicating the extent to which an asset is affected by the hazard, and *exposure* as measure of the extent to which a singular asset is exposed to hazard. These two supplementary notions of vulnerability and exposure transform floods into a risk of insurable property. However, they do so only in an institutional setting dominated by private insurers. The Franco-German report mentioned above did not define flood-risk in terms of individual assets but rather as a collective problem within a geographically limited, political constituency. Instead of referring to vulnerable individual assets, now the threat is specified by *ecological functionality* of a region and *original land-use* when policy makers aimed at setting acceptable risk levels applicable to all residents in a certain area. The practical use of the risk concept unveils the secondary level of additional criteria and factors that are accounted for. Again, these criteria seem to vary with the institutional setting. Risk is therefore not a universal assessment tool but heavily dependent on the institutional constraints, reinforcing the institutional variations of insurance regimes.

6.5 Analysis and Concluding Remarks

Discussing the interpretative liberties build into the practical use of insurability and risk indicated mechanisms of the social construction of climate related hazards. The main points concern, first, the dependency of how to cope with climate change on institutional settings and, second, the use of secondary criteria for the adaptation of general concepts; institutions influence the criteria. These elements help to explain the differences in the practical approaches to climate change management and highlight the need to go beyond the surface of methods and concepts applied.

Applying the experiences from flooding, we can hypothesize that the choice of managerial strategies to curb the effects of global warming will define the political weight of events, of who ought to be protected and within what time horizon the problem may be conceived as hazardous. For example, choosing private insurance implies that disastrous effects on property are ranked higher on the political agenda than for example losses in biodiversity or economic consequences for poorer groups in society. Contrary to this privatization of climate change, public policies transform global warming into a collective good-problem. Specifically when state and insurance firms cooperate (e.g., in form of Public Private Partnerships (PPPs)) this generates not only different weights and ambiguous rankings, but also the need to equilibrate those differences. Risk becomes not only a regulatory, but also (or even mainly) a communicative risk. Due to the variations of definitions sketched above, we hardly know what we mean when we talk about flood except for ‘too much water’. The flood example taught us how the institutional path dependency chosen at an early stage shapes the political and managerial manoeuvrability of risk management for a long period. Against the general impression that risk unifies and from a critical perspective ‘normalizes’ the management of a certain group of events as it provides a common managerial language, my brief analysis shows that it rather veils the managerial intent and sets an opaque path dependency that once established is difficult to disclose and challenge. Thus responding to climate change in terms of insurance and risk may add to confusion and uncertainties rather that contribute to feasible solutions.

Insurance is a tool that fosters adaptive strategies while climate change requires rather preventative policies. From the brief overview of the variability of insurance regimes we can draw two lessons: First, the ingenuity of institutional settings is able to adapt to threats that have been considered unmanageable. While Beck took a conservative position emphasizing the inertia of societal institutions, practical experience indicates diverse loopholes overcoming the constraints of insurability. Second and tightly connected to the first point, the fundamental problem can be captured by the juxtaposition of adverse selection and moral hazard. The essential problem of managing climate related risks by insurance is to decide *at a political level* what type of failure is preferable. If the inclusion of all citizens under the flood management umbrella is the ultimate goal, costs are distributed equally among the exposed and the not-exposed property owners. This unfairness can be resolved by excluding areas or specific groups of society that are either overexposed or unable to purchase coverage. In both cases, the problem is not resolved by just shifted to other instances; unwanted social costs emerge in any case.

The need of insurance to cope with some aspects of changing environmental conditions can be confirmed. However, there are some evident restrictions to the problem. First, the privatization of climatic effects seems an unviable strategy, due to the size of problems and due to the distributive effects. Second, the ability of societies and their institutional settings to adapt to new situations should not be underestimated. However, they ought not to be overestimated either. The economic constraints are often tightly interrelated with cultural values and ideas, political concepts of justice and sustainability that favour certain solutions. Third, these preferred solutions are mirrored in the predictive tools applied. Apart from the problem of emphasizing specific features that depend on institutional settings, this variation turns into a communicative risk. The need to coordinate interventions at a European or international level is threatened by the same language and the different meanings. As the English and the American people are divided by the same language, the language of risk and insurance is not a safe common ground, but may be an additional challenge to the successful management of climate change.

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Chapter 7
Climate Science, Weather and Climate Engineering, and Scientific Objectivity

William R. Cotton

7.1 Introduction

My main research areas are in modeling and observation of clouds and storms and how aerosols can influence clouds and storms, and as a result climate. I have recently co-authored two books and a chapter in another book that are relevant to the topic of this chapter. They are "*Human Impacts on Weather and Climate*, 2nd Edition" (Cotton and Pielke 2007), "*Aerosol Pollution Impacts on Precipitation: A Scientific Review*" (Levin and Cotton 2008), and "*Perturbed Clouds in the Climate System*" (Cotton 2009). When writing chapters in these books it became quite apparent to me all scientists walk a tightrope between being objective scientists and being advocates of their particular disciplines. For some if not most, they try hard to remain objective in their presentations and evaluations of their scientific studies. As our science has become more politically relevant, it is becoming increasingly difficult for many scientists to remain objective. The theme of this chapter is "scientific objectivity" and how it has become more difficult for scientists working in areas like climate change and weather and climate engineering to remain objective.

I begin by discussing weather modification science as one example where maintaining scientific objectivity has been a challenge. I then move to global climate change. I then discuss climate engineering which will surely become a topic that will challenge scientific objectivity. I conclude with further comments on science versus politics.

7.2 The Science of Weather Modification

The modern science of weather modification began with Vincent J. Schaefer's discovery that introducing dry ice into a cold chamber filled with supercooled cloud droplets could lead to the complete conversion of the cloud into ice crystals

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(Schaefer 1948). Subsequently Schaefer and colleagues under the direction of Nobel Laureate Irving Langmuir carried out a series of exploratory seeding experiments in Project Cirrus in supercooled stratus, convective clouds in the southwest U.S., and even a hurricane. Langmuir and his team were convinced that seeding supercooled clouds would clear stratus and fog, increase precipitation from cumulus clouds, and mitigate hurricanes. Cloud seeding captured the attention of the public and news media. As a child I even remember cartoons of Donald Duck seeding clouds! Major funding for research in weather modification followed those exploratory studies in the U.S. and other countries. Moreover, an operational cloud seeding industry developed worldwide.

Commercial cloud seeders and many scientists were convinced that seeding clouds led to desirable results like increased precipitation. Following seeding some cumulus clouds were observed to undergo explosive growth which the investigators were convinced were due to seeding. The more skeptical scientists demanded that well designed statistical studies of cloud seeding effects be carried out. For a period of over 30 years randomized statistical cloud seeding experiments were carried out around the world. Some of these were accompanied by physical measurements in the clouds that were intended to show that the expected responses in cloud microstructure actually took place. But by the 1980s few of these studies confirmed the basic cloud seeding hypotheses. One exception was seeding orographic clouds to increase snowpack where significant increases in precipitation were observed. However, there is still debate about the amount of precipitation increases that can be expected. There are also some promising results of field studies in which supercooled deep convective clouds were seeded with hygroscopic materials. But those studies are not designed to show how precipitation is altered over a fixed area on the ground, but instead for individual storms tracked by radar (see review in Cotton and Pielke 2007).

It is perhaps relevant for this essay to note that scientific funding for weather modification research in the U.S. fell to such a low level and became so fragmented by the end of the 1980s that no Federal agency kept track of it. The causes of the crash in weather modification funding are many and have been discussed in some detail by William R. Cotton and Roger A. Pielke, but one thing that stands out is that weather modification was oversold to the public and to funding agencies. Once it became clear that increased rainfall, reductions in hail damage, and reduced intensity of tropical cyclones by cloud seeding cannot be relied on for some time to come, the funding agencies became quite disillusioned. That is weather modification lost its credibility with much of the public and funding agencies. Note that this did not stop operational cloud seeding programs in the U.S. or throughout the world. While there is no Federal funding for operational cloud seeding in the U.S., state, local water boards, farm organizations, etc. are spending considerable resources to support operational programs. It clearly shows that curtailing research does not inhibit operational programs; they just go forward without the guidance from sound scientific investigations.

Overall the history of scientific research into weather modification has provided a number of lessons that are relevant to understanding human impacts on global climate and to climate engineering studies. Because of the challenge of attributing observed changes in clouds such as precipitation to cloud seeding, the scientific community has established a set of criteria for determining that there is 'proof' that seeding has enhanced precipitation. For firm 'proof' (see NRC 2003; Garstang et al. 2005) that seeding affects precipitation, both strong physical evidence of appropriate modifications to cloud structures and highly significant statistical evidence is required. The same can be said for attributing observed changes in climate to human induced enhancements in CO_2 or that a hypothesized method for engineering climate works. Use of models by themselves do not constitute proof as they only provide some physical evidence of causality. Observations of physical effects and highly significant statistical evidence are required as well.

Another lesson from evaluating cloud seeding experiments is that 'natural variability' of clouds and precipitation can be quite large and thus can inhibit conclusive evaluation of even the best designed statistical experiments. The same can be said for evaluating the effects of climate engineering or that human-produced CO_2 is altering climate. If the signal is not strong, then to evaluate if human activity has produced some observed effect (cause and effect), one requires much longer time records than are available for most if not all data sets. For climate variability we have to resort to 'proxy' data sets which results in uncertainties in calibrations, inconsistencies between older data estimates and more recent measurements, large noise in the data, and inadequate coverage of sampling of the selected control variables. Thus we do not have an adequate measure of the 'natural variability' of climate.

The National Research Council of the National Academy of Sciences (NRC) has placed a rather high bar in defining what constitutes 'proof' that cloud seeding has a desired effect; it is so high in fact that virtually no cloud seeding hypothesis has come close to meet the proof requirements (NRC 2003). As noted above, the absence of strong proof that cloud seeding works has not hindered the implementation or continuation of operational cloud seeding projects.

7.3 Climate Variability

While the subject of weather modification may be controversial and even today newsworthy it is nothing compared to that of climate change. Climate change is at the forefront of political campaigns and debates, and has become almost a religion amongst the lay community if not the scientific community. To read reports like IPCC (2007) or even many scientific papers, climate change is thought of only in terms of greenhouse gas emissions. Yet, as reviewed by William R. Cotton and Roger A. Pielke the climate can change as a result of a number of factors, some of which are not fully quantifiable or predictable (Cotton and Pielke 2007). They are:

- Changes in concentrations of greenhouse gases.
- Changes in solar luminosity and orbital parameters.
- Changes in surface properties.

- Natural and human-induced changes in aerosols and dust.
- Differential temporal responses to external forcing by the atmosphere and oceans.

There is considerable evidence that the planet earth is warming. Furthermore, the concentrations of CO_2 are also increasing at alarming rates. The question is are these cause-and-effect or is the planet warming for other reasons? Or is the rise in CO_2 levels due purely to human contributions or are CO_2 concentrations responding to changes in climate for other reasons? The so-called 'Hockey stick' paper of Michael E. Mann et al. provides the strongest evidence that the current period of global warming is unprecedented over the last 1,000 years or so (Mann et al. 1998). Their analysis is based on proxy data including ice cores, tree rings, marine sediments, and historical sources from Europe and Asia. These data are therefore evidence for warming in the northern hemisphere as southern hemisphere proxy and historical data are very sparse. But this paper has been criticized by a number of scientists (McIntyre and McKintrick 2003; von Storch et al. 2006; Soon et al. 2003) as having major problems in the statistical treatment of the data and the proper use of proxy data. In 2006, NRC reported on an independent evaluation of the Mann et al. conclusion and on the use of proxy data (NCR 2006). They concluded that the last few decades of the twentieth century were warmer than any period in the last 400 years. They stated that the Mann et al. conclusion that it was warmer than any period in the last 1,000 years is 'plausible' but that they had less confidence that the warming was unprecedented for periods prior to 1,600 owing to fewer proxies at fewer locations are available prior to 1,600. They noted that none of the reconstructions indicated that it was warmer during the Medieval Climate Optimum than during the end of the twentieth century. That there were regions of the northern hemisphere that were warmer during the Medieval Climate Optimum can be seen from reconstructions of surface temperatures for the Sargasso Sea (Robinson et al. 2007) as well as tree-ring analysis for central Asia (Esper et al. 2002). These data suggest that the warming period that we are experiencing has been going on for over 300 years; since the end of the Little Ice Age, and that the Medieval Climate Optimum period 1,000 years ago was much warmer over much of the Northern Hemisphere. There is also circumstantial evidence that the climate in Greenland, for example, was much warmer than now during the Medieval Climate Optimum period as the glaciers were much reduced in coverage and the seas around Greenland were more open to navigation as indicated by Norse sagas. Considering the scarcity of data I find it difficult to conclude that we know enough about the 'natural variability' of climate over the last 1,000 years to say that this recent period of warming is unprecedented.

CO_2 is clearly a major absorber of longwave radiation and therefore contributes to so-called greenhouse gases. But keep in mind that it is not "the" major greenhouse gas as water vapor has that distinction. Thus much of the greenhouse warming in models is due to feedbacks that involve higher concentrations of water vapor in the atmosphere which then contributes to most of the greenhouse warming. Clouds are very important absorbers of longwave radiation as well as the albedo of planet earth. Low clouds tend to enhance the earth's albedo (a cooling effect) while having little influence on the longwave radiation budget because their temperatures are close to that of the earth's surface. On the other hand, high clouds tend to absorb more longwave radiation while, except for optically-thick tropical anvil-cirrus clouds, reflect small amounts of shortwave radiation, and therefore serve as greenhouse warmers. Because models depend on rather crude parameterizations of clouds it is still uncertain how clouds respond to a warming planet and to enhanced water vapor content of the atmosphere. The question is, are there more high clouds versus low clouds in a warming planet and how does the cloud variability vary with latitude? Increased cloud cover at high levels of the atmosphere generally contributes to warming the planet whereas increased low-level cloud cover contributes to cooling the planet. Likewise, increased cloud cover at high latitudes contributes to a warming trend in the Arctic and Antarctic since the annually-averaged surface energy budget at high latitudes is dominated by longwave radiation.

While greenhouse gases, especially water vapor, are a major contributor to the habitability of planet earth, is the variability of these gases the dominate contributor to climate change?

Changes in earth orbital parameters, the so-called Milankovitch cycle (Imbrie and Imbrie 1979; Berger 1982) is believed to be responsible for the onset of ice ages. But, it cannot explain the current warming trend as it predicts we will be moving into an ice age in the next 5,000 years. While there is evidence of a small variation in the sun's irradiance, the amount of variability is too small to account for recent or even climate variations over the last 1,000 years. While there have been many studies which suggest statistical correlations between varying solar parameters and earth's climate (i.e., Svensmark and Friis-Christensen 1997), the physical causes of those correlations are for the most part not well founded (Sun and Bradley 2002). Nonetheless, this does not mean that some unknown amplification process related to solar parameters could be contributing to the current warming trend. It remains as part of the uncertainty in climate science and climate prediction.

Variations in land-surface properties affect the planetary albedo and alter the surface energy budget such that surface fluxes of sensible and latent heat can be changed. Human activity contributes to changes in surface properties largely through agricultural land-use and urbanization. Moreover, changes in land-use and vegetation respond to climate changes in a nonlinear way thus altering both the planetary albedo and the surface energy budget. While changes in land-surface properties are a significant contributor to the planetary energy budget, they probably do not rank as high as greenhouse warming (IPCC 2007). Nonetheless, IPCCs estimates are based on changes in albedo only and do not include changes in sensible and latent heat fluxes which should make changes in global climate by land-use changes larger than estimated by IPCC.

Cotton and Pielke devoted an entire chapter to human induced changes in aerosols (Cotton and Pielke 2007). The chapter considers both the direct and semi-direct effects of aerosols and dust as well as indirect effects that alter the earth's albedo and hydrologic budget through alterations in cloud properties. Large uncertainties exist in estimating the consequences of aerosols on climate largely because of the fact that a major contributor is related to cloud processes which are poorly represented in GCMs. Nonetheless it is generally believed that human-induced changes in aerosols contribute to a net cooling in the climate system which offsets greenhouse warming by roughly one-third that of greenhouse gas warming (IPCC 2007) or to what is sometimes referred to as 'global dimming'. Some GCM simulations of greenhouse warming and direct and indirect aerosol effects (Liepert et al. 2004) show that the indirect and direct cooling effects of aerosols reduce surface latent and sensible heat transfer and, as a consequence, act to dry the atmosphere and thereby substantially weaken greenhouse gas warming. Since greenhouse warming causes a moistening of the atmosphere, and aerosol direct and indirect cooling counteracts that, the potential influence of aerosols on global climate could be far more significant than previously thought.

A major "wild card" in the climate system is naturally-produced aerosols and specifically aerosols in the lower stratosphere induced by volcanic activity. I had thought until recently that volcanic activity was purely random. A series of papers by Reid Bryson and colleagues (Bryson and Goodman 1980a, b; Bryson 1982, 1989; Goodman 1984) suggests otherwise. These papers suggest that volcanic activity is modulated by the sun-moon-earth tidal variations. Under this scenario, periods of global warming such as we are now experiencing can be attributed to periods of very low volcanic activity like between 1920 and 1940 (Robock 1979) and the Medieval Climate Optimum period. On the other hand, periods of extensive cooling like the Little Ice Age, were periods of maximum alignment of the sun-moon-earth tidal forcing which contributed to very active episodes of volcanic activity and global cooling. The consequence of this is that forecasts or projections of global greenhouse gas warming are at the mercy of climate variability due to volcanic activity. Periods of greater than normal volcanic activity could completely override or mask the forcing by greenhouse gases. Is it possible that the current warming period is due to a period of below normal volcanic activity?

Finally the atmosphere and ocean have very different time scales of response to external forcing, with the atmospheric time scale being of the order of months and the ocean mixed layer being the order of 10 years and the deep ocean being 100 years. Thus the current climate is being influenced by changes in external forcing that occurred as long as 100 years ago. This mismatch between ocean and atmosphere response to external forcing is a major contributor to 'natural variability' of the climate system. Even well known shorter term phenomena like El Nino Southern Oscillation (ENSO) has substantial influence on climate variability yet that is not simulated well by current generation general circulation models.

As a scientist I feel compelled to critique and question whether our climate is changing principally as a result of increases in greenhouse gas emissions. There should continue scientific debates on climate variability and not blindly accept that our climate is warming by greenhouse gas emissions and will continue to do so for the foreseeable future. That is what science is all about. It is not about "belief" or "consensus". As scientists we must seek to "prove" that greenhouse gases are the dominant contributor to climate variability. As established by NRC and discussed by Michael Garstang et al. for cloud seeding, we should also require that both strong physical evidence and highly significant statistical evidence be required as a basis of ‘proof’ that greenhouse gases are the dominant contributor to climate variability (NRC 2003; Garstang et al. 2005).

7.4 Climate Engineering and Politics

I recently prepared a chapter in the book “*Clouds in the Perturbed Climate System: Their Relationship to Energy Balance*” on “Weather and Climate Engineering” (Cotton 2009). In that chapter I focused on hypotheses for engineering changes in the earth’s albedo or longwave radiation rather than get into policies for reducing carbon emissions, sequestration of carbon and so forth. The main topics I considered are:

- Seeding with sulfate aerosols into the stratosphere.
- Seeding with soot particles in the lower stratosphere.
- Introducing small manufactured mirrors in space.
- Introduce a solar shield at the Sun-Earth Lagrange.
- Hygroscopic seeding of marine stratocumulus clouds to enhance their albedo.
- Selective seeding of Mid-level stratus clouds to increase their albedo during the daytime and at low latitudes and increase outgoing longwave radiation at night time and at high latitudes.
- Wide-area seeding of cirrus clouds with soot or carbonaceous aerosols to desiccate clouds and increase outgoing longwave radiation.

Few of these hypotheses have undergone advanced development and testing with climate models or evaluated with well-designed physical experiments. I also discussed possible adverse consequences of employing such procedures. In fact I referenced Alan Robock’s (Robock, 2008) recent paper titled “Twenty Reasons Why Geoengineering May be a Bad Idea”. In that paper he noted that one possible response to climate engineering to mitigate greenhouse gas warming is that precipitation is likely to be modified both globally and regionally. Some countries may find themselves in a drought in response to climate engineering. Many of the cloud-related climate engineering hypotheses are likely to impact the hydrological cycle, especially those hypotheses associated with modification of middle and high-level clouds. Other reasons listed by Alan Robock were (Robock 2008):

- Continued ocean acidification.
- Ozone depletion.
- Effects on the biosphere.
- Enhanced acid precipitation.
- Effects on cirrus clouds (reference to S seeding in the stratosphere).
- Whitening of the sky (reference to S seeding in the stratosphere).

- Less solar radiation for solar power, especially for those requiring direct solar radiation.
- Rapid warming when it stops.
- How rapidly could effects be stopped?
- Environmental impacts of aerosol injection.
- Human error.
- Unexpected consequences.
- Schemes perceived to work will lessen the incentive to mitigate greenhouse gas emissions.
- Use of the technology for military purposes.
- Commercial control of technology.
- Violates current treaty.
- Would be tremendously expensive.
- Even if it works, whose hand will be on the thermostat? How could the world agree on the optimum climate?
- Who has the moral right to advertently modify the global climate?

Despite those concerns, I recommended that major initiatives in climate engineering design using the most advanced models be implemented throughout the world. Before implementation of climate engineering can be done fundamental research is needed to advance our quantitative understanding of the climate system, of climate variability, the scientific possibilities of climate engineering, technical requirements, social impacts, and political structures needed for its implementation. I suggested that climate engineering should be considered a ‘last gasp’ measure to prevent catastrophic consequences of a changing climate. One of my motivations for suggesting that climate engineering research be pursued is a result of my cynicism with political decision making. As I noted with weather modification, curtailment of research in weather modification did not curtail operational weather modification. This is in spite of the lack of strong scientific evidence that cloud seeding works. I refer to this as the use of political placebos. I anticipate that if we find ourselves in a true climate crisis, that politicians will call for climate engineering measures that will alter the adverse climate trends. This will be mainly motivated to show that something is being done. If we do not proceed with climate engineering research, this could be done without the most advanced level of knowledge of the climate system and the full consequences of our actions.

7.5 The Science vs. Politics Conflict

As science becomes more and more linked to politics I am concerned that objectivity in science is being compromised. Scientific objectivity is not something that can be quantified. As people, all scientists have a certain amount of baggage associated with our social upbringing, political, and religious backgrounds that must be overcome as objective scientists. It takes an effort as a scientist to throw off that baggage and make decisions and evaluations that are solely based on the quantifiable facts and not what is seen as best, for example, for society.

Consider when I was a new Ph.D. graduate working in a NOAA laboratory in Florida. The purpose of the laboratory was to evaluate the hypothesis that "dynamic seeding" of convective clouds could enhance rainfall (Cotton and Pielke 2007). At the time south Florida was experienced a pronounced drought. During a program review, the program manager from Boulder, Colorado argued that we should volunteer to seed clouds over the peninsula to alleviate the drought consequences. I spoke up that we were a long way from proving that our methods work. I still can picture the program manager waving his finger inches from my nose saying we can't wait until the method has been scientifically proven and must take action now! Shortly after a group of us scientists in the laboratory got together to discuss how we should respond to such a request. I argued that because we were supposed to be objectively evaluating the hypothesis, our credibility as objective scientists would be compromised if we went out to seed clouds for the explicit purpose of minimizing the impacts of the drought. Shouldn't we follow a similar line of reasoning when advocating political actions with regard to climate change?

Personally I am quite liberal and green-minded. I bike 6.5 miles each way to work, I drive a Toyota Prius, I paddle kayaks and sail boats, and I fly a sailplane. Yet in spite of this baggage, I try to objectively evaluate the science of climate change and/or weather modification on its quantifiable merits. As a result I am considered a skeptic. In today's political climate it is like being labeled a religious heretic! My scientific credibility has been called into question on some blog sites, and I am thought to be in support of the conservative Bush administration policies (I am not). More importantly, I feel that an important component of the scientific method, namely debate of the fundamental scientific issues, is being squelched.

Perhaps the scientific method is not as objective as we scientists like to think. I am reminded of a quote in Cotton and Pielke in which we noted that the scientific community has accepted the results obtained in studies such as METROMEX (study of urban impacts on precipitation) as being valid, yet question the validity of cloud seeding-induced changes in rainfall inferred from well-designed, randomized cloud seeding experiments (Cotton and Pielke 2007).

We noted that the answer to this paradox lies in human psychology. As an example, Dr. Stan Changnon described a conversation he had with Dr. John Tukey, one of the world's leading statisticians, following a meeting of the Weather Modification Advisory Board about 10 years ago. Stan asked John why the statisticians had been very critical of attempts to prove planned weather modification of clouds and rainfall was successful, yet were not so critical of inadvertent weather modification (i.e., the cities are not randomized). John looked up at Stan and said, "Well, Stan, in the end it is just a lot more believable that a big city can cause clouds, rain, and hail than it is that a small amount of seeding material can". In other words, no matter how objective we attempt to be, a certain amount of subjectivity is involved in accepting the results of any scientific study. We can see that it is easy to "believe" that human activity on the global scale is altering global climate. But as scientists we seek reproducible scientific results, and require that there is both strong physical evidence that humans are altering climate (this includes the use of verifiable models) and there is highly significant statistical evidence that the climate is varying beyond the bounds of natural variability.

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Chapter 8
Utilizing Participatory Scenario-Based Approaches to Design Proactive Responses to Climate Change in the Face of Uncertainties

Livia Bizikova, Sarah Burch, John Robinson, Alison Shaw, and Stephen Sheppard

8.1 Introduction

Despite the recent upsurge in research, the complex and inter-related processes driving climate change continue to be characterized by significant uncertainty. One of the major issues for policy-makers is how to deal with this considerable uncertainty in ways that enable pro-active measures rather than complicate or discourage them. A great unknown is the extent to which human actions may alter the climate system over decades and centuries to come. In this case, widely varying assumptions alter the set, rate and extent of projected impacts (Kasemir et al. 2003; Banuri and Weyant 2001; Oppenheimer et al. 2008). The assessment of changes in components of the climatic system, including the prediction of impacts of GHG concentration on changes in climatic variables, radiative forcing, climate response, and impact sensitivity, remain highly uncertain as well (Dessai and Hulme 2004; University of Washington 2007). In light of such uncertainties, current attempts to better understand the implications of changing climate are based on assessing the outlook for future emissions (and emission reductions) of GHGs and aerosols, the resulting changes in climatic variables and their impacts on ecosystems and society, and

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finally the extent and effectiveness of adaptation actions to ameliorate impacts (O'Neil and Melnikov 2008).

A traditional view of uncertainty, which has been embodied in much climate change research and commentary, holds that a lack of understanding of human responses to climate change can best be addressed by more and better analysis. In other words, more research leads to better understanding, and thus better ability to predict. An alternative view, however, has been brought to the climate change arena, which argues that, because of the existence of intentionality, the actions of human systems are exceedingly complex and inherently impossible to predict (Rayner and Malone 1988; Jasanoff and Wynne 1998). Accounting for the human dimensions of change therefore requires specific attention to human choice and indicates that certain heuristics, such as likelihood of impacts, may not be a useful concept. If socio-economic pathways are inherently incommensurable and we are unable to attach probabilities to scenarios depicting socioeconomic, political, and cultural systems (Nakicenovic and Swart 2000), then it follows that an additional, possibly greater, form of uncertainty exists in all climate change scenarios. Such arguments give rise to approaches to studying the future of human systems based upon various forms of scenario analysis, including backcasting (Robinson 2003; Swart et al. 2004).

Different types of data, models, and analysis are required depending on whether a predictive or non-predictive approach is used to better understand the uncertainties of the future. In the past, predictive approaches to uncertainty tended to use models and be quantitative, while non-predictive approaches tended to use stories and be qualitative. Over the past decade or so, however, researchers have sought to develop approaches that combine quantitative models and storylines (see for example: Nakicenovic and Swart 2000; Nakicenovic et al. 2005; Raskin et al. 2002; Robinson et al. 2006; Raskin 2005; Shaw et al. 2009). Instead of attempting to predict the future, diverse tools such as storylines, 3D visioning, and backcasting (described in the sections to follow) are used to explore plausible futures.

The purpose of this chapter is to describe innovative research approaches that use quantitative and qualitative analysis in order to explore alternative climate change futures. These approaches take the view that responses to climate stimuli will increasingly involve complex socioeconomic decisions about desirable development pathways. An emphasis on development pathways is viewed as a useful way to guide development priorities and promote action, while explicitly accounting for adaptation and mitigation in the face of uncertainty. Local case studies in British Columbia are presented, which utilize participatory scenario-building processes and demonstrate ways of considering uncertainty in the design of locally-relevant responses to climate change. The chapter concludes with lessons learned from the local case studies, and presents the barriers to developing adaptation and mitigation responses to climate change that help communities transition toward resilient and sustainable development pathways, despite the uncertainties surrounding climate change.

8.2 Key Characteristics and Approaches for Dealing with Climate Change Uncertainty

8.2.1 Characteristics of Climate Change Uncertainties

In 1990, the IPCC First Assessment Report provided guidance on how to handle uncertainties within climate models and impact predictions by addressing: what was certain, what could be calculated with confidence, what was predicted, and what was likely based on the judgment of the authors (Manning 2006). In the Third Assessment Report, published in 2001, this approach was further developed by introducing a formal scale for assessing levels of confidence, which expresses confidence in terms of the odds of being correct (see Table 8.1) (IPCC 2006). In the recent Fourth Assessment Report (IPCC 2007a), expressions of confidence have been supplemented with formal expressions of likelihood.[1] In this report, the IPCC distinguishes between three types of uncertainties including unpredictability, structural uncertainty, and value uncertainty, applying them to both changes in human decisions and changes in climatic variables. Unpredictability is described as uncertainty in evolution of society as well as the unpredictability of chaotic components of a complex climate system. Structural uncertainty includes challenges from issues such as inadequate models, incomplete or competing conceptual frameworks, lack of agreement on model structure, ambiguous system boundaries or definitions, significant processes, or relationships wrongly specified or not considered. Finally, value uncertainty, according to the IPCC, refers to missing, inaccurate or non-representative data due to inappropriate spatial or temporal resolution. Although uncertainties in human decisions and climate systems share the same types of uncertainties within the IPCC taxonomy, we argue below that they must be treated differently.

The physical climate system is highly complex, has aspects that are inherently chaotic, and involves non-linear feedbacks operating on a wide variety of time scales. Our empirical knowledge of this system ranges from being good on decadal time scales and moderate over time scales of 100–1,000 years, to being quite limited at 10,000 years and longer (Manning 2006). Structural and value uncertainties in the prediction process associated with both natural climate variations and with the representation of physical processes in the applied models make it difficult to give definitive answers to questions about how much and how soon temperature and other climatic variables will change (Forest et al. 2004; Manning et al. 2004). Furthermore, when the focus is on actual adaptation actions, current models' predictions are appropriate for large-scale impacts and average levels of climate

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[1] Combining both likelihood and confidence created some difficulties in communicating uncertainties, because some combinations of likelihood and confidence (as these concepts are defined by the IPCC) are difficult to interpret. For example, very high/low likelihoods only seem meaningful if interpreted as statements of high confidence (Risbey and Kandlikar 2007).

Table 8.1

Levels of confidence and a likelihood scale by IPCC

Levels of confidence	**Degree of confidence in being correct**
Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance
Likelihood scale	**Likelihood of the occurrence/outcome**
Virtually certain	>99% probability of occurrence
Very likely	>90% probability
Likely	>66% probability
About as likely as not	33–66% probability
Unlikely	<33% probability
Very unlikely	<10% probability
Exceptionally unlikely	<1% probability

Source: IPCC 2005b, pp. 3–4

variables, but not always feasible for regional impacts and information about extreme weather events that are often demanded by decision-makers (Dessai and Hulme 2004; Downing and Patwardhan 2005).[2]

As suggested above, when it comes to human systems or decisions, the problems of uncertainty are complicated by the existence of volitional consciousness in the field of observation, which introduces questions of choice and intention that do not apply to biophysical systems. In particular it is important to recognize that humans make choices that are not deterministic, based to some degree upon expected outcomes, but also on a complex array of other factors, such as values, norms, hopes, etc. In the IPCC classification system, these factors contribute to the unpredictability of human systems.

To illustrate potential societal choices and futures, and their contribution to the problem of climate change, the IPCC developed a set of emissions scenarios. The scenarios were presented as alternative development pathways with related changes in concentration of CO_2-eq, but none of them included explicit consideration of GHG reduction policies. The IPCC Special Report on Emission Scenarios (SRES) provided explicit linkages between development choices and level of GHGs, illustrating that development decisions could considerably alter the level of future emissions and thus climate change impacts. For example, the SRES scenarios showed that getting close to the stabilization target of 450 ppm would only be possible by choosing pathways that promote decisions on the basis of economic, social and environmental sustainability at both global and local scales (Nakicenovic and Swart 2000). This means that some of the decisions that different jurisdictions will make about the future course of development will have nothing explicitly to do

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[2] Handling extremes and extreme events is perhaps the most difficult for current downscaling techniques and from a ‘bottom up’ perspective, sensitivity to extreme events is often poorly captured in impact models (Downing and Patwardhan 2005; Dessai and Hulme 2004).

with climate change, but will nevertheless have a huge impact upon both the level of GHG emissions and on societal adaptability. Coherent responses that attend to long-term biophysical and socioeconomic decisions are possible, yet cannot easily be evaluated in terms of relative probability of impact on global climate change. In such cases, the goal should not be so much to characterize the types of uncertainty as to express the range of development choices and constraints available for decision-makers with respect to fostering coherent development decisions and policy options in the face of uncertainty.

8.2.2 Dealing with Uncertainty to Promote Mitigation and Adaptation Responses to Climate Change

Recognizing the importance of human choice and constraints in addressing climate change uncertainty brings to the fore the question of the relationship between development pathways and climate mitigation and adaptation. Since 1992, the scientific community of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol process identified the need to deal with climate change within the context of sustainable development. In the early stages, this led to a growing body of literature on estimating critical thresholds for GHG concentrations and their implications for sustainable development, food security and ecosystem health. Since the publication of the Third IPCC Assessment Report (IPCC 2001), the scientific community has explicitly acknowledged and explored the inter-linkages between climate change and sustainable development, particularly the deep, multiple and varied links between development and responses to climate change. This work emphasizes the need to move from an exclusive focus on climate policy to an investigation of the broader context of development, equity, and sustainability (Munasinghe and Swart 2000; Swart et al. 2003; Wilbanks 2003; IPCC 2005a).

Despite these developments, which received further support in the IPCC's Fourth Assessment report (IPCC 2007c), current experience in assisting decision-makers to respond to climate change is often centered on developing adaptation and mitigation actions that remain disconnected from local issues and long-term sustainability priorities that will often heavily influence human responses. For example, the present focus on developing adaptation actions is often a response solely to climate impact assessments, many of which are driven by disciplinary research teams instead of offering a priori consideration to users' needs and local development challenges (Downing and Patwardhan 2005). What are needed are approaches that offer an integrated view of climate change, which is embedded within explicit consideration of the development choices available to a given jurisdiction.

This would also require developing responses to climate change that are relevant to policy-makers and stakeholders, which require new strategies to improve the science-policy interface through participation and communication. Specifically, such strategies should include creating effective two-way information flows between scientists and decision-makers that are based on explicit recognition of the role of intentionality and choice in determining future outcomes. Since these choices are essentially political acts and not scientific decisions, it is desirable that all participants are engaged in actively co-producing the developed knowledge and in defining the research outcomes (Robinson et al. 2006). John Robinson and James Tansey suggest involving the participating decision-makers and stakeholders as partners, with whom the research team collaborates in the co-production of knowledge (Robinson and Tansey 2006). Participatory integrated assessment (PIA) and scenario development approaches seem to be a useful way to achieve a level of participation and integration between global and local issues, to facilitate the integration of biophysical and socio-economic aspects of climate change responses and sustainable development, and to create opportunities for shared experiences in learning, problem definition, and design of potential solutions (Rotmans and van Asselt 1996, 2004; Hisschemöller et al. 2001; Toth and Hysznyik 2008). PIA also helps to improve the link between science and policy-making especially when the focus is on local planning activities including responses to climate change. To deliver results that resonate with local decision-makers, PIA makes use of integrated models and scenario development approaches developed through participatory methods like focus groups, or simulation and gaming techniques to include local knowledge and additional information in the assessment process (Ridder and Pahl-Wostl 2005).

Scenarios as heuristic tools represent an excellent opportunity to begin an exploration of different futures that make mental maps more explicit (Berkhout et al. 2002), and as aids to social and organizational learning (Chermack and van der Merwe 2003). Furthermore, scenarios can be used as tools for scanning the future in a rigorous, creative, and policy-relevant way that explicitly incorporates normative elements (Swart et al. 2004), and as a means by which we may explore the effects of alternative courses of action for future problems involving multiple actors, risk and uncertainty (Mayer et al. 2004). The three most commonly-used types of scenarios are exploratory scenarios, which posit a range of underlying socioeconomic conditions upon which alternative futures may be constructed; extrapolatory scenarios, which provide forecasts based on baseline trends; and normative scenarios, or backcasting scenarios, which are built on positive and negative visions of the future, and explore pathways of change that might lead to them (Berkhout et al. 2002; Swart et al. 2004). Given the focus of backcasting work on explicit choice, we focus here on this approach. While the value and quality of a predictive forecast depends upon the degree to which it accurately suggests what is likely to happen under specified conditions, backcasting is intended to suggest the implications of different futures, chosen not on the basis of their likelihood but on the basis of other criteria defined externally to the analysis (e.g., criteria of social or environmental desirability) (Hojer and Mattson 2000; Robinson 2003; Quist and Vergragt 2006).

Unlike predictive forecasts, backcasts are not intended to reveal what the future will likely be, but to indicate the relative feasibility and implications of pursuing different development goals. Backcasting is thus explicitly normative, and involves working backwards from a particular desired future end-point or set of goals to the present in order to determine the physical feasibility of that future and the policy measures that would be required to reach it (Robinson 2003; Robinson 1988).[3] When planning with complex systems, backcasting can be used in stakeholder engagement processes so that the preferred scenarios are an emergent property of the bi-directional consultation process (Robinson 2003). In this way, backcasting can be a process of collective discovery and social learning, since the focus is placed on the ideas that can solve the development challenge through collective engagement rather than merely pursuing scientific validity (Dreborg 1996). This includes stakeholder involvement, not only because of their context-specific knowledge, but also for achieving endorsement for results and implementing the proposed action agenda, which is crucial for progress in responding to climate change.

Given the anticipated impacts of human-induced climate change, it is evident that actions are needed at the regional and local as well as the global scale. Based on the IPCC SRES scenarios it has also been shown that promoting local and global sustainability could significantly contribute to GHG reduction and could increase capacities for adaptation (Swart et al. 2003). For instance, the SRES B1 scenario includes changes in land-use planning and urban design that significantly reduce GHGs without explicit climate policy. Integrating climate change responses with broader sustainable development priorities is essential, because many decisions will be made by millions of organizations and local governments that in turn influence societal development paths, emissions, and climate change impacts. Through the use of PIA, scenario approaches and developing partnerships between researchers and decision-makers help to integrate climate-related decisions with local conditions, non-climate considerations and local interests (Morgan et al. 2006). Finally, by investigating the relationship between the climate change measures and the human development decisions under a single framework, decision-makers can consider natural, social, and economic factors in an integrated way and can in this way deal with the complexity and interconnections within and between natural and human environments (Wilbanks 2005; Downing and Patwardhan 2005).

In the case of climate change in the next decade, policy-makers face new imperatives for meeting relatively stringent GHG reduction targets (Sheppard and Pond 2008), in order to be consistent with post-SRES stabilization scenarios (e.g., B1450) that are more likely to stay within 2° average warming (IPCC 2007c). This would seem to call for a backcasting approach, from pre-set end-points in order to avoid even greater uncertainties at higher levels of climate change. Again, an integrated approach is required to avoid adaptive emissions that would threaten attainment of challenging GHG reduction targets.

In order to examine how to design locally-relevant responses to climate change in the context of sustainability and to address uncertainty in a way that is centered on developing mitigation and adaptation actions, the following key framing

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[3] John Robinson defines this type of backcasting as a ‘second generation’ (Robinson 2003).

principles have been developed and applied in the local case studies described in the next section:

First, since achieving a sustainable world is as important as getting climate policy right, it is the combination of sustainability, adaptation and mitigation that will allow us to address the issue of climate change effectively. This includes important collective decisions on issues such as urban form, land use, transportation infrastructure, energy and water systems, etc. that will determine the framework within which we adapt and mitigate; this will also include cultural, social and psychological dimensions of values, lifestyle and consumption behavior (The British Columbia Climate Change Action Charter 2008).

Second, the linkages between changing climate variables and their implications at the local level require far more understanding than what is captured in regional and global climate models. Participation of local partners is necessary to facilitate integration of climate impacts information with local development issues. This requires a participatory, 'problem-based' focus, which leads to the direct involvement of various community partners, or stakeholders, in the research and decision making process. This process and subsequent implementation should be influenced by the interests of stakeholders, rather than by the scientific literature alone (van Wynsberghe et al. 2003; Carmichael et al. 2004; Robinson et al. 2006).

Finally, understanding adaptation and mitigation as part of a sustainable development pathway requires a new breed of climate change impact assessment–one that portrays realistic decision making, environmental, economic and social signals, and guidance for actions. This involves balancing the focus on specific risks and opportunities, especially in the case of adaptation to the biophysical risks associated with climate change and in mitigation from narrowly-defined sectoral GHG reduction policies – with issues such as well-being, capacity, resilience, and long-term sustainability. A 'backcasting' approach can be used to attain these specified targets by a given date, based on identifying the various ways people can work collectively or individually toward bringing about a more sustainable world (Robinson 2003).

8.3 British Columbia Case Studies

8.3.1 The Georgia Basin Futures Project

In the Georgia Basin Futures Project (GBFP), a 5-year participatory integrated assessment, the focus was explicitly on the co-production of knowledge whereby 'expert' knowledge was combined with partner knowledge at multiple stages of the project in order to give rise to an emergent understanding of sustainability options at a regional scale. The focus was much less on the communication of technical knowledge to stakeholders than on the co-production of understanding about the choices and consequences facing the region (Tansey et al. 2002; Robinson et al 2006). Key goals of the GBFP were to contribute to increased public involvement in the discourse about sustainability issues, to explore pathways to sustainability in the region, to create a database of public preferences, values, (un)acceptable trade-offs, etc. that can be analyzed to give a picture of how participants feel about sustainability issues, and to evaluate the relationship between the use of computer-based simulation tools and the beliefs, values and behaviours of users of these tools (Tansey et al. 2002).

In order to assist in identifying sustainable development pathways, the project had two sets of goals:

1. Through scenario analysis, to better understand the inter-related dynamics of the ecological, economic and social systems in the Georgia Basin, and to identify policy interventions that could enhance human well-being while reducing the adverse environmental effects of human activities.
2. To evaluate the role of game-like simulation tools in enhancing public understanding of these dynamics, and of the complex trade-offs involved in sustainability.

Expert analysis of key relationships among the social, ecological, and economic systems in the Georgia Basin, together with stakeholder-identified key issues, guided the development of a number of software tools for engaging stakeholders in sustainability issues (Robinson et al. 2006). The methodological core of the GBFP was the development and use of Georgia Basin QUEST (GB-QUEST), a computer-based scenario generation and evaluation system designed to encourage public participation in thinking about sustainability in a regional context. Through QUEST, users explored different possible scenarios of the future in terms of their social, economic and environmental characteristics. At the same time, local and regional possibilities and consequences depend on the trajectory of global developments such as population growth, regional trade and global environmental change. QUEST's dual scale spatial capability allowed global scale to be explored (Robinson et al. 2006) in the context of preferred regional and local development choices.[4] The goal was to acquaint users with the complex realities of decision-making, specifically the uncertainties involved, necessary trade-offs, and the role of subjective values. For the GB-QUEST modeling system, the geographical range encompassed the whole of the Canadian side of the Georgia Basin at a temporal scale of 40 years (Carmichael et al. 2004).

The GB-QUEST approach provided insights into the way that participants feel and think about sustainability issues and uncertainties surrounding their choices. This approach also provided opportunities to evaluate how the use of computer-based simulation tools affect the beliefs, values, and behaviours of the users of those tools (Tansey et al. 2002). Through QUEST, the user was asked to express their underlying beliefs about key aspects of human nature, technology and the natural world. These choices are important for two reasons: first, they were used to incorporate uncertainty

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[4] At the regional and local scales , scenario choices included personal transportation, the density and location of urban growth, the style of neighborhoods, agricultural trends and practices, forestry practices, economic activity and practices, water conservation, energy efficiency, government taxation and spending, and personal choices like diet and consumption practices (Robinson et al. 2006).

regarding behavioural change and scientific processes into the models within the tool; second, by allowing a user to view this range of uncertainty, while at the same time expressing their own beliefs about the way the world works, the user was able to see how important their underlying assumptions about reality are in determining the outcome of their scenario, and thus the values of the scenario indicators. QUEST includes a dual scale spatial capability, which allows consideration of how global forces affect local outcomes. At the global scale, four scenarios are offered, representing different pathways of global development. Each global scenario gives rise to different regional implications, such as population growth and regional trade (Robinson et al. 2006). The integrated model allowed scenarios to be created that are informed by regional and cross-sectoral changes (van Wynsberghe et al. 2003). Future air quality in the region provides a good example. Air quality is dependent on pollution from point, area, and mobile sources. Point-source pollution emission impacts are principally influenced by sector-specific changes in technology and resource use, both of which are uncertain and may be influenced by choices made by society (Carmichael et al. 2004).

A major challenge in developing models to be used in community engagement processes in the GBFP was the question of how to convey uncertainty in ways that are understandable and approachable. In GB-QUEST, users are asked to give their views of the relative adaptability of human behaviour, fruitfulness of technological change, including actions needed for responding to climate change, and the fragility of ecosystems. GB-QUEST accepts their choices and changes the appropriate model parameters accordingly. The user is led to understand that uncertainty exists about these key parameters, that it can usefully be expressed in terms of the holistic properties of socio-ecological systems, and that different assumptions may give rise to quite different outcomes (Carmichael et al. 2004). The point is that there is no correct answer about these uncertainties, but users of QUEST were encouraged to recognize their existence and to devise scenarios that might be resilient against the range of outcomes that might occur if these underlying parameters changed.

The approach employed in the GBFP also led to an improved understanding of how users perceive the opportunities and trade-offs that are part of their local futures. Since the backcasting approach does not attempt to predict the most likely future but instead asks users to define what constitutes a desirable future, the critical concern about whether the representation of human agents is predictively accurate is to a large degree by-passed. That is, human choice is exogenized, and occurs outside the modeling system in the heads of the QUEST users: it becomes a driver ("what if we did this?") rather than just a variable in the system ("what will people do?"). Once the user makes the choices they consider desirable, the model projects them across the region in order to represent the consequences. In QUEST, the consequences of the user's choices are deterministic. While this is an unrealistic way to represent actual outcomes,[5] it allows researchers to discover with a

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[5] This is why backcasting models like QUEST are not useful for predictive forecasting. They are intended to illustrate the consequences of different choices, not to predict the likelihood of such choices.

relatively high degree of certainty, what is considered a desirable future, what trade-offs are acceptable, what individuals and groups are able to learn about the future, and what the relationship is between knowledge of some of the issues the region faces and actual behavior (Tansey et al. 2002; Carmichael et al. 2004; Robinson et al. 2006).

The project tested the idea that complex public policy issues can be illuminated by the use of scenario analysis tools and processes, especially when these scenarios were created not by experts but by the users. This made the process more engaging, created a higher degree of user buy-in to the process and a greater sense of responsibility for the outcomes (Robinson et al. 2006). Through participation, this approach explicitly considers behavioural barriers to change, the social acceptability of technologies, and the willingness to bear short term costs for longer term gains. The outcomes provide insights into what is feasible and acceptable at the individual and societal level when responses to climate change are being developed.[6]

Providing opportunities for stakeholders and decision-makers to understand and to learn about the consequences of different behaviors allows them to explore futures that may be less likely but nevertheless desirable. Such an approach is in contrast with many current approaches in climate change research that try to predict the course of development and behavioral choices without investigating what the specific concerns and desires at the local and regional level are, and how these might alter the likelihood of different outcomes. Furthermore, to facilitate stakeholder engagement about future choices and preferences, the spatial and temporal scale of the QUEST model needed to be consistent with the cognitive frame of the users (Robinson et al. 2006). This would probably require developing short- and medium-term adaptation strategies as part of a collaboratively developed long-term strategy to transition to the more sustainable pathway instead of only focusing on the nearly 100-year timeframe that is often applied in predictions of climate change.

Finally, participating stakeholders clearly indicated their interest in exploring scenarios at the local scale. At the same time, local possibilities and consequences often depend critically on large scale phenomena including climate change. QUEST's dual scale spatial capability allowed both global and regional scales to be explored (Robinson et al. 2006); however, current SRES scenarios of development pathways, as well as predictions of the impacts of climate change, often operate on the global or large regional (i.e., continental) level. This may reduce the relevance of such scenarios and predictions for use in potential responses and policies for stakeholders and decision-makers, and consequently won't encourage actions.

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[6] The QUEST approach used in the GBFP led to the development of the Metroquest software, which has now been purchased by 16 municipalities in Canada and the US to engage their citizens on sustainability issues.

8.3.2 The Local Climate Change Visioning Project

The Local Climate Change Visioning Project in British Columbia, Canada, represents a new approach which builds on recent work that bridges the divide between predictive, quantitative approaches and narrative-based qualitative methods of addressing the uncertainty inherent in climate change. It incorporates novel three-dimensional (3D) visualization techniques with elements of participatory integrated assessment to explore alternative climate futures for two communities located in the Greater Vancouver region. Building on the wealth of scholarship and current practice in community development and land-use planning (Tress and Tress 2003; Sheppard 2005), the Local Climate Change Visioning Project incorporates participatory processes which introduce practical knowledge and experiences at the community scale in order to enrich the integrated assessment of the complexities of climate change (Rotmans and van Asselt 1996; van Asselt and Rijkens-Klomp 2002). The development of 3D visualizations utilized downscaled global scenarios, existing relevant regional and local data and a structured group process (see Fig. 8.1) that facilitated the articulation of local knowledge, values, and preferences. This process was meant to increase awareness, inform policy in the municipal context, build capacity, and potentially motivate action on climate change.

The first phase involved the development of a conceptual framework, which outlined four alternative climate futures ranging from a low proactivity/high

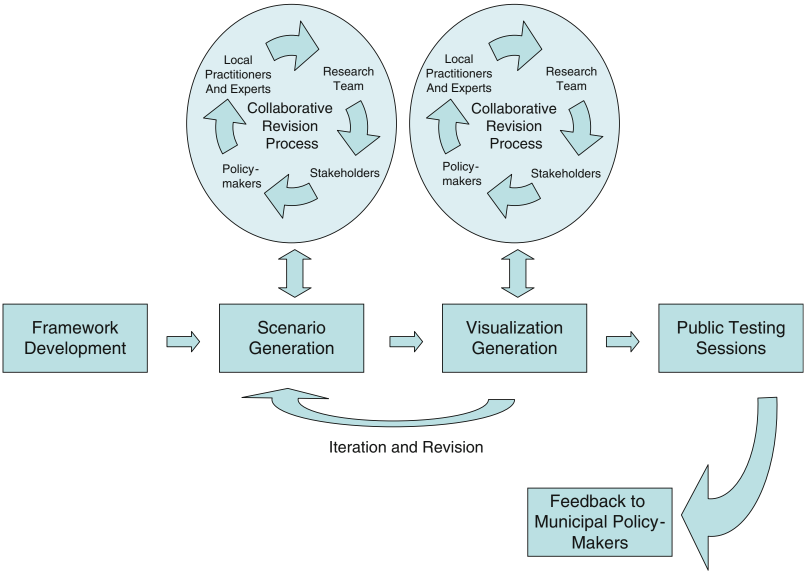

Fig. 8.1 The Local Climate Change Visioning Project. The research process included opportunities for iteration, revision, and consultation with an extended team of stakeholders, local experts, and municipal decision-makers (Courtesy of the authors)

emissions future to a low emissions future, employing various response strategies. These included:

1. A high emissions 'Do Nothing' scenario with no effective action on climate change, that acts as a baseline to illustrate projected impacts;
2. A high emissions 'Adapt to Risk' scenario that emphasizes proactive adaptation to projected impacts;
3. A moderate emissions 'Efficient Development' scenario with incremental mitigation and strong adaptation measures; and
4. A low emissions 'Deep Sustainability' scenario that includes strong and early mitigation which stabilizes greenhouse gas concentrations leading to delayed adaptation measures.[7]

This framework helped to organize a plethora of qualitative and qualitative data, from the global to the local level (Sheppard and Shaw 2007). Key biophysical and socioeconomic drivers were collated from the Intergovernmental Panel on Climate Change's *Special Report on Emissions Scenarios* (Nakicenovic and Swart 2000; Banuri et al. 2001a, b), the Millennium Ecosystem Assessment (Raskin 2005), and the scenarios of the Global Scenario Group (Raskin et al. 2002) to fit the parameters of the framework. These scenarios were then downscaled using global and regional impact assessment data and climate-related policy information as a bridge to the local scale. Regional socio-economic data was generated using the pre-existing GB-QUEST model described above (Carmichael et al. 2004). In addition to generating socio-economic data, the model was used to match regional and global emission assumptions while maintaining internal consistency with socio-economic drivers. Four regional storylines and narratives were developed which utilized the combined data provided by global models, regional assessments, local expertise, and GHG emission assumptions (see Fig. 8.2).

These alternative climate futures were used to stimulate dialogue with a local working group of municipal, expert, and community participants to consider what the local landscapes would look like under the impact and response assumptions of each 'world'. The output comprised local scenarios projecting conditions in 2020, 2050, and 2100. Using these outputs, the research team then created 3D computer-generated visualizations of key climate change impacts (such as sea-level rise, forest character and species changes) and various combinations of response options that had been discussed in the local workshops (including, for example, an adaptive response involving the raising of dikes, or a combined adaptation/mitigation strategy leading to compact mixed-use development patterns and alternative transportation choices). The images depicted local, iconic places in order to heighten the relevance of different development decisions and their climate implications for community members (see Fig. 8.3 showing examples from the Delta community).

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[7] As explained later, Post-SRES B1 was used for the low emissions world in order to account for explicit mitigation policy.

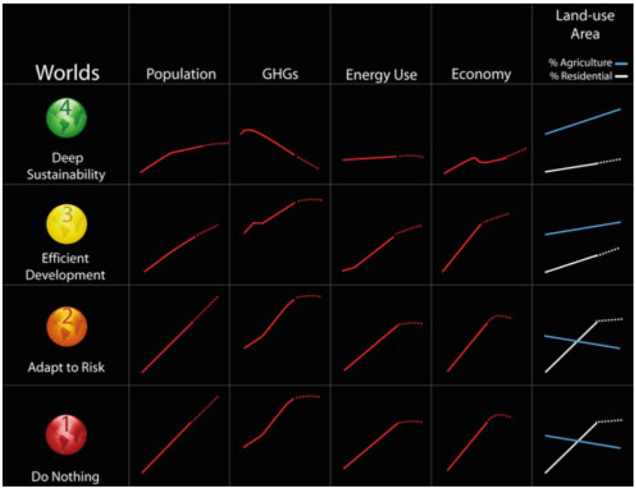

Fig. 8.2 Underlying socio-economic assumptions for each scenario. The GB-QUEST model provided general consistency between these main indicators
Source: Sheppard SRJ et al., 2008b and Shaw et al. 2009

Fig. 8.3 The coastal community of Delta, Canada. In order from top left, images show increasing levels of response to climate change in four futures
Source: Sheppard SRJ et al., 2008b and Shaw et al. 2009

Final ‘visioning packages’, a combination of visualizations, narratives, and supporting information, were presented to Delta community members in order to determine their impact on community members with regard to climate change awareness, emotional engagement, and motivation to act. The results of this research show that local scenarios paired with realistic 3D imagery of familiar places are powerful tools for exploring complex and uncertain development pathways. Results from participants' self-assessments and researchers' observations suggest that cognition of local climate change impacts and possible response options increased significantly, along with a heightened sense of urgency and stronger support for adaptation and mitigation policies (Sheppard et al. 2008a). The results address the theme of this chapter in three key ways.

First, scenario development and local expertise can in part compensate for significant uncertainty. A substantial amount of 'buy-in' to the scenarios occurred among participants due to the exploratory nature of alternative scenarios and also due to the two-way exchange and contextualization of knowledge that occurred between researchers and local experts. Most participants were readily able to understand and explore the four-world scenario framework, and by the end of the sessions were repeatedly utilizing the new concepts and framework that had been introduced to them during the sessions. Participants generally felt that Delta should try to achieve World 4, the most sustainable, low emissions scenario, but thought that Delta's current development policies corresponded either to a World 1 or World 2. They recognized that different development decisions made in the near future determine different emissions paths, leading, in turn, to nominally better or worse climate futures. Factors such as self-selection of interested participants in the testing sessions and pre-existing worldviews may have influenced these findings.

Second, it is necessary to illustrate the ways in which aggregate development choices made today at the regional/local level play a role in determining which climate change path society is on. For example, most respondents were convinced of the need to act early in the century (within the next 10 years) in order to reduce greenhouse gas emissions. This is especially significant because one of the central goals of the project was to make the global and abstract concept of climate change, meaningful at the local level.

Third, integrating climate change responses explicitly into development priorities and pathways can help the public to understand how to reduce emissions while improving community resilience. The visualization package provided new and fairly detailed information about adaptation strategies, and respondents reported a significantly better understanding of how their family could adapt to climate change. Despite the importance of issues such as sea-level rise in Delta, however, most respondents' (76%) felt that adaptation alone will not be sufficient to address the climate change problem. Respondents thus appeared able to make the connection between land-use planning, urban form, transportation, energy and water systems, etc. as key to reducing emissions and thus climate change impacts. They also suggest that adapting to climate change impacts without addressing local causes of climate change (GHG emissions) is not seen as sufficient action.

8.4 Opportunities for Designing Responses to Climate Change despite Uncertainties

The case studies described here show that approaches to climate change uncertainty, especially those that have to do with the intentionality and choices associated with human systems, can be very fruitfully addressed by means of the PIA backcasting techniques. In particular, they show that it is possible to address, in a meaningful way, futures that contain a continuum of uncertainty, ranging from unreliability to more fundamental uncertainty (or unpredictability).

Uncertainties in the category of unreliability are usually measurable or can be calculated, in that they stem from well-understood systems or processes (van Asselt and Rotmans 2002). This implies that uncertainty can be described quantitatively as probabilities or likelihoods, an approach that was adopted by the IPCC. On the other end of the continuum there are fundamental uncertainties, including lack of knowledge about system conditions and underlying dynamics, the prospects for innovation and surprise and, most importantly, the intentional nature of human decision-making. In addressing these latter forms of uncertainty, probabilistic approaches do not seem very useful. Instead approaches based on backcasting scenario methods and the explicit articulation of choices and exploration of consequences may be more useful. In the case studies described above, participants seemed to appreciate approaches and information that helped them structure future pathways and enable them to move forward in considering specific local responses.

We believe that scenario development, participation and local expertise can in part address the different kinds of uncertainty that characterize human systems and foster proactive adaptation and mitigation actions. Using backcasting in the participatory context created significant ‘buy-in’ to the scenarios among participants in the two case studies, due to the flexibility given to them to define their own desired future with support from exchange with researchers. In general, using scenario approaches can enable decision-makers to better understand choices, options and the impacts associated with alternative futures. Such scenarios support the process of prioritizing and choosing between potential adaptation responses and translating them into short- and medium-term policy goals, while moving towards a long-term scenario. In both case studies, the majority of respondents saw changes from the current development path to a more sustainable development path as a desirable long-term target.

During the scenario development exercise, assessments of climate change impacts help in identifying areas of high vulnerability that need to be taken into consideration when developing local pathways. The desire for a sustainable development pathway also frames actual adaptation and migration options. There are a number of ways to respond to climate change impacts and to reduce GHG emissions. However, the options selected depend not only on the impact of climate change and available technologies, but also on current and future local, regional and national priorities. Consequently, planning for climate change without considering local development priorities could lead to maladaptation in the long-run.

In both case studies, the development of responses to climate change occurs in the context of the overall development pathway, which at least enables practitioners to address linkages between climate change adaptation, mitigation and other development choices. In both cases, local development choices were informed by global scenarios; however, the applied participatory approaches and backcasting included elements of creativity and 'thinking outside of the box' in the ways that the identified options were linked to local development priorities. The method helped reveal tradeoffs and synergies between various adaptation and mitigation measures, and demonstrate the inherently local nature of responses to climate change.

Linking climate change with human activities often introduced new uncertainties to local decision-makers, including model-related uncertainties. Although uncertainty analyses are possible within individual modeling systems, in the hybrid-modeling approach used in the Local Climate Change Visioning Project, the lack of connection between different models, between models and visualization needs and techniques, and amidst data retrieved from different spatial, and temporal scales makes it difficult to estimate uncertainties systematically within the integrated system used for creating the local scenarios. In the GBFP, uncertainty was explicitly treated as a function of discrete assumptions about technological change, behavioural adaptability and ecological resilience. The point was less to characterize or reduce uncertainty than to recognize the importance of developing proposed responses that are resilient to irreducible uncertainty.

The case studies suggest that collaboration with experts and local decision-makers can be used to interpret and to some extent validate model outputs and in this way establish credibility and confidence among team-members. Rich local knowledge compensated in part for the limitations of available models, and participants became comfortable with the idea of integrating adaptation and mitigation in pursuit of a fundamentally sustainable future. In the future, more explicit testing of the role and magnitude of uncertainty in visioning and scenario development processes would be valuable, such as exploring how uncertainty bands on features such as rising snowlines or sea-levels can be visually represented in visualizations, or extending GBFP-type workshops to develop a typology of resilience of scenarios.

Postponing actions on climate change until uncertainty is reduced will significantly impair our ability to alter the course of development in time to avoid dangerous or catastrophic climate change. If we are really going to deal with the kinds of uncertainty that are associated with human systems, we believe that we need approaches such as those adopted in the case studies, using: structured scenarios that integrate adaptation, mitigation and sustainable development; engaging and credible deliberative processes; and holistic interactive approaches to informing potential actors on choices, trade-offs, and possible consequences. This needs to be done with clear acknowledgment of the massive uncertainties involved, but in a way that enables actors to make decisions and accelerate the shift towards development pathways and behaviours that reduce or avoid climate change. These conclusions strongly suggest the need to increase our efforts in disseminating lessons learned from such case studies and similar experiences elsewhere, to inform global policy-making and to help align climate change action and long-term development decisions within local contexts that, when aggregated, have a tremendous impact.

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Chapter 9
Image Politics: Picturing Uncertainty. The Role of Images in Climatology and Climate Policy

Birgit Schneider

9.1 What is Expected of Informational Images

Pictures are linked to contradictory expectations. On the one hand, good and successful pictures are meant to reveal knowledge at first sight; according to popular opinion they should be clear, undistorted and concise. Pictures are thought of in contrast to texts. These expectations for images are summarized by the adage “a picture is worth a thousand words”. The axiom articulates the notion that pictures have a pedagogical ability to show complex connections in an easy and understandable way—to “condense” knowledge into a form that is easy to digest. In general images are thought to be “a more easily accessible medium of communication than (conceptual) language” (Hüppauf and Weingart 2009, p. 14; quote translated by the author).

In contrast to these positive views on the power of images, strong reservations also exist. These reservations are likewise contrasted with the understanding of texts. From this negative perspective, pictures are regarded to provide only a blurred version of reality. They are considered to belong to the realm of emotions and subjectivity, whereas texts are thought to belong to the field of rationality. Accordingly, images leave the door open for deception, illusion and seduction, and have been an object of great distrust (Latour and Weibel 2002). All of these expectations also apply to the realm of informational images.

With the help of contemporary examples, this paper argues for the importance of a critical look at images showing climate change, as in this context pictures are widely used by all concerned; at the same time these images are only rarely discussed in their own right (Monmonnier 1999; Brönnimann 2002; Nocke and Schneider von Deimling 2008), as they are thought to be either self-evident or mere instruments for mediating (‘illustrating’) scientific results. The more normal

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these images become in their daily usage in the whole spectrum of different contexts, the more they are looked *through* and taken for granted. From the moment an image is used in practice and its use becomes common, there is a tendency to forget about its artificial character (Bredekamp et al. 2008; Heintz and Huber 2001). By halting the process of climate-image consumption in order to defamiliarize what is obvious, the knowledge contained within the images can be revealed: knowledge that goes beyond the obvious in a way the art historian Panofsky called 'disguised symbolism' (Panofsky 1953, p. 141).

At the same time there exists a gap between the understanding of texts and of images, which has a lot to do with the expectations regarding images mentioned above. Though text understanding and critique are taught at school, visual competence or 'visual literacy' (Elkins 2003) is not given a place in the general curricula. This leads to a contrast between the increasing usage and consumption of images and how they are understood.[1] A critical look at informational images is even more important, as these "are arguably the majority of all images" (Elkins 1999, p. 4). It is thus vital to expand upon the existing methods that have been developed within the key disciplines for dealing with visuality and the interpretation of images (Elkins 2003, p. 125 et seq.). Sound methods for this purpose have been developed in the fields of art history, semiotics, media studies, psychology, neurology and the broad field of visual studies (*Bildwissenschaft* cf. Mitchell 1994; Elkins 2003; Schulz 2005; Belting 2007; Bredekamp et al. 2008).

Through critical analysis of the visual part of climate discourse—the 'viscourse' (Knorr-Cetina 1999, p. 247), a common visual space of communication becomes tangible. By taking a close look at climate images that have been reproduced again and again in different contexts, it is possible to demonstrate the complex ways in which images have the power to reinforce and accentuate the threatening results presented by climatologists. In this process even a matter-of-fact graph can turn into a strong image with marked repercussions. As even graphs are part of a visual culture and history and thus culturally symbolic, the red, rising end of a temperature curve, for example, can be perceived as the modern way of picturing disaster. At the same time, as the images are transferred to other contexts they are connected with new interests such as the demand of politics and society for a steady basis for decision, since they offer "semantic flexibility and identity for various recipient groups" (Nikolow and Bluma 2009, p. 48; quote translated by the author).

There are two main lines of evidence for which climatologists seek to use images in order to bring home the relevance of climate change: the spectrums of uncertainty/certainty and of normality/abnormality.[2] Examples have thus been chosen to illustrate the ways in which these categories are argued visually. These examples

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[1] A theoretical reaction to the increasing usage and consumption of images has thus been the 'pictorial turn' (Mitchell 1992, 1994; Boehm 1994).

[2] Visualization strategies for climate data are broadly discussed in the field of computer graphics, where "uncertainty visualization" is a key phrase (for an overview see Nocke et al. 2008).

present reconstructions of climate history and models of possible climate futures that have been published within the last 10 years. Before analysing the examples, some general remarks about scientific images and their role in climatology will be made.

9.2 The Status of Scientific Images

Images are the ‘showplace of science’ (Heintz and Huber 2001, p. 34). Scientific images fulfil several roles that differ greatly from art. They can generate evidence, function as empirical proof, explain, demonstrate and document a connection or correlation, or ‘make visible’ (Rheinberger 2001) complex processes and data structures. A key role of scientific images involves their potential to visualize scientific objects previously inaccessible to perception; in these terms, visualization is nothing less than a method for making the invisible visible.[3] The status of climate images is particularly crucial, as they are visualizations in a literal sense: they make entities visible which otherwise, as statistical items, could not become evident. Climate as an epistemic object is not something simply given, but has to be constructed and mediated. In the light of these assumptions, this article is guided by the thesis that images picturing climate do not simply represent or illustrate information, but in the process actively *produce* and *shape* knowledge.[4]

Pictures have played a significant role in climatology ever since its beginnings around 1800. Since then climate has been defined as the statistics of weather phenomena, meaning long-term observations, measurements and calculations of weather events (Konersmann 2008). The history of climatology began with the transferral of the increasing amounts of weather data into graphs and maps.[5] Pictures portraying climate are in most cases generated using the instrument of *analytical graphics*. This old designation pinpoints the aim of this method: analytical graphics is a tool of interpretation. *Synopsis* (‘seeing together’), the method of creating images based on statistical thinking, gave form to shapeless and spatially detached weather events. It was only through these new strategies of visualizing observations and measurements that the climate could become ‘e-vident’ and as such an epistemic object of research. As climatology was developed in conjunction with the methods of analytical graphics, behind the history of climatology there lies a broad history of diagrammatic methods of visualization. The new visualization

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[3] For the concept of visualisation (Hacking 1983; Rheinberger et al. 1997; Snyder 1998).

[4] In German this difference is embodied within the words *darstellen* (represent) and *herstellen* (create, produce).

[5] This is what German naturalist Alexander von Humboldt (1769-1859) did in 1817, when he outlined the first set of isotherms—statistical lines of average temperature—on a map structure. By introducing isotherms he was able to give an idea of climatic zones (Humboldt von 1817; Monmonnier 1999).

strategies during the nineteenth century evolved into a powerful medium for interpreting the increasing data based on a great trust in numbers.

To the present day, the connection between analytical graphics and scientific knowledge has not only persisted, but actually intensified. Indeed, different types of images, such as maps, diagrams and graphs, have come to play a crucial role when it comes to transforming the increasing series of observations and measurements into instruments of knowledge production and knowledge communication.

Whereas weather phenomena are perceived by people, the character of climate is first and foremost an abstract statistical entity. The difference between perceivable and concrete weather events and the climate as a scientifically constructed entity in those regions where the impacts of climate change cannot be experienced, leads to a paradox: while the climate is a calculated, abstract and virtual object of science, the mediated images of this *abstractum* have started to change people's awareness of life in the subtlest of ways. "The statistical trellis-work of diagrams and signs has banished all other perceptions of climate and along with them the metaphysical, mythological, symbolic and aesthetic traditions of interpretation" (Konersmann 2008, p. 32; quote translated by the author). Climate charts shape the way this world is thought about and seen.

Informational images produced by climatologists, such as charts and graphs, involve numbers, letters and other symbols.[6] Nevertheless, in this article they are treated as images since their specific logic is grounded on their ability to structure space, surface and place in a topological way with the help of colours, dots, lines and planes—these capacities being the basis for any picture (Boehm 2007). By dealing with graphs and charts in the category of an image, questions can be posed that arise from the domain of visuality.

9.3 An Abnormal Truth

In his film *An Inconvenient Truth* the former U.S. Vice President Al Gore integrated climatological graphs, maps and schemes in a particularly dramatic way. Through his 'staging' of graphs he was able to argue for the threat of climate catastrophe not only through a realistic use of moving photographs and spectacular film takes of affected people and nature, but also by employing ostensibly dry and rational scientific charts.

One of the highlights of his film is the presentation of the results deduced from an ice core, as published in 2005 in *Science Magazine* (Siegentaler et al. 2005). The ice core 'Dome C' was recovered from Antarctican ice at a depth of over three kilometres. Ice cores are used as natural climate archives delivering proxy data. Trapped air bubbles can be examined through chemical analysis to reconstruct the atmospheric composition of trace gases and local temperature variations from previous time periods. The ice is in chronological order, as the snowfall over the years is accumulated in

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[6] For the relationship between texts and pictures see Nelson Goodman as well as Horst Bredekamp and Sybille Krämer (Goodmann 1968; Bredekamp and Krämer 2003).

Fig. 9.1 An Inconvenient Truth. Al Gore's staging of an ice-core record showing 650,000 years of climate history. Film still taken from the movie An Inconvenient Truth, 2006
Source: An Inconvenient Truth, DVD, 2006

layers. The glaciologists visualized the results of the analysis in the form of curves which, in conjunction with other records, present the variations in the temperature and concentration of atmospheric CO_2 of Antarctica over the last 650,000 years.

Gore projected the two curves in their whole length onto his giant video screen (see Fig. 9.1), which was thus transformed into a 'walkable' stage design for the climate plot. He then started walking the curve as though it were a mountain chain, beginning in the left part of the stage and at the same time informing viewers of the eight glacial cycles and warm periods, which stand out through the silhouette of mountains and valleys over the last 650,000 years.

The evidence said to be derived from the ice-core graph is produced by the correlation of the two curves showing temperature and CO_2 within one data space. The two lines apparently trend in an analogous way: the rising of one curve is followed by that of the other. This underpins the conclusion of the research, which is that temperature and the concentration of CO_2 are two interdependent values. The ice-core record thus became one of the main pieces of evidence used to prove human-induced climate change, for the growth rate of atmospheric carbon dioxide has never been as high as in the last few years. The curve showing temperature is of a 'hot' red colour, while the curve for the atmospheric gas CO_2 is consequently shown in a sky blue. By adding red dots for today's global concentration of atmospheric CO_2 and a forecast for 2050 at the right end of the graph (in 2005: 375 ppm), Gore was able visually to extrapolate the evidence provided by the chart into a grim forecast: if a certain variation in CO_2 values has been 'normal' for ice ages and warm periods during the last 650,000 years, what is mankind to expect if today's CO_2 level already exceeds the normal range many times over?[7] And what will

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[7] Scientists had raised this argument themselves, but did not add the level of today's CO_2 concentration to their graph of the ice-core record (Canadell 2007).

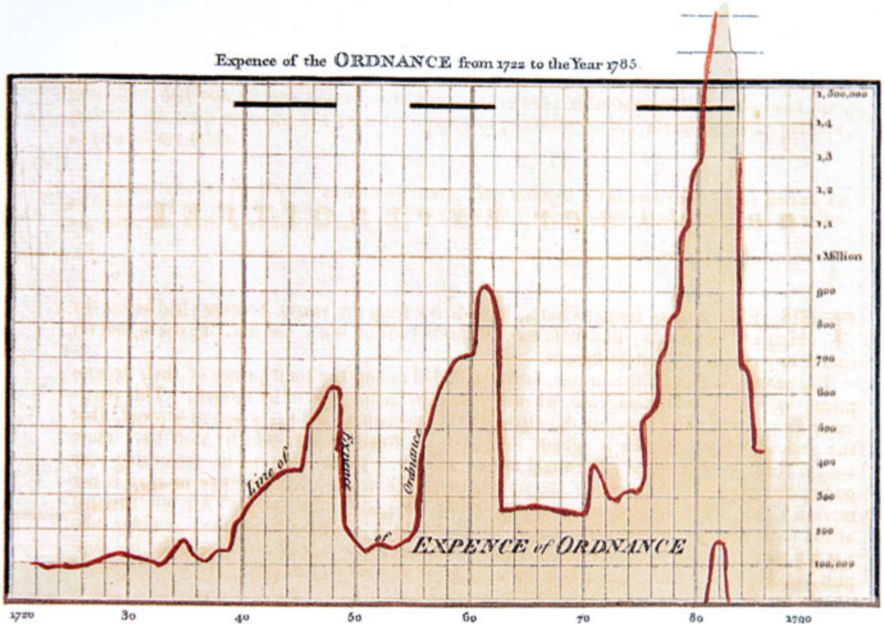
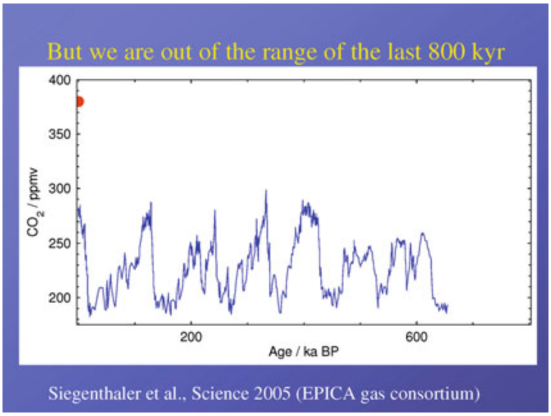


Fig. 9.2 Spill-over-effect. This effect was used to demonstrate unusually high expenses during wartime in a graph by William Playfair, 1786
Source: Playfair 1786

happen to the earth's climate in 2050 if mankind continues as it is today and does not reduce emissions? The highly abnormal status of the present and the catastrophe scenario for the future have been translated into the clear language of the graph: in the last quarter of the twentieth century the progression of the curve starts to go beyond the graph's limits. The future value of CO_2 is no longer in the frame. The red line leaves the space of the graph, spilling over the framed coordinate system; it literally goes through the roof by shooting in a vertical progression to the ceiling of the auditorium.

This clear and persuasive 'spill-over-effect' (Tufte 1990, p. 107) had already been developed in one of the earliest uses of charts by the engineer and political economist William Playfair (Playfair 1786). By means of this visual rhetoric, he wanted to illustrate the comparatively high cost of British ordnance during wartime in 1882 (see Fig. 9.2). Though this effect has become a visual convention of chart design, Gore goes even further in highlighting the abnormal trend of the curve, using a new and more emphatic way of rhetorical staging. By employing the oversized technique of a car lift to bring himself up to the ceiling and implying that only thus can he follow the trend of anthropogenic CO_2, he is able to make a joke about any possible doubts concerning the curve's message: humans need some sort of prosthetic technology merely to follow the abnormal trend of the climate, itself a product of their own misuse of technology.



But we are out of the range of the last 800 kyr

Siegenthaler et al., Science 2005 (EPICA gas consortium)

Fig. 9.3 Slide by the glaciologist Eric Wolff. As glaciologists use the time axis in the opposite way, the red dot marking today's CO_2 concentration is situated at the top left-hand side
Source: http://www.epa.ie/downloads/pubs/other/events/olg/eric%20wolff%20lecture_reduced_13022008.pdf

The form of a time-series graph of the Earth's history, which has been speeding up since 1860, has become the clearest and most convincing figure of climate change. The curves are interpreted under the premise that it is the CO_2 concentration being released by economic human activity that is the cause of rising temperatures. This correlation evidence, however, can only be interpreted by methods that are not explicit within the curve itself. The statements and conclusions derived from the ice-core evidence are not 'wrong' or 'falsified', though it might be argued that the current global CO_2 value was not derived from the ice core (see Fig. 9.3). Gore used the specific logic of visualization to present the conclusions derived from the scientific results as obvious and unambiguous.

Techniques seeking to increase the power of images to convince with their evidence have been employed not only by environmental activists. The insertion of today's average CO_2 concentration into the graphs of ice-core records has since also been used by the scientists themselves with the aim of highlighting the global relevance of their findings. This was the case for example in the talks of Eric Wolff, who also recovered the ice core. Wolff commented on the red dot introduced on the top left-hand side of the graph with the words: "we are out of the range." This is just one example showing that the process of popularisation is not a linear movement in one direction only, and that convincing graphical strategies are also sought by scientists.[8]

As the results obtained by climatologists are highly relevant for society, the search is for methods of transferring these results into convincing and plastic images that can immediately be understood. In their desire to provide a basis for straightforward political actions and decisions, activists like Al Gore and climatologists use

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[8] Eric Wolff elucidated his power point slide with the sentence "This is the planet's heart beating" (Wolff 2008, Chart 32).

the same visual strategies.[9] The requirements of political decision-making are confronted with the complex methods and the probabilities of climatologists. While the field of politics is all about making statements that are normative, science is meant to be governed by the ideal of objectivity. In this sense, scientists are responsible first and foremost to reason as opposed to morality and norms, those issues so important in politics. The mixture between the two value systems comes to the fore in the images chosen for public debate. Here images are sought that can function simultaneously as mission statements, evidence and guidelines, at the same time satisfying aesthetic values. In this way they provide wider possibilities for viewers' identification, as illustrated even more graphically by the next example.

9.4 The Red Blade of a Hockey Stick

'Hockey Stick graph' is the name given to a curve made famous in two papers published by Michael E. Mann and his colleagues in 1998 and 1999. This graph, which preceded the ice-core graph, was the first figure to make the issue of abnormal climate history popular. It immediately became the subject of a wide-ranging controversy. In the *Nature Magazine* article, the palaeoclimatologists had visualized the reconstructed estimates of northern hemisphere mean temperature changes over the past 600 years in the form of a curve. In the following article, published in the Geophysical Research Letters, they expanded the spectrum of the curve to the last millennium (see Fig. 9.4).[10]

The name "hockey stick" is in itself an interpretation of the curve's form: the main alignment presents mean temperatures, which run within quite a constant range; from 1900 the curve's alignment changes significantly. The graph suddenly ascends to values that had not been reached in the 1,000 years before. The form is interpreted as a hockey stick, with the rise in temperatures since the mid-nineteenth century figuring as the blade of the stick, whereas the temperatures of the 850 years from 1000 until 1850 represent the shaft. This sharply rising form of a red curve—the hitting blade of an item of sports equipment—came to serve as an important symbol of climate change. The simple, abstract shape of the graph has the potential to accommodate a full range of different emotions, focusing upon climate change as a threatening natural disaster, punishment or apocalypse.

To tell whether today's observations of rising global temperatures since the end of the nineteenth century are abnormal, a very wide frame of comparison is needed. Yet systematic meteorological measurements and measurement networks have only been established since the middle of the nineteenth century. To provide evidence of

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[9] The conjunction of present average values of global temperature and CO_2 concentrations can be also found in graphs published in popular climate atlases (Dow and Downing 2006, p. 34).

[10] For his first study Michael E. Mann and his team reconstructed the Earth's climate history since 1400 (Mann et al. 1998). In the next study they reconstructed 1,000 years (Mann et al. 1999).

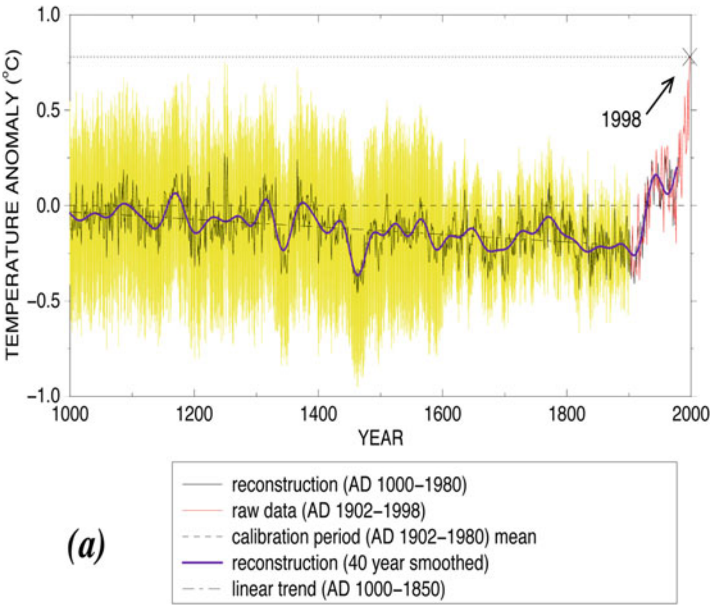

Fig. 9.4 'Hockey Stick graph'. Mean temperatures in the northern hemisphere during the last 1,000 years, Michael E. Mann et al., 1999
Source: Mann et al. 1999, Fig. 3

climatic conditions before this time, researchers have therefore developed indirect methods that rely on proxy data (surrogate data). Proxy data allow the deduction of information about climate history on the basis of certain parameters that are dependent on temperature. In this case the graph is grounded mainly on the analysis of tree rings, although sediment, historical documentary indicators, corals and ice-core data are also used in this context. Like ice-core records, tree rings are employed as natural climate archives, as they are arranged in chronological order (Hauser 2002, p. 88 et seq.).

In the graph, data derived through instrumental measurement are called 'raw data' and shown as a red coloured line (see Fig. 9.4). The 'reconstruction' is marked as a black zig-zag line. This presents the results of the proxy method. A violet line gives a clearer form to the graph, showing the mean values over 40 year periods. The linear-trend line finally interpolates the curve into the form of a straight, black dotted line, the hockey stick. The yellow-coloured areas highlight the corridor of trust in the numbers, which broadly encloses some sections of the curve. In the front section of the curve the yellow corridor is very broad because of the low data density prior to 1400. For this period of the investigation only nine records of the *International Tree Ring Data Bank* and three ice-core records could be used. The article treats the issue of uncertainty in general terms, yet in the caption of the figure the meaning of the colour yellow is not explicated, unlike the other colours which are explained in the caption (Mann et al. 1999, pp. 2 and 5).

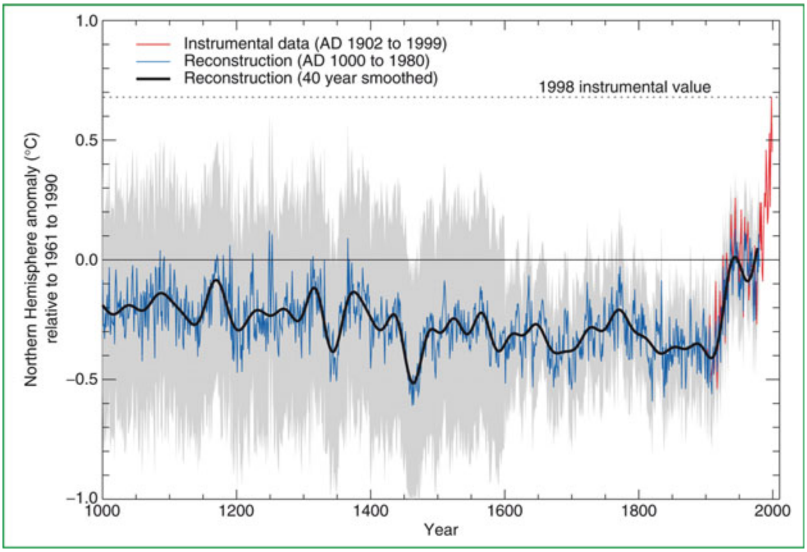

Fig. 9.5 'Hockey Stick graph' in the version published in the IPCC Report of 2001
Source: IPCC 2001, Fig. 2-20

In the year 2001 the Intergovernmental Panel on Climate Change (IPCC) took the graph on for its report. The graph was published several times in prominent positions within the reports (see Fig. 9.5); Michael E. Mann was co-author of the explanatory paragraphs. The presence of the graph on page three of the Summary for Policy Makers in particular reveals the high evaluation of the chart from a scientific perspective, but also the esteem in which it was held as a clear and visually convincing image, good for popularisation. People seeking information on climate change could not overlook the graph because of the great popularity of the IPCC Report. As a consequence many interest groups used the curve for their own purposes. Environmental organisations and politicians adopted the picture for their publications and talks; it was published in several newspapers; and it was repeatedly printed in climate atlases and reference books on climate change issues for the broader public. In this way the graph became a main piece of evidence for the existence of human-induced climate change, which at the time was still a matter of great controversy.

In the process of being transferred from its former context to the IPCC Report for the purpose of broader popularisation, the graph changed its appearance. The colour symbolism and design were modified in order to produce a more straightforward message and an aesthetically more pleasant image. The front section of the curve is now blue, and the rise in the curve is still red; this colour coding conforms to the convention of red and blue marking hot and cold temperatures, which has existed since the end of the nineteenth century. The calculated interpolation condenses the curve to a dominant black line; the shaft of the hockey stick is presented in a dotted pink outline. Finally, the corridor, which marks the uncertainty of the data in question, is now printed in a colourless, soft grey. This information not only fades into the background because of its colour, but is again not mentioned in the figure's caption. It can be assumed that the highlighting of the uncertainty within the scientific image has been reduced because it stands in opposition to the clear message needed in political contexts.

As in the ice-core graph in the movie *An Inconvenient Truth*, the abnormal development of the Earth's climate during recent decades is enhanced by a large frame of comparison. The form of a hockey stick is a product of the chosen scale, which makes variations in temperatures obvious within a range of ±1°C on the axis of ordinates. Moreover, the graph published in the *Geophysical Research Letters* (see Fig. 9.4) offered a significant point of identification for all readers. When the article was published in 1999, people had just experienced the hottest year since records had begun. The year 1998 therefore marks the highest point in the line's trajectory, a point remote from the 'normality' that had prevailed over previous centuries, not only since weather records began, but since the year 1000. In the graph, the end of the curve is marked with an extra arrow, which functions rather like a landmark saying 'you are here'. The colour red in this chart has two meanings. Firstly it shows that temperatures began to rise at the same time as meteorologists started to record the weather using meteorological instruments. Of much greater importance, though, is the contemporaneity of industrialization and rising temperatures, which the curve makes evident.

All of these visual strategies are part of the traditional conventions of informational graphic design, where colours and signs are used in symbolic ways and scales are employed to achieve significant forms. Choosing a scale to make the trend of a curve more meaningful has nothing to do with distortion, as the graphical clarification is consistent with the numerical representation of the data (Tufte 1997, p. 55). Yet even within the existing range of consistency there are certain strategies for highlighting one's information. Within these conventions Mann and his colleagues channelled the results of their research into the form of a clear image, showing climate history as it develops into an alarming abnormal increase in temperature. The colour red signifies the danger of a development which seems impossible to reverse. Assuming this trend continues, the curve presents the striking image of an imminent man-made climate catastrophe, calling for rigorous action.

The hockey stick graph succeeded in mobilizing public opinion to fight against global warming. At the same time, as already briefly mentioned, it sparked off a controversy about the correctness of Mann's methods. The graph had turned into the main evidence when it came to doubting human-induced global warming, so to prove the flawed basis of the graph was also to prove that the present climate situation merely represented a natural cycle and was therefore "normal". Through these doubts some sceptics hoped not only to find the errors in Mann's reconstruction, but to disprove his core statement, which was that the Earth's climate is changing because of human economic activities. Healthy scepticism is part of the process of doing science, of course, paving the way for new research. Parallel to the spread of Mann's graph, therefore, there arose a great number of critiques, further investigations, and sceptical reconstructions of the curve in different contexts and disciplines, which did indeed show that in some points Mann's reconstruction contained errors.[11] New reconstructions, which followed Mann's method using the same proxy data or new proxies, show greater variations in the temperature trends, yet the general trend of the curve and thus also the message of the graph has remained valid. Because of the uncertainties always associated with proxy methods in the reconstruction of climate history, there cannot be a "true" reconstruction of the Earth's climate, but only an approximation.

Because of its clarity and significance, Mann's graph became one of the most famous pictures in the debate on global warming. The curve is therefore the visual element of the discourses of one-upmanship that shape the popular "problem construct" of climate change (Peters and Heinrichs 2005; Weingart et al. 2008).

In 2004, a spectacularly illustrated report by the Arctic Panel, the *Arctic Climate Impact Assessment*, subsequently combined the different graphs representing climate history (see Fig. 9.6; Arctic Council 2004). The chart is given a three-dimensional design, showing three history curves from an unusual, oblique perspective. On the left side, at the very front of the picture the curves start in the past, and the passage of time leads towards the back of the image, into the present. In the background, Mann's temperature reconstruction is shown as a thin pink zig-zag line, in this case even more reminiscent of a temperature curve; at the front of the curve the designers inserted a brown shape showing the reconstruction of atmospheric CO_2 concentrations derived from ice cores. In the foreground plane they placed the annual release of atmospheric carbon dioxide through economic activities, differentiated into yellow (land-use changes) and pink (fossil-fuel carbon emissions). In contrast to the insubstantial line recording the temperature, the curves showing CO_2 concentrations and emissions seem to possess a heavy materiality, rather like geological sediments. In this image the different origins of the data—Antarctica or the northern hemisphere, ice core or tree rings—have been combined into a collage. The corridor of uncertainty accompanying Mann's chart is omitted completely from this version; it is not part of the reproduction. Instead the correspondence between human economic activities and the rise in CO_2 concentrations and temperatures is now presented in a way that leaves little room for debate on the graph's core statement. Climate history is not only gathered within one space, but even turned into one uniform story. The modification of the curves into a three-dimensional perspective can be interpreted as making the sober curves seem more interesting and pleasant to the eye. On the other hand, the combined scientific graphs have been modified in a way that makes them seem more convincing and clear in their meaning for people without a climatological background.

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[11] Because of the relevance of the graph's message, the US Senate eventually ordered a detailed study to assess the meaning of Mann's reconstruction of climate history (National Research 2006).

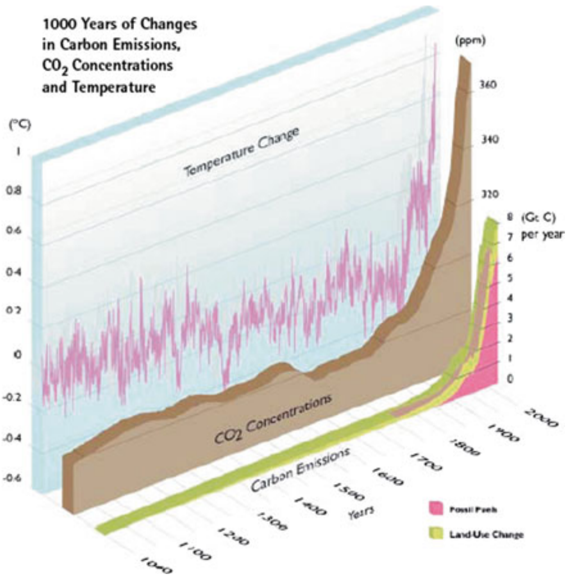

Fig. 9.6 Hockey Stick composite graph. Chart published in the report "Impacts of Warming Arctic" (2004), which was ordered by the intergovernmental
Arctic Council
Source: Arctic Council 2004, p. 3

9.5 Collages of Time and Space: Picturing Possible Futures

Another chart composition extends the hockey stick graph of the northern hemisphere over the last millennium into the global future as far as the year 2100 (see Fig. 9.7). Historical reconstructions, measurements from 1860 to today, and projections to the end of the current century are shown in one coherent space. This version is taken from the IPCC Synthesis Report 2001. It has been reprinted, for example, in a book by the reinsurance company Münchner Rück (Rückversicherung 2005), which was published for the broader public to give a summary of the relevant information about climate change. This chart will be the final example, as it is an attempt to produce an understandable image representing the complex issue of possible climate futures.

The solid red line has distinct connotations in the four different segments marked by different shades of yellow, grey and green, with each of the four sections of the line representing a different kind of knowledge. The first segment represents the reconstruction of the climate history of the northern hemisphere by proxy data. The second segment tells the ongoing history calculated on the basis of instrumental observation (weather records). What interests us here is the continuation of the graph into the green segment, entitled 'projections'. At this point the red line fans out into seven different lines. These linear projections provide an image of the future.

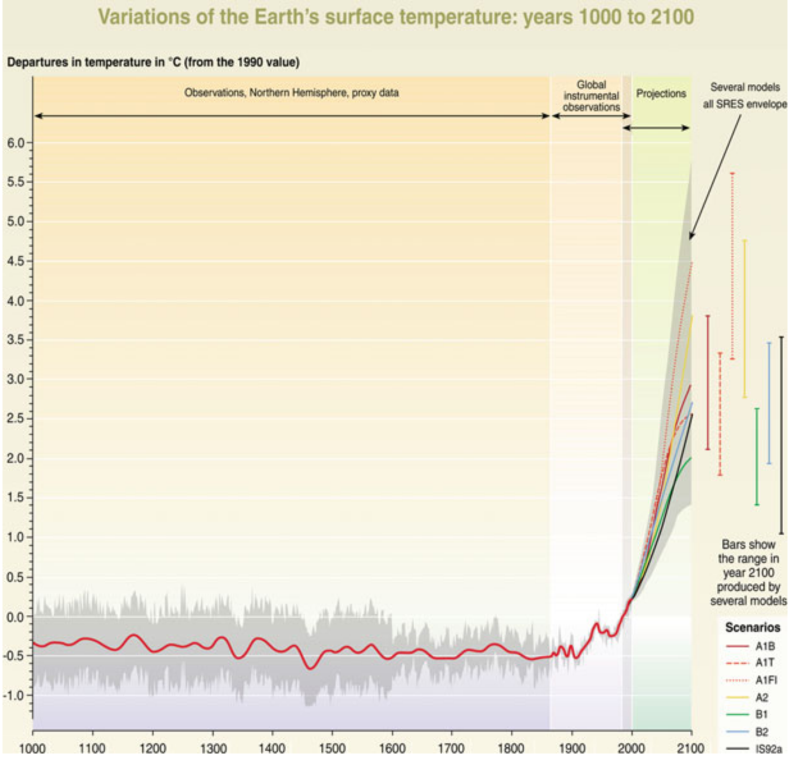

Fig. 9.7 Collage made from different mean-temperature graphs, juxtaposing historical reconstructions based on proxy data and future projections as far as the year 2100 *Source*: IPCC 2001

The seven coloured lines show various possible futures depending on the 'story lines' of the different future scenarios that underlie the model. In the context of present-day climatology, the most important graphs picturing the future are known as SRES-Scenarios.[12] The *Special Report on Emissions Scenarios* (Nakicenovic and Swart 2000) outlines 40 future emission scenarios that can be used for driving global circulation models on supercomputers to calculate climate change scenarios. They vary in their assumptions about future greenhouse gas pollution, depending on whether political measures are taken on a global or regional scale, as well as on population growth, world economic development and technological factors. The coloured lines show six scenarios, with one scenario from the 1995 report, known as the IS92a, by way of comparison. The projections shown are again enclosed by a grey corridor, which in this case is not an indicator of the trust in numbers, but shows the trajectories of all the models.

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[12] These new scenarios replaced the IS92 scenarios used for the IPCC Second Assessment Report of 1995 (see also Chap. 2 of this volume).

While the Earth's climate history is an interesting issue in its own right, the future of the climate is, of course, the focus of present socio-political interest. By developing their space into the future, the images make it possible not only to situate the present in relation to a historical range of 'normality', but to estimate possible futures within the same long-term framework. It becomes clear that the warming currently taking place is abnormal in relation to the course of the last 1,000 years. This special type of image confronts its observers with a hybrid space inhabited simultaneously by history, the present and future projections.

At the same time future graphs are even more delicate than the climate-history graphs discussed above. As soon as they leave the scientific context to be brought to the eyes of a broader public, they face the problem that many people are not used to thinking about futures in terms of probabilities or scenarios. Instead, there is a tendency to mistake the probability of possible futures for a forecast—to take fiction for reality. Probabilistic theory knows that possible futures will never materialize according to plan. "A world in which people take decisions not only has an uncertain future that depends on the decisions taken in the present. In this world the uncertainty is further multiplied by the number of people who take decisions" (Esposito 2007, pp. 51 and 52; quote translated by the author). Even so, scenarios play an important role in creating a contingent, global reality, for the space spanned by such visualizations makes it possible to discuss which future scenarios are desirable and which should be avoided (best case/worst case). As the philosopher Elena Esposito has suggested probabilistic theory is the modern way of coping with an uncertain future. It has become the tool of modernity to calculate the future. However, the probable has the status of the fictional, because the theory of probabilities "constructs a coherent world on the basis of explicitly imaginary premises" (Esposito 2007, p. 55–56; quote translated by the author). The fictional status of the probable is why it works since "... only for this reason does it provide us with the possibilities for orientation that 'real reality' cannot provide" (Esposito 2007, p. 55; quote translated by the author). Although the future will never go according to plan, the calculation promises its 'plannability' (Esposito 2007, p. 54). Statistical visualizations like the graph of the SRES scenarios do influence our conception of reality, as they are able to change what is perceived as normal by modification or adaptation. The space spanned by the fictional scenarios of future temperature development is therefore the framework within which it becomes possible to plan and discuss future reality, however this reality may turn out (Rosentrater 2010).

9.6 Conclusions: The Role of Pictures of Climate Change

It makes a difference what sort of images are brought into discussions about climate change, how they are designed and for what purpose, and with what effect they are distributed. The interplay of plain metaphors, scientific conventions like the trust in numbers of statistical thinking, strategies of visualization, narrative aesthetics and the passed-on conventions of visualization are shaping how this urgent socio-political field is conceived.

Even though the graphs picturing the history, present and future of the climate do not show images that are powerful in the conventional sense, as they are not as spectacular or overwhelming as the takes of melting poles or polar bears, the red end of a hockey stick graph can become an emblem of climate research in its entirety. It is also perceived as an evident symbol testifying to the presence of climate change in the language of science. This means that in the eyes of the public even a matter-of-fact graph like the hockey stick can be embedded into the meta-narratives of climate change, i.e. the plot of threat, realization, morality and possible salvation through timely action. Images thus represent logos, concentrated highlights of the debate, which stand for something much greater, which cannot be grasped fully by a single image.

The task of the images of popular science seems to be based on the assumption that the more powerfully and incontrovertibly the results are presented, the greater the capacity of politicians to take action. On the other hand—and this is where a contradiction lies—climatology deals in probabilities. In this area of research, statistics is the central discipline that provides the insights. For the interpretation of the curves in question, it is thus the spectrum of normality that serves as the decisive criterion of order (Link 2002).

The fact that a sober curve developed into the logo for the core statement of present-day climatology is part of a twentieth-century development that saw statistical curves in general become points of identification for a modern collective symbolism (Link 2002). This symbolism includes the interpretation of curve trajectories that contravene what is considered normal, such as drastic declines and exponential increases, as well as the projected extrapolation of the curve's trajectory beyond the limits of the graph. The red blade rising at the end of the hockey stick curve successfully unleashes the image of a climate catastrophe, with temperatures out of hand and the catastrophe beginning beyond the right-hand limit of the curve. The curve provides a fruitful frame of evaluation for today's weather: heat waves, hurricanes and floods are given an explanation by the blade of the hockey stick. Henceforth they are experienced as abnormal, even if there are times when they are just today's weather, and not yet the incontrovertible symptoms of a changing climate (Storch von and Stehr 2005).[13] In this sense, it is only by reference to the curve that even the press photos of the latest natural disaster are endowed with higher meaning.

Mann, who together with the IPCC won the 2007 Nobel Peace Award, seems to have recognized the power of images in evidence-creation through the varying responses to his climate-history curve. He is the author of the book *Dire*

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[13] That the public does not react more strongly to the threat of climate change when faced with graphic images of catastrophe is shown by a study published in 2006 by the Tyndall Centre for Climate Change Research. In this work experiments were carried out to find out whether watching films such as *The Day after Tomorrow* produces in individuals a greater reaction to the potential dangers of climate change than scientific texts with the same content (Lowe 1998).

Predictions, published in 2008, subtitled the *Illustrated Guide to the Findings of the IPCC*. This lavishly laid-out book is akin to a diagrammatically illustrated bible on the topic of climate change. Numerous climate atlases have also appeared on the same subject in recent years. The fact that the scientist Mann is now himself popularizing his insights again shows the broader, social construction of climatological knowledge: it is not only politicians who see their task as using the evidence of images to convince the general public, but climatologists themselves as well.

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His research focuses on methodological questions pertaining to a wide range of models and on political science questions related to dealing with uncertainty in policymaking. He has been active within the context of Working Group I of the Intergovernmental Panel on Climate Change (IPCC) – both as an expert and as a member of Dutch government delegations to IPCC meetings – to reflect on the assessment of uncertainties in climate models. He has led the agency's effort to reflect on and consolidate the modelling and scenario methods that the agency uses to produce its Sustainability Outlooks. He was a member of the core team for the production of the Second Sustainability Outlook. As the Director of the Methodology and Modelling Programme, he is closely involved in the agency's efforts in sustainability modelling, specifically the construction of the Global Integrated Sustainability Model (GISMO). He focuses on the question of how to deal with uncertainties and worldviews in sustainability assessment and how to account for institutions and governance in a modelling framework. The latter is done is close collaboration with the Institute for Environmental Studies (IVM) at the VU University Amsterdam.

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Abbreviations and Glossary

AAU Assigned Amount Unit. The quantity of greenhouse gases comprising one metric tonne of carbon dioxide equivalents that an Annex I country can release in accordance with the Kyoto Protocol, during the first commitment period of that protocol (2008–2012).

AeMP Aeronautical Meteorology Programme. A WMO program that provides meteorological support to meet the requirements of aviation for safe, economic and efficient air navigation. http://www.wmo.int/pages/prog/amp/aemp

AGGG Advisory Group on Greenhouse Gases. An advisory group established jointly by WMO, UNEP, and ICSU in 1985.

AGM Agricultural Meteorology Programme. A WMO program that supports food and agricultural production and activities. http://www.wmo.int/pages/prog/wcp/agm/agmp_en.html

AIRD Adaptation and Impacts Research Division. A division of Environment Canada concerned with current and future changes in the atmosphere. http://www.forestry.ubc.ca/aird

AMDAR Aircraft Meteorological Data Relay. The AMDAR Network is a subsystem of the WWW/GOS and provides high-quality wind and temperature data at cruising level as well as at selected levels in climb out and descent in the vicinity of selected major airports. Over 230,000 AMDAR reports are produced per day. http://www.wmo.int/pages/prog/www/Earthwatch/wmo-aeronaut-amdar.html

AMIP Atmospheric Model Intercomparison Project. AMIP-style simulations are routinely performed at many climate and NWP centres during model development in order to evaluate atmospheric model performance and identify errors. The systematic intercomparison of atmospheric model components is currently being coordinated under the Coupled Model Intercomparison Project (CMIP), which includes AMIP simulations as an integral part. http://www-pcmdi.llnl.gov/projects/amip/index.php

AMP Applications of Meteorology Programme. A WMO program that consists of four essential areas: Public weather services, agricultural meteorology, aeronautical meteorology and marine meteorology and oceanography. http://www.wmo.int/pages/prog/amp

Annex I Annex I Parties. The industrialized countries listed in this annex to the Convention which were committed return their greenhouse-gas emissions to 1990 levels by the year 2000 as per Article 4.2 (a) and (b). They have also accepted emissions targets for the period 2008–2012 as per Article 3 and Annex B of the Kyoto Protocol. They include the 24 original OECD members, the European Union, and 14 countries with economies in transition. (Croatia, Liechtenstein, Monaco, and Slovenia joined Annex 1 at COP-3, and the Czech Republic and Slovakia replaced Czechoslovakia.) List of Annex I Parties: http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php

APE Aqua-Planet Experiment Project. APE compares idealised climates simulated by global atmospheric circulation models which are being used and developed for numerical weather prediction and climate research. The experiment aims to provide a benchmark of current model behaviour and, more importantly, to stimulate research to understand the causes of inter-model differences, arising from different subgrid-scale parameterization suites, different dynamical cores, and different methods of coupling the two. http://www-pcmdi.llnl.gov/projects/amip/ape

APFM Associated Programme on Flood Management. APFM is a joint initiative of the WMO and the Global Water Partnership (GWP). It promotes the concept of Integrated Flood Management as a new approach to flood management. http://www.apfm.info

AREP Atmospheric Research and Environment Programme. AREP is a WMO program that co-ordinates and stimulates research on the composition of the atmosphere and weather forecasting, focusing on extreme weather events and socio-economic impacts. http://www.wmo.int/pages/prog/arep/overview.html

ARGO International observation system for the Earth's oceans. Argo is a global array of 3,000 free-drifting profiling floats that measures the temperature and salinity of the upper 2,000 m of the ocean. This allows, for the first time, continuous monitoring of the temperature, salinity, and velocity of the upper ocean, with all data being relayed and made publicly available within hours after collection. http://www.argo.ucsd.edu/

AR4 Fourth Assessment Report. Climate Change 2007. Assessment report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm#1

AR5 Fifth Assessment Report. Climate Change 2014. Assessment report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/activities/activities.htm#1

AOGCM General Circulation Atmosphere-Ocean Model. A mathematical model of the general circulation of a planetary atmosphere coupled with a model of the general circulation of the ocean. In 1969 Syukuro Manabe and Frank O. Bryan published their results of the first coupled ocean–atmosphere model developed at GFDL, which was able to reproduce the effects of ocean currents on the atmosphere's temperature and humidity (Manabe and Bryan 1969; see Chap. 2).

A/R WG Afforestation and Reforestation Working Group. The working group on afforestation and reforestation CDM project activities of the UNFCCC which was established to prepare recommendations on submitted proposals for new baseline and monitoring methodologies for A/R CDM project activities. http://cdm.unfccc.int/Panels/ar

BCC Beijing Climate Center, China. The BCC is one of the contributors of global climate model results to the IPCC Assessment Reports (BCC-CM1 model for AR4). http://bcc.cma.gov.cn/en/

BCCR Bjerknes Centre for Climate Research, Norway. The BCCR is one of the contributors of global climate model results to the IPCC Assessment Reports (BCM2.0 model for AR4). http://www.bjerknes.uib.no

BIPM Bureau International des Poids et Mesures. International Bureau of Weights and Measures which ensures world-wide uniformity of measurements and their traceability to the International System of Units (SI). http://www.bipm.org

Box model. Box models are simplified versions of complex models reducing them to boxes and describing flows across and within the different components of the climate system. They are used for testing parametrizations and for deriving analytical formulas.

BSH Basic Systems in Hydrology. A WMO program that assists National Hydrological and Hydrometeorological Services in the development and maintenance of their activities for the provision of data and products with an emphasis on quality assurance, thereby promoting the effective use of hydrological data and information in support of sustainable socio-economic development. http://www.wmo.int/pages/prog/hwrp/basicsys.html

CALP Collaborative for Advanced Landscape Planning. A group that is specialized in landscape visualization, public consultation in land use planning, and environmental perception at the University of British Columbia. http://www.calp.forestry.ubc.ca

CAS Chinese Academy of Sciences. The CAS is one of the contributors of global climate model results to the IPCC Assessment Reports (FGOALS-g1.0 model for AR4). http://english.cas.cn

CBH Capacity-building in Hydrology and Water Resources Management. A WMO program that facilitates the rational development and operation of National Hydrological and Hydrometeorological Services, including staff education and training, increased public awareness of the importance of hydrological activities, and provision of support through technical cooperation activities. http://www.wmo.int/pages/prog/hwrp/capbuild.html

CCA Climate Coordination Activities. A WMO program that supports implementation of climate-related Conventions and Protocols. http://www.wmo.int/pages/prog/wcp/cca/cca_home_en.html

CCS Carbon Capture Storage. Technology to prevent the carbon dioxide building up in the atmosphere by storing it.

CCSM Community Climate System Model. One of the very first community models in climate research developed by the US-American University Corporation for Atmospheric Research (UCAR) in the mid 1990s. CCSM is the forerunner of the Community Earth System Model (CESM). http://www.cesm.ucar.edu

CCSR Center for Climate System Research, Japan. The CCSR, together with the Japanese National Institute for Environmental Studies and the Frontier Research Center for Global Change, is one of the contributors of global climate model results to the IPCC Assessment Reports (MIROC3.2 model for AR4). http://www.ccsr.u-tokyo.ac.jp

CDM Clean Development Mechanism. The mechanism provided by Article 12 of the Kyoto Protocol, designed to assist developing countries in achieving sustainable development by permitting industrialized countries to finance projects for reducing greenhouse gas emission in developing countries and receive credit for doing so. http://cdm.unfccc.int

CDM AP CDM Accreditation Panel. The panel prepares the decision making of the CDM EB in accordance with the procedure for accrediting operational entities. http://cdm.unfccc.int/Panels/accreditation/index.html

CER Certified Emission Reduction. A unit of greenhouse gas emission reductions issued pursuant to the Clean Development Mechanism of the Kyoto Protocol, and measured in metric tons of carbon dioxide equivalent. http://www.cdmrulebook.org/304

CESM Community Earth System Model. A fully-coupled, global climate model that provides state-of-the-art computer simulations of the Earth’s past, present, and future climate states. CESM is developed by the US-American University Corporation for Atmospheric Research (UCAR). http://www.cesm.ucar.edu

CFCs Chlorofluorocarbons. Chemical compounds which were developed in the early 1930s and used in a variety of industrial, commercial, and household applications. They are non-toxic, non-flammable, and non-reactive with other chemical compounds. CFCs have been implicated in the accelerated depletion of ozone in the Earth’s stratosphere. They are short-lived species of greenhouse gases.

CGCM Canadian Centre for Climate Modelling and Analysis. The CGCM is one of the contributors of global climate model results to the IPCC Assessment Reports (CGCM3.1 model for AR4). http://www.ec.gc.ca/ccmac-cccma/

CH_4 Methane. Methane is a natural, invisible, and odourless gas. Methane enters the atmosphere from both natural (30%) and anthropogenic (70%) sources. As a greenhouse gas it ranks second to carbon dioxide.

CIMO Commission for Instruments and Methods of Observations. Commission of the WMO Instruments and Methods of Observation Programme (IMOP) that sets technical standards, quality control procedures and guidance for the use of meteorological instruments and observation methods in order to promote development documentation and world-wide standardization. http://www.wmo.int/pages/prog/www/IMOP/IMOP-home.html

CITL Community Independent Transaction Log. Each EU Member State has its own national registry containing accounts which will hold the EU allowances. These registries interlink with the Community transaction log, operated by the Commission, which will record and check every transaction. http://ec.europa.eu/environment/ets

CliC The Climate and Cryosphere Project. A WCRP program that stimulates, supports, and coordinates research into the processes by which the cryosphere interacts with the rest of the climate system. http://www.climate-cryosphere.org

ClimDevAfrica Climate for Development in Africa. An integrated, multi-partner program, coordinated by the WMO, that addresses climate observations, climate services, climate risk management, and climate policy needs in Africa. http://www.wmo.int/pages/prog/gcos/index.php?name=ClimDevAfrica

CLIMBER Climate and Biosphere Model. An Earth system model of intermediate complexity of the Potsdam Institute for Climate Impact Research. http://www.pik-potsdam.de/research/past/1994-2000/poem/climber/index.html

CLIPS Climate Information and Prediction Services. A WMO program that strives to take advantage of current data bases, increasing climate knowledge and improving prediction capabilities to limit the negative impacts of climate variability and to enhance planning activities based on the developing capacity of climate science. http://www.wmo.int/pages/prog/wcp/wcasp/wcasp_home_en.html

CLIVAR Climate Variability and Predictability. A WCRP project that observes, simulates, and predicts the Earth's climate system with a focus on ocean-atmosphere interactions in order to better understand climate variability, predictability and change. http://www.clivar.org

CMIP Coupled Model Intercomparison Project. A model intercomparison project for global coupled ocean-atmosphere general circulation models that started in 1995 under the auspices of the IPCC Working Group on Coupled Modelling (WGCM). The purpose of the current CMIP5 experiments is to address outstanding scientific questions that arose as part of the IPCC AR4 process, improve understanding of climate, and to provide estimates of future climate change that will be useful to those considering its possible consequences. http://www-pcmdi.llnl.gov/projects/cmip/index.php

CNRM Centre National de Recherches Meteorologiques, France. The CNRM of Météo-France is one of the contributors of global climate model results to the IPCC Assessment Reports (CNRM-CM3 model for AR4). http://www.cnrm.meteo.fr

COP Conference of Parties. The meeting of parties to the United Nations Framework Convention on Climate Change. http://unfccc.int/meetings/items/2654.php

CO_2 Carbon dioxide. A natural, colourless gas comprising 0.039% of the atmosphere. Carbon dioxide is a greenhouse gas that transmits visible light but absorbs strongly in the infrared and near-infrared. It plays an important part in vital plant and animal process, such as photosynthesis and respiration. Due to human activities, the amount of CO_2 released into the atmosphere has been rising extensively during the last 150 years of about 280 ppm in 1850 to nearly 390 ppm in 2010.

CO_2 eq. CO_2-equivalent. The concentration of carbon dioxide that would cause the same amount of radiative forcing as a given mixture of carbon dioxide and other greenhouse gases. A quantity that describes how much global warming a given type and amount of greenhouse gas may cause. The IPCC uses the unit of billion metric tonnes of CO_2 equivalent ($GtCO_2eq$).

CRB Change Review Broad. The board prioritises tasks and prepares a Core Team development schedule, and plans, authorizes, and reviews the content of the US-American Earth System Modelling Framework (ESMF) releases. http://www.earthsystemmodeling.org/management/crb/

CORDEX Co-ordinated Regional Climate Downscaling Experiment. A WCRP project for developing Regional climate downscaling (RCD) techniques, including both dynamical and statistical methods. http://copes.ipsl.jussieu.fr/RCD_CORDEX.html

CRM Cloud Resolving Models. A cloud model which consists on a fine resolution that resolves cloud-scale and mesoscale circulations.

CS Climate Sensitivity. CS refers to the equilibrium change in the annual mean global surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration. In 1979 the so-called Charney report firstly computed climate sensitivity using models developed by Syukuro Manabe et al. and James Hansen et al. (Charney et al. 1979; see Chap. 2).

CSIRO Marine and Atmospheric Research, Australia. The CSIRO is one of the contributors of global climate model results to the IPCC Assessment Reports (CSIRO-MK3.0 model for AR4). http://www.cmar.csiro.au

CWI Cooperation in Water-related Issues. A WMO program that supports and assists international river basin authorities and non-governmental and international organizations in their work in hydrology and water resources management. http://www.wmo.int/pages/prog/hwrp/watrel.html

C4E4 Cyberinfrastructure for End-to-End Environmental Exploration. An US-American project that provides a web-based platform which enables the environmental research and remediation community to address the challenges of environmental data management and integration in real-world settings. https://c4e4.rcac.purdue.edu:8453/gridsphere/gridsphere

DBCP Data Buoy Cooperation Panel. The DBCP is an international program coordinating the use of autonomous data buoys to observe atmospheric and oceanographic conditions, over ocean areas where few other measurements are taken. http://www.jcommops.org/dbcp

DDC Data Distribution Centre. Web-based platform of the Intergovernmental Panel on Climate Change. The DDC provides climate, socio-economic and environmental data, both from the past and also in scenarios projected into the future. http://www.ipcc-data.org/

DEISA Distributed European Infrastructure for Supercomputing Applications. A consortium of leading European national supercomputing centres that aims at fostering the European computational science research. http://www.deisa.eu

DOE Designated Operational Entity. An independent entity, accredited by the CDM Executive Board, which validates CDM project activities, and verifies and certifies emission reductions generated by such projects. http://cdm.unfccc.int/DOE/index.html

DRR Disaster Risk Reduction Programme. A WMO program that includes observing, detecting, monitoring, predicting and early warning of a wide range of weather-, climate- and water-related hazards. http://www.wmo.int/pages/prog/drr/

EB Executive Board. The Executive Board supervises the CDM under the authority and guidance of the Conference of the Parties (COP) serving as the meeting of the Parties to the Kyoto Protocol. http://cdm.unfccc.int/EB/index.html

EBM Energy Balance Models. EBMs calculate the radiative fluxes and the surface temperature assuming that all transport is diffusive.

ECMWF European Centre for Medium-Range Weather Forecasts. The ECMWF is an intergovernmental organisation supported by 32 European states, based in Reading, west of London. http://www.ecmwf.int

ECV Essential Climate Variables. ECVs are atmospheric, oceanic, and terrestrial variables which are technically and economically feasible for systematic observation, e.g., temperature, air pressure, salinity. ECVs are required to support the work of the UNFCCC, the IPCC and other organisations. http://gosic.org/ios/MATRICES/ECV/ecv-matrix.htm

ECX European Climate Exchange. ECX manages the product development and marketing for ECX Carbon Financial Instruments (ECX CFIs), listed and admitted for trading on the ICE Futures Europe electronic platform. http://www.theice.com

EEA European Environment Agency. EEA is an agency of the European Union that was adopted in 1990 and that provides information on the environment. It is a major information source for those involved in developing, adopting, implementing and evaluating environmental policy, and also the general public. http://www.eea.europa.eu/

EMIC Earth Models of Intermediate Complexity. EMICs include more processes and integrate more climate components than simple energy balance models. EMICs consist on a coarse horizontal resolution but they allow long-time integrations for studies of paleo climate or sensitivity studies.

ENES European Network for Earth System Modelling. European network for developing an advanced software and hardware environment in Europe, under which the most advanced high resolution climate models can be developed, improved, and integrated. The Infrastructure for the European Network for the Earth System Modelling (IN-ENES) is an FP7-Project funded by the European Commission under the Capacities Programme, Integrating Activities. http://www.enes.org

ENSO El Nino Southern Oscillation. ENSO is a quasi-periodic climate pattern that occurs across the tropical Pacific Ocean on average every 5 years, but over a period which varies from 3 to 7 years. It is characterised by variations in the Pacific Ocean's surface temperature that cause extreme weather such as floods, droughts and other weather disturbances.

EPA Environmental Protection Agency. EPA is an agency of the federal government of the United States charged with protecting human health and the environment. http://www.epa.gov

ERA Emergency Response Activities. A WMO program that involves the application of specialized atmospheric dispersion-modelling techniques to track and predict the spread of airborne hazardous substances in the event of an environmental emergency. http://www.wmo.int/pages/prog/www/DPFSERA/EmergencyResp.html

ERA ECMWF Reanalysis. Reference data set based on reanalysis data from the period 1989 to present provided by the European Centre for Medium-Range Weather Forecasts (ERA-15, ERA-40, ERA-Interim). http://www.ecmwf.int/research/era

ERU Emission Reduction Unit. A unit of emission reductions issued pursuant to Joint Implementation. This unit is equal to one metric ton of CO_2 eq.

ESG Earth System Grid. ESG integrates supercomputers with large-scale data and analysis servers located at numerous national labs and research centres in the USA to create an environment for next generation climate research. http://www.earthsystemgrid.org

ESM Earth System Model. ESMs are based on coupled ocean-atmosphere models, which include additionally biosphere and/or chemistry modules. ESMs simulate the behaviour of the atmosphere, the ocean, the cryosphere, the biosphere, and the interactions between these different components of the Earth system as well as the impact of human activities on climate.

ESMF Earth System Modeling Framework. US-American collaboration for building a high-performance, flexible software infrastructure to increase ease of use, performance portability, interoperability, and reuse in climate, numerical weather prediction, data assimilation, and other Earth science applications. http://www.earthsystemmodeling.org

ETRP Education and Training Programme. A WMO program that serves as an advisory body on all aspects of technical and scientific education and training in meteorology and operational hydrology. http://www.wmo.int/pages/prog/dra/etrp.php

EUA European Union Allowance. The tradable unit under the EU ETS. One EUA represents the right to emit one ton of CO_2.

EU ETS European Union Emissions Trading Scheme. The emissions permit trading scheme established by EU directive 2003/87/EC. http://ec.europa.eu/clima/policies/eu/index_en.htm

FAR First Assessment Report. Climate Change 1990. Assessment report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm#1

FEMA Federal Emergency Management Agency. US Federal emergency management organisation that collects data and information concerning emergency response strategies. http://www.fema.gov

FORTRAN Formula Translator. One of the oldest programming languages developed by a team of programmers at IBM led by John Backus and first published in 1957. FORTRAN is widely used for scientific modelling, e.g., in meteorology.

FRCGC Frontier Research Center for Global Change, Japan. The FRCGC, together with the Japanese National Institute for Environmental Studies and the Center for Climate System Research, is one of the contributors of global climate model results to the IPCC Assessment Reports (MIROC3.2 model for AR4). http://www.nies.go.jp

GAW Global Atmosphere Watch. A WMO program that provides reliable scientific data and information on the chemical composition of the atmosphere, its natural and anthropogenic change, and helps to improve the understanding of interactions between the atmosphere, the oceans and the biosphere. http://www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html

GBFP Georgia Basin Futures Project. A 5-year research initiative of the Sustainable Development Research Institute (SDRI) at the University of British Columbia, which combines expert knowledge and considers public opinion to explore pathways to sustainability through the use of emerging digital library/semantic learning networks (GBExplorer) and scenario modeling tools (GBQuest).

GB-QUEST Georgia Basin-QUEST. A computer-based scenario generation and evaluation system of the Sustainable Development Research Institute (SDRI) at the University of British Columbia.

GCM General Circulation Atmosphere Model. A mathematical representation of the general circulation of a planetary atmosphere or ocean, based on the Navier-Stokes equations applied on a rotating sphere. Atmospheric GCMs (AGCMs) and oceanic GCMs (OGCMs) are coupled together to form an atmosphere-ocean coupled general circulation model (AOGCM). AOGCMs are state-of-the-art models since TAR.

GCOS Global Climate Observing System. A conjoint WMO, IOC, UNEP and ICSU program that provides comprehensive information on the total climate system, involving a multidisciplinary range of physical, chemical and biological properties, and atmospheric, oceanic, hydrological, cryospheric and terrestrial processes. http://www.wmo.int/pages/prog/gcos

GDP Global Gross Domestic Product. A measure of a country's overall economic output.

GDPFS Global Data-processing and Forecasting System. A WMO program that prepares meteorological analyses and forecast products. http://www.wmo.int/pages/prog/www/DPS/gdps.html

GÉANT European high-speed net. The GÉANT network is a fast and reliable pan-European communications infrastructure of the European research and education community. http://www.geant.net

GEIA Global Emissions Inventory Activity. Created in 1990 as an activity of the International Geosphere-Biosphere Program (IGBP), GEIA develops and distributes global emissions inventories of gases and aerosols emitted into the atmosphere from natural and anthropogenic (human-caused) sources. http://www.geiacenter.org

GENIE Grid-ENabled Integrated Earth system model. A British grid-based computing framework to flexibly couple together state-of-the-art components to form a unified Earth System Model. http://www.genie.ac.uk

GEWEX Global Energy and Water Cycle Experiment. An integrated program of the WCRP to reproduce and predict the variations of the global hydrological regime, its impact on atmospheric and surface dynamics, and variations in regional hydrological processes and water resources and their response to changes in the environment, such as the increase in greenhouse gases. http://www.gewex.org

GFDL Geophysical Fluid Dynamics Laboratory, USA. GFDL is one of the contributors of global climate model results to the IPCC Assessment Reports (CM2.0 and CM2.1 models for AR4). http://www.gfdl.noaa.gov

GHG Greenhouse gases. These are the gases released by human activity that are responsible for climate change and global warming. The six gases listed in Annex A of the Kyoto Protocol are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_{20}), as well as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).

GISS NASA Goddard Institute for Space Studies, USA. GISS is one of the contributors of global climate model results to the IPCC Assessment Reports (GISS-AM, -EH, and -ER models for AR4). http://www.giss.nasa.gov

GNP Gross National Product. An economic statistic that includes GDP.

GMT Global Mean Temperature. Averaged data set of temperature records, e.g., GISS Surface Temperature Analysis http://data.giss.nasa.gov/gistemp

GOS Global Observing System. Observing facilities that provide from the Earth and from outer space observations of the state of the atmosphere and ocean surface for the preparation of weather analyses, forecasts, advisories and warnings, for climate monitoring and environmental activities carried out under programmes of

WMO and of other relevant international organizations. http://www.wmo.int/pages/prog/www/OSY/GOS.html

GRIB Gridded Binary. WMO featured data format commonly used in meteorology to store historical and forecast weather data. http://www.wmo.int/pages/prog/www/WDM/Guides/Guide-binary-2.html

GWP Global Warming Potential. An index, based upon radiative properties of well-mixed greenhouse gases, measuring the radiative forcing of a unit mass of a given well-mixed greenhouse gas in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide. The GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation.

Had Hadley Centre for Climate Prediction and Research/Met Office, UK. The Hadley Centre is one of the contributors of global climate model results to the IPCC Assessment Reports (UKMO-HadCM3 and UKMO-HadGEM models for AR4). http://www.metoffice.gov.uk/climatechange/science/hadleycentre/

HDF5 Hierarchical Data Format. A data model, library, and file format for storing and managing data.

HFC Hydrofluorocarbons. HFCs are man-made chemicals containing the element fluorine used predominantly as refrigerants and aerosol propellants. They are colourless, odourless and chemically unreactive gases. They are greenhouse gases, primarily being used as replacements to ozone damaging CFCs and HCFCs.

HFWR Hydrological Forecasting in Water Resources Management. A WMO program to promote the application of hydrological modeling and forecasting techniques, and of risk assessment and management approaches to the risk reduction and prevention of water-related disasters. http://www.wmo.int/pages/prog/hwrp/for_appl.html

HOMS Hydrological Operational Multipurpose System. A WMO program for the transfer of technology in hydrology and water resources. http://www.wmo.int/pages/prog/hwrp/homs/homs_index.html

HPC High-Performance Computing. Computing based on supercomputers and computer clusters to solve advanced computation problems. The TOP500 list ranks the world’s 500 fastest high-performance computers. http://www.top500.org

HWRP WMO Hydrology and Water Resources Programme. A WMO program which is concerned with the assessment of the quantity and quality of water resources. http://www.wmo.int/pages/prog/hwrp/index_en.html

ICSU International Council of Scientific Unions. Founded in 1931 to promote international scientific activity in the different branches of science and its application for the benefit of humanity. The ICSU is one of the oldest non-governmental organizations in the world. Its aim is to strengthen international science. http://www.icsu.org

IET International Emission Trading. International Emissions Trading (Article 17 of the Kyoto Protocol) specifies that Annex I countries be allowed to trade assigned amount units (AAUs) with each other. The International Emissions Trading Association is an independent, non-profit organization dedicated to the establishment of effective systems for trading greenhouse gas emissions. http://www.ieta.org

IFM Integrated Flood Management Helpdesk. The HelpDesk is a facility that provides guidance on flood management policy, strategy, and institutional development related to flood issues. It is a joint initiative of the WMO and the Global Water Partnership (GWP). http://www.apfm.info/helpdesk.htm

IGY International Geophysical Year. An international scientific project (July 1, 1957 to December 31, 1958) that allowed scientists from around the world to take part in a series of coordinated observations of various geophysical phenomena. It was modelled on the International Polar Years of 1882–1883 and 1932–1933.

IIASA International Institute for Applied Systems Analysis. An international research organization that conducts policy-oriented research into problems that are too large or too complex to be solved by a single country or academic discipline. http://www.iiasa.ac.at

IMO International Meteorological Organization. International organisation (1873–1953) for exchanging weather information, which was the forerunner of the WMO.

IMOP Instruments and Methods of Observation Programme. A WMO program that sets technical standards, quality control procedures and guidance for the use of meteorological instruments and observation methods in order to promote development documentation and world-wide standardization. http://www.wmo.int/pages/prog/www/IMOP/IMOP-home.html

INC Intergovernmental Negotiating Committee on Climate Change. A committee, established by the General Assembly of the UN, that produced the text of the United Nations Framework Convention on Climate Change (UNFCCC) which was opened for signature on May 9, 1992.

INM Institute for Numerical Mathematics, Russia. INM is one of the contributors of global climate model results to the IPCC Assessment Reports (INM-CM3.0 model for AR4). http://www.inm.ras.ru

IOC Intergovernmental Oceanographic Commission. A commission of UNESCO that promotes international cooperation and coordinates programmes in marine research, services, observation systems, hazard mitigation and capacity development in order to learn more and better manage the nature and resources of the ocean and coastal areas. http://ioc-unesco.org

IPCC Intergovernmental Panel on Climate Change. A co-sponsored program of the WMO and the UNEP which is the leading body for the assessment of climate change. The IPCC is a scientific body. It reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change. It does not conduct any research nor does it monitor climate related data or parameters. Thousands of scientists from all over the world contribute to the work of the IPCC on a voluntary basis. The IPCC publishes the IPCC Assessment Reports. http://www.ipcc.ch

IPCC AR Assessment Report of the Intergovernmental Panel on Climate Change. Since 1990 four Assessment Reports have been published by the IPCC: FAR 1990, SAR 1995, TAR 2001, AR4 2007. The fifth IPCC Assessment Report AR5 will be released in 2014. Each report consists of three volumes prepared by the three IPCC Working Groups. http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm

IPCC WG Working Groups of the Intergovernmental Panel on Climate Change. The IPCC work is shared among three Working Groups, a Task Force and a Task Group. The activities of each Working Group and of the Task Force are coordinated and administrated by a Technical Support Unit. WGI assesses the physical scientific aspects of the climate system and climate change. WGII assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it. WGIII assesses options for mitigating climate change through limiting or preventing greenhouse gas emissions and enhancing activities that remove them from the atmosphere. http://www.ipcc.ch/working_groups/working_groups.htm

IPCC TGI Task Force on National Greenhouse Gas Inventories. The task force was established by the IPCC to oversee the IPCC National Greenhouse Gas Inventories Programme (IPCC-NGGIP). http://www.ipcc-nggip.iges.or.jp/

IPCC TGICA Task Group on Data and Scenario Support for Impacts and Climate Analysis. The task group was established to facilitate co-operation between the climate modeling and climate impacts assessment communities. The TGICA oversees a Data Distribution Centre (DDC) which provides data sets, scenarios of climate change and other environmental and socio-economic conditions. http://www.ipcc.ch/working_groups/working_groups_tgica_and_ddc.htm

IS92 Emission Scenarios. Six alternative scenarios (IS92a to f) which were used for the Second IPCC Assessment Report in 1995 and which were published in the 1992 Supplementary Report. http://sedac.ciesin.columbia.edu/ddc/is92/

ISPL Institut Pierre Simon Laplace, France. ISPL is one of the contributors of global climate model results to the IPCC Assessment Reports (IPSL-CM4 model for AR4). http://www.ipsl.fr

ITL International Transaction Log. Verifies transactions (AAU, ERU, CER etc.) proposed by registries to ensure they are consistent with rules agreed under the Kyoto Protocol. http://unfccc.int/kyoto_protocol/registry_systems/itl/items/4065.php

JI Joint Implementation. Mechanism provided by Article 6 of the Kyoto Protocol, whereby a country included in Annex I of the UNFCCC and the Kyoto Protocol may acquire Emission Reduction Units when it helps to finance projects that reduce net emissions in another industrialized country, including countries with economies in transition. http://unfccc.int/kyoto_protocol/mechanisms/joint_implementation/items/1674.php

KMA Korea Meteorological Administration. The KMA, together with the German Meteorological Institute of the University of Bonn and the Model and Data Group Hamburg, is one of the contributors of global climate model results to the IPCC Assessment Reports (ECHO-G model for AR4). http://web.kma.go.kr/eng/

KP Kyoto Protocol. Adopted at the Third Conference of the Parties to the United Nations Convention on Climate Change held in Kyoto, Japan in December 1997, the Kyoto Protocol commits industrialized country signatories to reduce their greenhouse gas (or "carbon") emissions by an average of 5.2% compared with 1990 emissions, in the period 2008–2012. http://unfccc.int/kyoto_protocol/items/2830.php

M&D Model and Data Group, Germany. The M&D group provides support for development and implementation of best practice methods for Earth system modelling and related data management. Together with the German Meteorological Institute of the University of Bonn and the Korean Meteorological Administration it is one of the contributors of global climate model results to the IPCC Assessment Reports (ECHO-G model for AR4). http://www.mad.zmaw.de/

Meteo-Bonn Meteorological Institute of the University of Bonn, Germany. The Meteorological Institute, together with the Korean Meteorological Administration and the German Model and Data Group Hamburg, is one of the contributors of global climate model results to the IPCC Assessment Reports (ECHO-G model for AR4). http://www.meteo.uni-bonn.de

MMM Multi-model mean. Un-weighted: An average of simulations in a multi-model ensemble, treating all models equally. Weighted: An average across all simulations in a multi-model dataset that does not treat all models equally. Model 'weights' are generally derived from some measure of a model's ability to simulate the observed climate (i.e., a model quality metric/index), based on how processes are implemented or based on expert judgment. Weights may also incorporate information about model independence. http://www.ipcc.ch/pdf/supporting-material/IPCC_EM_MME_GoodPracticeGuidance Paper.pdf

MMOP Marine Meteorology and Oceanography Programme. A WMO program that regulates, coordinates and facilitates the sustained provision of global and regional coverage observational data, products and services to address the continued and expanding requirements of the maritime user community for met-ocean services and information, focusing on safety of life and property at sea, and integrated coastal management and societal impacts. http://www.wmo.int/pages/prog/amp/mmop/

MOP Meeting of the Parties. Since 2005 COP is accompanied by the Meeting of the Parties to the Kyoto Protocol. http://unfccc.int/meetings/items/2654.php

MRI Meteorological Research Institute, Japan. The MRI is one of the contributors of global climate model results to the IPCC Assessment Reports (MRI-CGCM2.3.2 model for AR4). http://www.mri-jma.go.jp

NIES National Institute for Environmental Studies, Japan. The NIES, together with the Japanese Frontier Research Center for Global Change and the Center for Climate System Research, is one of the contributors of global climate model results to the IPCC Assessment Reports (MIROC3.2 model for AR4). http://www.jamstec.go.jp

N_2O Nitrous Oxide. Laughing gas, a colourless non-flammable gas, with a slightly sweet odour and taste, which was first synthesized in 1772. It is a major greenhouse gas and air pollutant. Considered over a 100 year period, it has 298 times more impact per unit weight than carbon dioxide.

MPI-Met Max Planck Institute for Meteorology, Germany. The MPI-Met is one of the contributors of global climate model results to the IPCC Assessment Reports (ECHAM5/ MPI-OM model for AR4). http://www.mpimet.mpg.de

NCAR National Center for Atmospheric Research. A US-American federally funded research and development center, located at Boulder CO, devoted to service, research and education in the atmospheric and related sciences. The Community Earth System Model (CESM) is the latest in a series of NCAR-based global models developed over the last 30 years. NCAR is one of the contributors of global climate model results to the IPCC Assessment Reports (CCSM3 and PCM models for AR4). http://ncar.ucar.edu

NCDC US-National Climatic Data Center. NCDC is the world's largest active archive of weather data. It operates the World Data Center for Meteorology which is co-located at NCDC in Asheville, North Carolina, and the World Data Center for Paleoclimatology which is located in Boulder, Colorado. http://www.ncdc.noaa.gov/oa/ncdc.html

NECP US-National Centers for Environmental Prediction. NCEP delivers national and global weather, water, climate and space weather guidance, forecasts, warnings and analyses to its Partners and External User Communities. http://www.ncep.noaa.gov

netCDF Network Common Data Form. A freely available set of software libraries and machine-independent data formats that support the creation, access, and sharing of array-oriented scientific data. http://www.unidata.ucar.edu/software/netcdf/

NGO Non Governmental Organisation. A legally constituted organization created by natural or legal persons that operates independently from any government.

NOAA National Oceanic and Atmospheric Administration. An US-agency for environmental issues including the National Environmental Satellite, Data, and Information Service; the National Marine Fisheries Service, the National Ocean Service, the National Weather Service, the Office of Oceanic and Atmospheric Research and the Office of Program Planning and Integration. http://www.noaa.gov

Non-Annex I Non-Annex I Parties. Refers to countries that have ratified or acceded to the United Nations Framework Convention on Climate Change that are not included in Annex I of the Convention. http://unfccc.int/parties_and_observers/parties/non_annex_i/items/2833.php

NWP Numerical Weather Prediction. Weather forecast based on mathematical models and calculated on computers. In 1950 the first weather model was computed by Jule Charney and his team on ENIAC. In 1956 the first climate model was computed by Norman Phillips (Charney et al. 1950, Phillips 1956; see Chap. 2).

OECD Organisation for Economic Co-operation and Development. An international economic organisation founded in 1961 to stimulate economic progress and world trade. http://www.oecd.org

O_3 Ozone. A gas that is an air pollutant in the lower atmosphere, but prevents potentially damaging ultraviolet light from reaching the Earth's surface in the upper atmosphere (ozone layer).

PBL Netherlands Environmental Assessment Agency. A Dutch institute for strategic policy analysis in the field of environment, nature and spatial planning. http://www.pbl.nl

PCMDI Programme for Climate Model Diagnosis and Intercomparison. A program which was established in 1989 at the Lawrence Livermore National Laboratory (LLNL) that develops improved methods and tools for the diagnosis and intercomparison of general circulation models (GCMs) that simulate the global climate, in particular for the IPCC simulation runs. http://www-pcmdi.llnl.gov

PDD Project Design Document. A project-specific document required under the CDM rules which will enable the Operational Entity to determine whether the project (i) has been approved by the parties involved in a project, (ii) would result in reductions of greenhouse gas emissions that are additional, (iii) has an appropriate baseline and monitoring plan. http://cdm.unfccc.int/Reference/PDDs_Forms/PDDs/index.html

PFCs Perfluorocarbons. Fluorocarbons that are extremely potent greenhouse gases with a lifetime up to 50,000 years. Primary source of tetrafluoromethane in the environment is from the production of aluminium by electrolysis of alumina.

PI Performance Index. Ranking of model performance from poor to good performance.

PIA Participatory integrated assessment. Integrated assessment approach that includes participating stakeholders.

PIK Potsdam Institute for Climate Impact Research, Germany. An interdisciplinary research institute located at Potsdam which foccusses on Earth system analysis, climate impacts and vulnerabilities, sustainable solutions and transdisciplinary concepts and methods. http://www.pik-potsdam.de

PITAC US-President's Information Technology Advisory Committee. Committee which reports to the President of the United States http://www.nitrd.gov/pubs/pitac/index.html

PMIP Paleoclimate Modelling Intercomparison Project. An international project that studies the role of climate feedbacks arising for the different climate subsystems and evaluates the capability of state of the art climate models to reproduce climate states that are radically different from those of today. http://pmip2.lsce.ipsl.fr

PRISM European Partnership for Research Infrastructures in Earth System Modelling. A distributed network of experts to help share the development, maintenance and support of standards and state-of-the-art software tools to assemble, run, and analyse the results of Earth System Models based on component models (ocean, atmosphere, land surface, etc.) developed in the different climate research centres in Europe and elsewhere. http://www.prism.enes.org

ProClim Swiss Forum for Climate and Global Change. Online platform of the Swiss Academy of Science which serves as an interface and enhances communication between science, public administration, politics, economy and the public. http://www.proclim.ch

PWSP Public Weather Services Programme. A WMO program that assists the National Meteorological and Hydrological Services to provide forecasts in the areas of weather, climate and water and to give warnings and information of high impact weather and extremes of climate, to government authorities. http://www.wmo.int/pages/prog/amp/pwsp

RA-I Reanalysis I. Reference data set based on reanalysis data for years 1968–1996 provided by the Physical Science Division of the US-Earth System Research Laboratory. http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html

RCM Regional Climate Models. RCMs increase the resolution of a GCM in a small, limited area of interest. The climate calculated by a GCM is used as input at the edges of the RCM. RCMs represent regional land surface (mountains, coastlines, changing vegetation characteristics etc.) on much smaller scales than GCMs.

RCP Representative Concentration Pathways. New scenarios of potential future anthropogenic climate change, underlying driving forces, and response options developed for the fifth IPCC Assessment Report. http://www.ipcc-data.org/guidelines/ddc_ar5_new_scenarios.html

RIT Registration and Issuance Team. The team assists the CDM Executive Board by appraising requests for registration of project activities and requests for issuance of CERs. http://cdm.unfccc.int/Panels/RIT/index.html

SAR Second Assessment Report. Climate Change 1995. Assessment report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm#1

SAT Space Programme. WMO Space Programme that coordinates environmental satellite matters, develops the space-based Global Observing System and promotes satellite data use for weather, water, climate and related applications. http://www.wmo.int/pages/prog/sat

SA90 Scenarios. The SA90 scenarios were used in the First IPCC Assessment Report in 1990 and updated by the IS92 scenarios.

SBSTA Subsidiary Body for Scientific and Technological Advice. One of the two permanent subsidiary bodies of the UNFCCC which give advice to the COP on scientific, technological and methodological matters. http://unfccc.int/essential_background/convention/convention_bodies/items/2629.php

SciDAC Scientific Discovery through Advanced Computing. Program of the US-Department of Energy to create the high performance computing software tools needed to advance scientific discovery using terascale supercomputers. http://www.scidac.gov

SEWG Software Engineering Working Group. Software Engineers of the Community Earth System Model of the US-American University Corporation for Atmospheric Research. http://www.cesm.ucar.edu/cseg/

SF_6 Sulphur hexafluoride. An inorganic, colourless, odourless, non-toxic and non-flammable gas which is the most potent greenhouse gas with a global warming potential of 22,800 times that of CO_2 when compared over a 100 year period.

SI International System of Units. International system of units of measurement based on six base units (metre, kilogram, second, ampere, kelvin, candela, and mole). The SI maintenance agency is the International Bureau of Weights and Measures (BIPM).

SMIP Seasonal Prediction Model Intercomparison Project. Experiments for evaluating seasonal predictability using ensembles of simulations with general circulation models, developed by the CLIVAR Working Group on Seasonal to Interannual Prediction. http://grads.iges.org/ellfb/SMIP2/smip.top.html

SO_2 Sulfur dioxide. A chemical compound produced by volcanoes and in various industrial processes which are a precursor to acid rain and atmospheric particulates.

SPARC Stratospheric Processes and their Role in Climate. A WCRP project that studies stratospheric processes and their role in climate. http://www.atmosp.physics.utoronto.ca/SPARC/index.html

SPM Summary for Policymaker. Summary of each volume of the IPCC Assessment Reports intended to aid policymakers. While the content is determined by the scientists, the form is approved line by line by governments. http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm

SPV Special Purpose Vehicles. A legal entity created to fulfil narrow, specific or temporary objectives.

SRES Special Report on Emission Scenarios. A set of 4 storylines and 40 emission scenarios developed for the Third and Fourth IPCC Assessment Reports and published in 2000 (Nakicenovic and Swart 2000; see Chap. 2). http://www.ipcc.ch/ipccreports/sres/emission/index.htm

SSC Small-Scale Panel. Working group established by the UNFCCC to prepare recommendations on submitted proposals for new baseline and monitoring methodologies for CDM small scale project activities. http://cdm.unfccc.int/Panels/ssc_wg

SWIC Severe Weather Information Centre. A WMO website that provides information based on advisories issued by Regional Specialized Meteorological Centres (RSMCs) and Tropical Cyclone Warning Centres (TCWCs), and official warnings issued by National Meteorological and Hydrological Services (NMHSs) for their respective countries or regions. http://severe.worldweather.org/

T21, T42, T63, T106. Horizontal resolution characteristic of the generations of climate models, e.g., used in the IPCC Assessment Reports: FAR (T21 $\approx$ 500 km), SAR (T42 $\approx$ 250 km), TAR (T63 $\approx$ 180 km), and AR4 (T106 $\approx$ 110 km).

TAR Third Assessment Report. Climate Change 2001. Assessment report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm#1

TCP Tropical Cyclone Programme. A WMO program that establishes national and regionally coordinated systems to ensure that the loss of life and damage caused by tropical cyclones are reduced to a minimum. http://www.wmo.int/pages/prog/www/tcp/

TFRCD Task Force on Regional Climate Downscaling. A WCRP task force for developing Regional Climate Downscaling (RCD) techniques for translating the global climate predictions into useful regional climate information, e.g., in the CORDEX experiment. http://wcrp.ipsl.jussieu.fr/SF_RCMTerms.html

THORPEX Observing System Research and Predictability Experiment. A WMO 10-year international research and development programme to accelerate improvements in the accuracy of 1-day to 2-week high impact weather forecasts for the benefit of society, the economy and the environment. http://www.wmo.int/pages/prog/arep/wwrp/new/thorpex_new.html

TOA Top of the Atmosphere. Used to specify the incoming radiative flux from the sun.

TSU Technical Support Units. Support unit for IPCC National Greenhouse Gas Inventories located at the Institute for Global Environmental Strategies (IGES) in Japan. http://www.ipcc-nggip.iges.or.jp/tsu/tsustaff.html

UCAR University Corporation for Atmospheric Research. US-American consortium of more than 70 universities in the field of atmospheric and related sciences located at Boulder CO, including the National Center for Atmospheric Research (NCAR). http://www.ucar.edu

UNCED United Nations Conference on Development and Environment. A UN conference which took place in Rio de Janeiro, Brazil, in 1992 June 2–14, also known as the Earth Summit. http://www.un.org/geninfo/bp/enviro.html

UNEP United Nations Environment Programme. An UN program that coordinates United Nations environmental activities and assists developing countries in implementing environmentally sound policies and practices. It was founded as a result of the United Nations Conference on the Human Environment in June 1972. http://www.unep.org

UNFCCC United Nations Framework Convention on Climate Change. The international legal framework adopted in June 1992 at the Rio Earth Summit to address climate change. It commits the Parties to the UNFCCC to stabilize human induced greenhouse gas emissions at levels that would prevent dangerous manmade interference with the climate system. http://unfccc.int

VER Voluntary Emission Reductions. Emission reduction from a voluntary project not bound to any legal framework or standard.

VER Verified Emission Reductions. An acceptable unit for Chicago Climate Exchange contracts, but not Kyoto.

The glossary is based on information provided by the listed websites, the IPCC Assessment Reports and various free encyclopaedias. All websites have been accessed in August 2010.

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