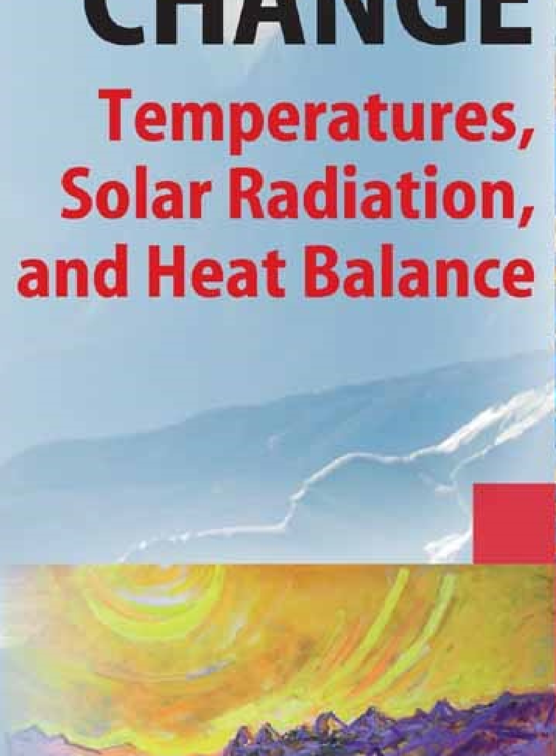
ASSESSING CLIMATE CHANGE

Temperatures, Solar Radiation, and Heat Balance



Donald Rapp

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PRAXIS

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Dr Donald Rapp
Independent Contractor
South Pasadena
California
USA

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Contents

Preface

THE GLOBAL-WARMING DEBATE

Global-warming alarmists believe that human production of greenhouse gases, particularly carbon dioxide, with its concomitant water vapor feedback mechanism, has begun to add to the natural greenhouse effect, thereby raising global temperatures inordinately during the 20th century, with predictions of further increases in the 21st century that could be catastrophic.

Dr. James E. Hansen, perhaps the most respected spokesman for the alarmists, said: ‘‘Ignoring the climate problem at this time, for even another decade, would serve to lock in future catastrophic climatic change and impacts that will unfold during the remainder of this century and beyond.’’ The Earth ‘‘is close to dangerous climate change, to tipping points of the system with the potential for irreversible deleterious effects . . . The planet is on the verge of dramatic climate change.’’ We ‘‘are forced to find a way to limit atmospheric CO_2 more stringently than has generally been assumed . . . We cannot shrink from our moral responsibilities . . . to preserve the planet for future generations.’’

Al Gore’s film *An Inconvenient Truth* has carried the message to many millions of people. This has spawned a growing world movement that is seeking controls on greenhouse gas emissions. Because such controls would have serious economic consequences, and furthermore, attempts to apply controls have been unbalanced relative to developed countries vs. developing countries, there has been strong resistance to such moves by naysayers.

Naysayers have maintained blogs and circulated reports, but generally have not penetrated the scientific literature that is dominated by alarmist publications. While the alarmists provide the impression of scientific integrity through peer-reviewed publications, the naysayers often lack the credentials of alarmists. But the important thing is data, not credentials.

Both sides have argued like trial lawyers with a case to be made, by craftily selecting bits and pieces of data to support their preconceived viewpoints. Fact, supposition, speculation, and pseudo-science have been mixed together in a brew that is confusing and difficult to resolve. One thing the world does not need is another high-level book arguing with assurance on one side of the question or the other, with little actual data content, manipulated to achieve an apparent conclusion based on specious arguments and cunningly selected references.

In this book, I have investigated a large body of technical data relevant to global climate change, approaching each element with necessary (but hopefully neutral) scientific skepticism. As Einstein said: "The goal is to be as simple as possible, but not simpler." Thus, by necessity, this book is quite technical, but hopefully still quite readable.

The essential questions are:

(1) How well has the world monitored near-surface temperatures of the 30% land and 70% ocean areas on Earth during the past 100 years or more, and how well can we characterize the changes in climate over that time span?
(2) What is the utility and significance of a single global average temperature?
(3) How has the Earth's climate varied over the past ice ages, the Holocene, the last millennium, and the past century, and what can we infer about "natural" variability of the climate prior to industrialization by humankind?
(4) How reliable are proxies for historical temperatures? What do we really know about past temperature variations? Is the *hockey stick* version of millennium temperatures credible, in which temperatures were flat for two thousand years prior to a sudden rise in the 20th century?
(5) How does the current global-warming trend compare with past fluctuations in the Earth's climate, and what is the likelihood that the warming trend we are experiencing now is primarily just another in a series of natural climate fluctuations as opposed to a direct result of human production of greenhouse gases?
(6) How credible are the global climate models that claim that greenhouse gases produced most of the temperature rise of the 20th century, and forecast much greater impacts in the 21st century?
(7) How good were the "good old days?" Was the climate of the Little Ice Age ideal, should we abhor warming from that baseline, and do we want to return to the climate of the 19th century?
(8) How will limits on fossil energy supplies constrain future CO_2 production and climate change, even if the climate models are accurate?
(9) How can the world provide itself with energy needed for a burgeoning population that will demand more and more energy in the future, considering the finite limits on fossil fuel resources?

According to Beckman and Mahoney (1998):

> "The vested interests on both sides of the argument between the 'greenhouse' party and the 'solar warming' party are obvious. Scientifically, the meteorologists,

climatologists, and atmospheric physicists, who were responsible for 'discovering' the human contribution to the terrestrial greenhouse effect, have been the most consistent champions of its importance, while the solar physics community, and especially those interested in solar–terrestrial relations, have increasingly stressed the possible importance of the long-term variations of the solar constant as the chief cause of climate change. Both communities tend to take the change for granted, and to neglect any purely statistical or chaotic effects which could lead to excursions of the Earth's surface temperature during periods of a couple of decades, without requiring a secular change either in the solar constant or in atmospheric transparency. In addition, the debate is conditioned by more powerful vested interest groups. The oil industry in all its guises would obviously like to believe, and would like the public to believe, that greenhouse warming has been greatly exaggerated, and exploits any genuine scientific differences to undermine the credibility of the climatologists."

Unfortunately, the majority of global-warming alarmists have weakened their cases by building them around models and analyses of dubious veracity, and in the case of the infamous *hockey stick* temperature profile, mathematically incorrect manipulations of past temperature data from proxies. From this, they have concluded improperly that the late 20th century is far warmer than any time in the distant past, and made other elaborate claims regarding recent warming trends and dire predictions for the near future that are unsupportable by the evidence. Furthermore, the network for monitoring the Earth's temperatures is inadequate to precisely characterize the trends in climate for the past ~100 years, and the utility of a single global average temperature is limited.

Projections for the 21st century are typically far out of line with realistic expectations. The credence attributed to global climate models belies their inherent fragility. This has provided the naysayers with plenty of ammunition with which to debunk these exaggerated claims. On the other hand, most of the naysayers made up their minds *a priori* that global warming in the 21st century due to CO_2 emissions is not a potential problem, and their arguments are often vague and hardly convincing.

A major problem in discussing climate change is that we lack a time period that we can objectively define as a base for comparison. As Anon. (N) emphasized, temperatures near the end of the 20th century were generally higher than those of the preceding four centuries. Taken at face value, this seems to imply that the preceding temperatures were normal, while the relatively higher temperatures at the end of the 20th century are comparatively abnormal. However, the preceding four centuries extended across the *Little Ice Age*, and therefore one might state the proposition differently: Temperatures during the preceding four centuries were colder than they were at the end of the 20th century. Stated this way, the abnormality is attributed to the *Little Ice Age*. Perhaps the most accurate statement is that there is no normal climate, and the climate of the Earth has always varied widely, and continues to do so to this day. As Balling, Vose, and Weber (1998) said:

"... it is entirely possible that the warming in the record of the past century has been caused by an unusually cool period 100 years ago as opposed to an unusually warm period in recent decades."

> Current warming trends seem more insidious when compared with a norm taken as the *Little Ice Age*.

By carefully sifting through the evidence, we find that there are no ironclad answers to major questions on global climate change. Our temperature data for the past century are fragmentary and sparse, both spatially and temporally. Urban heat islands and land clearing have affected measured temperatures. Past variations in solar irradiance can only be estimated with speculations. Proxies used to estimate the temperature history of the Earth over the past millennium are noisy and inconsistent, leaving us with uncertain indications of the past. Climate models do not deal realistically with water vapor, aerosols, and clouds, resulting in wide variations from model to model.

> The thesis of this book is that our data and models are presently inadequate to reach credible conclusions regarding how much global warming is likely to take place in the 21st century. We have emerged from the *Little Ice Age* in the latter half of the 19th century and the Earth has warmed, but the connection to greenhouse gases remains very unclear. The roles of urban heating and changes in ocean circulation appear to have been underestimated by modelers.

Scientists (and the public) abhor a vacuum. They can't seem to shrug their shoulders and admit that we just don't know the answers to important questions. They introduce explanations, however speculative. Thus, we are besieged with models purporting to describe the past millennium's history of the Earth's climate, and making firm predictions about the future, none of which stand up to detailed review. The alarmist group that controls the paleo-climatological literature has a political agenda to promote public concern about greenhouse gases, and in many cases, they have lost objectivity. The opposition, whom I call naysayers, tend to be less well informed, often quite shallow, and equally one-sided. We have ended up with two opposing camps: the alarmists and the naysayers, each 100% convinced they are right, and each firmly for or against a global-warming catastrophe, each seemingly more concerned with furthering their agendas than with discovering truth. The world will face a crisis sometime around 2030. But that crisis will not be calamitous global warming. The crisis will be that with oil, gas, and coal production going at full bore, the world will not able to supply the energy that is demanded by a growing world population intent on using energy at higher rates. This could lead to significantly higher energy costs, resulting in worldwide economic recession or depression. However, on the positive side, it will provide great incentive to develop renewable energy that will then become more competitive. Whether renewable energy can be developed and expanded rapidly enough to stave off economic collapse remains to be seen.

ORGANIZATION OF THIS BOOK

This book is based on a logical flow as shown below.

How climate has varied in the past and present

Proxies for estimating historical temperatures

⇓

Description of ice ages and sudden climate change

⇓

Fluctuations in the relatively benign Holocene (last ~10,000 years)

⇓

Temperature fluctuations during the past millennium (the *Medieval Warm Period* and the *Little Ice Age*)

⇓

The *hockey stick* controversy regarding temperatures in the last millennium

⇓

Temperature measurements in the last century; spatial and time dependence of 20th-century warming.

Factors that can cause the Earth's climate to change

Models to roughly estimate past variability of solar irradiance

⇓

Recent measurements of solar irradiance

⇓

Uncertainties in long-term stability of the Sun

⇓

Heat flows in the Earth's land–ocean–atmosphere system; the greenhouse effect

⇓

Role of ocean currents in heat transport

⇓

Global climate models, their predictions of heating due to greenhouse gases, and their limitations.

Carbon dioxide concentration in the atmosphere

Estimates of historical variability from proxies

⇓

Measurements in the 20th century

⇓

Fluctuations in the relatively benign Holocene (last $\sim$10,000 years)

⇓

Predictions of future levels and consequent temperature increases

⇓

Likely constraints imposed by limitations of available fossil fuels.

Impacts of future global warming

Alarmist–Naysayer orthogonality

⇓

Most significant concern: future sea level rise.

Public policy: Kyoto Protocol

Developed vs. developing countries

⇓

Free rein to China to generate greenhouse gases

⇓

Punishment of countries that have done the most to reduce emissions in the past

⇓

Fallacies of the Stern Report.

Summary

There is a good deal more that we don't understand about climate variability than we do understand

⇓

The warming of the 20th century represents emergence from the *Little Ice Age*.

⇓

The role of greenhouse gases in this warming remains uncertain

⇓

We need better data and better models; there are too many speculations that have hardened into beliefs.

Scientists have studied past climates using *proxies*. Proxies are residual data from processes that occurred in the past, when the processes were dependent on local temperatures at the times they took place, and the evidence is preserved in the present in an accessible form. Chapter 1 provides a description of various proxies and their limitations. Chapter 2 examines what we have learned from proxies about major climate changes that have occurred in the past, starting with recent ice ages, followed by the Holocene (the past ~10,000 years), and then the last millennium. A rather blurry picture emerges of wild and rapid climate changes in the past, followed by a relatively benign Holocene that included some smaller fluctuations. A detailed study of proxy evidence for climate fluctuations in the last millennium has led to a controversy. While some climatologists claim that temperature changes in the last millennium were small prior to the 20th century, leading to a *hockey stick* graph of temperature vs. time with an unprecedented sudden rise in the 20th century, there is considerable evidence that temperatures varied significantly during the past millennium, and the temperature rise during the 20th century represented emergence from the so-called *Little Ice Age*. This controversy is examined in considerable detail.

Chapter 3 analyzes the measurements of Earth surface temperature that were made in the past century and discusses the limitations of the measurement network. Temperature data are reviewed in considerable detail. The primary trend during the 20th century has been upward from the base of the *Little Ice Age*, but this temperature rise has not been uniform, either geographically or in time. The limitations of attempting to describe the Earth with a single global average temperature are emphasized.

Chapter 4 provides an in-depth review of solar irradiance: historical observations, recent measurements, theories and models, and use of proxies to estimate past irradiance. There remains considerable uncertainty as to how solar irradiance varies over time periods of centuries. It seems likely that these uncertainties tie closely to uncertainties in historical temperatures during the past millennium, since solar variations are a likely source of temperature change in the absence of large-scale anthropogenic influence.

In Chapter 5, the greenhouse effect is discussed in the context of the Earth's heat balance and the heat flows that take place between land, ocean, and atmosphere. The growing importance of urban heat islands is emphasized. The role of the oceans is certainly important. This chapter ends with a description of global climate models and their predictions of the role of greenhouse gases in producing future global temperature increases.

Chapter 6 describes what we know about CO_2 concentrations in the atmosphere, past and present. Projections of future growth in CO_2 concentration are reviewed and compared with likely scenarios based on limited future availability of fossil fuels. Many climatologists have projected very steep increases in CO_2 concentration for the 21st century, which global climate models claim would lead to significant temperature increases. However, it is shown that there probably isn't enough fossil fuel to produce these putative increases in CO_2, and the accuracy of global climate models in predicting temperature rise due to greenhouse gases remains uncertain.

Chapter 7 deals with the potential impacts of future global warming by contrasting the views of alarmists and naysayers. While alarmists have exaggerated many risks, a significant concern is the potential future rise in sea level.

Chapter 8 deals with the Kyoto Protocol. It is not an equitable plan, and it suffers from a number of faults. Developing nations are given *carte blanche* while developed nations are punished for past improvements. China, soon to be the world's leading generator of greenhouse gases is absolved. Credits to allow greenhouse gas generation are a step in the wrong direction. The requirements imposed on developed nations are unattainable.

Chapter 9 provides a summary and conclusions. The Earth's climate is very complex. There is more that we don't know than we do know about climate change. Past temperatures, long-term variation of solar irradiance, variations in ocean circulation, heat exchange between the Earth and the atmosphere all remain (like most analyses of climate) speculative, conjectural, and unproven.

The Appendix reviews the widely viewed Al Gore film *An Inconvenient Truth*, for which he received a Nobel Prize. This glossy, glib presentation has little actual content.

Figures

Tables

* Unnumbered table.

Acronyms and abbreviations

ABL	Atmospheric Boundary Layer
ACRIM	Active Cavity Radiometer Irradiance Monitor
AE	Auroral Electrojet (index)
AIT	*An Inconvenient Truth*
AOGCM	Atmosphere–Ocean General Circulation Model
BP	Before the Present
CET	Central England Temperature
CFI	Comprehensive Flare Index
CFR	Climate Field Reconstruction
CME	Coronal Mass Ejection
CNES	Centre National d'Etudes Spatiales
CO_2e	Equivalent CO_2 concentration to produce the equivalent effect of all greenhouse gases.
CQSM	Constant Quiet Sun Model
DIC	Dissolved Inorganic Carbon
DTR	Diurnal Temperature Range
EA	East Antarctica
EAIS	East Antarctica Ice Sheet
ELA	Equilibrium-Line Altitude
ENSO	El Niño/Southern Oscillation
EOS	Earth Observing System
ERB	Earth Radiation Budget
ERBS/ERBE	Earth Radiation Budget Satellite/Earth Radiation Budget Experiment
EOF	Empirical Orthogonal Function
EPICA	European Project for Ice Coring in Antarctica
GCM	Global Climate Model
GDP	Gross Domestic Product

GHG	GreenHouse Gas
GIS	Greenland Ice Sheet
GISS	Goddard Institute for Space Studies (NASA)
GMST	Global Mean Surface Temperature
GRACE	Gravity Recovery And Climate Experiment
GSL	Global Sea Level
GSN	Group Sunspot Number
GST	Ground Surface Temperature
HadCM3	Hadley Climate Model 3
HFC	HydroFluoroCarbon
IMF	Interplanetary Magnetic Field
IPCC	Inter-government Panel on Climate Change
IR	InfraRed
LFO	Low Frequency Oscillation
LGM	Last Glacial Maximum
LIA	Little Ice Age
LULC	Land Use/Land Clearing
M&M	McIntyre and McKitrick
MBH	Mann, Bradley, and Hughes
MDI	Michelson Doppler Imager
MIROC3.2	Model for Interdisciplinary Research on Climate
MM	Maunder Minimum
MOC	Meridional Overturning Circulation (Atlantic)
MSU	Microwave Sounding Unit
MWP	Medieval Warm Period
NADW	North Atlantic Deep Water
NAO	North Atlantic Oscillation
NCEP–NCAR	National Centers for Environmental Protection/National Center for Atmospheric Research
NDVI	Normalized Difference Vegetation Index
NH	Northern Hemisphere
NOAA	National Oceanic and Atmospheric Administration
OHCA	Ocean Heat Content Anomaly
OPEC	Organization of Petroleum Exporting Countries
PC	Principal Component; Politically Correct
PCA	Principal Component Analysis
PFC	PerFluorohydroCarbon
ppmv	parts per million by volume
RE	Radiative Effectiveness
RSL	Relative Sea Level
SD	Standard Deviation
SEAS	NOAA's XBT program
SH	Southern Hemisphere
SMAX	Sunspot MAXimum
SMIN	Sunspot MINimum

SMM	Solar Maximum Mission
SN	Sunspot Number
SO	Southern Oscillation
SOHO	SOlar Heliospheric Observer
SOI	Southern Oscillation Index
SORCE	SOlar Radiation and Climate Experiment
SST	Sea Surface Temperature
TAV	Tropical Atlantic Variability
TIM	Total Irradiance Monitor
TMN	Temperature Measurement Network
TOA	Top Of Atmosphere
TOPEX-Poseidon	Ocean Topography Experiment
TSI	Total Solar Irradiance
UAH LT	University of Alabama in Huntsville Lower Troposphere
UARS	Upper Atmosphere Research Satellite
UHI	Urban Heat Island
UNFCCC	U.N. Framework Convention on Climate Change
U/P	Umbra/Penumbra
USHCN	U.S. Historical Climate Network
UT	Upper Troposphere
VEI	Volcano Explosivity Index
VIRGO	Variability of solar IRradiance and Gravity Oscillations
WA	West Antarctica
WAIS	West Antarctica Ice Sheet
XBT	eXpendable BathyThermographs
YBP	years before the present

1

Historical variations in the Earth's climate

1.1 HISTORICAL TEMPERATURES

A recurring theme in most of Isaac Asimov's science fiction novels is the search for historical roots in the fog that obscures the past. These books have been very successful and are very readable, partly because they are well conceived and well written, but also because they evoke an empathetic response from our natural desire to understand our origins and roots. Similarly, the history of climatic variations leaves behind a fog that is difficult to penetrate. Many incredibly ingenious proxy methods have been devised to peer into the past. However, none is entirely satisfactory, and many uncertainties remain. In addition to proxy data, there are many anecdotal accounts in historical records that indirectly infer information about past climate (e.g., extent of glacier expansion and contraction in the Swiss Alps, paintings showing skaters on lakes that presently don't freeze, etc.). All of these have been utilized in the imperfect attempt to estimate past climates.

1.1.1 Use of proxies to estimate historical temperatures

In the context of historical temperatures, proxies are residual data from processes that occurred in the past, when the processes were dependent on local temperatures at the times they took place, and the evidence is preserved in the present in an accessible form. In all cases, extraction of implied past temperature data from confounding influences requires considerable analysis and manipulation. As a result, the credibility and reliability of such proxy data vary widely from data set to data set, as well as in the eye of the beholder. For example, there are trees that are several thousand years old. The growth (width and density) of tree rings depends on the temperature prevailing during the growth period. By examining old tree rings corresponding to historical times, one can infer past temperatures. However, tree growth is also affected by other factors (water availability, humidity, wind, cloudiness, CO_2 content in the atmosphere, nutrients, etc.). These add noise to the temperature signal. Hence, it is not a simple matter to extract accurate historical temperature data from tree rings (or other proxies, for that matter).

A listing of some prominent potential proxies is as follows:

- Tree rings (width, density, stable isotope composition)
- Ice cores (oxygen isotope ratios, gas content in bubbles)
- Ocean sediments
- Pollen
- Boreholes
- Corals.

1.1.1.1 Tree rings

A cross section of a temperate forest tree shows a variation of lighter and darker bands that are usually continuous around the circumference of the tree. These bands are the so-called tree rings and are due to seasonal effects. Each tree ring is composed of large thin-walled cells called early wood and smaller more densely packed thick-walled cells called late wood. The average width of a tree ring is a function of many variables including the tree species, tree age, stored carbohydrates in the tree, nutrients in the soil, and climatic factors including sunlight, precipitation, temperature, wind speed, humidity, and carbon dioxide availability in the atmosphere. Obviously there are many confounding factors, so the challenge is to extract the temperature signal and thus distinguish the temperature signal from the noise caused by the many confounding factors. Temperature information is usually derived from inter-annual variations in the ring width as well as inter-annual and intra-annual density variations. Density variations are valuable in paleo-climatic temperature reconstructions because they have a relatively simple growth function that, in mature trees, is approximately linear with age. The density variations have been shown empirically to contain a strong climatic temperature signal. Two values of density are measured within each growth ring: minimum density representing early wood and maximum density representing late wood. Maximum density values are strongly correlated with April to August mean temperatures in trees across the boreal forest from Alaska to Labrador. Both tree ring width and density data are used in combination to extract the maximal climatic temperature signal.

The climate signal is strongest in trees that are under stress. Trees growing in sites where the climate does not limit growth tend to produce rings that are uniform. Trees that are growing close to their extreme ecological range are greatly influenced by climate variations that strongly influence annual growth increments. Two types of stress are commonly recognized: moisture stress and temperature stress. Trees growing in semi-arid regions are limited by water availability, and thus variations in ring width reflect this climatic moisture signal. Trees growing near their ecological limits either in terms of latitude or altitude show growth limitations imposed by temperature, and thus ring width variations in such trees contain a relatively strong temperature signal. However, the biological processes are extremely complex, so very different combinations of climatic conditions may cause similar ring width increments. Tree growth and carbohydrate production by a tree in one year will precondition the tree for strong growth in the subsequent year so that there is a strong autocorrelation in the ring width time series. Photosynthetic processes are accelerated with the increased availability of carbon dioxide in the atmosphere and, hence, it is conjectured that ring growth would also be correlated with atmospheric carbon dioxide. Robinson, Robinson, and Soon (2007) and Idso and Idso (2007) provide data and references that indicate that plant growth is stimulated by increased CO_2 concentration in the atmosphere, particularly at warmer temperatures. There is some evidence that long-lived 1,000–2,000-year-old pine trees have shown a sharp increase in growth during the past half-century. Other examples are provided by Robinson, Robinson, and Soon (2007). In addition, oxides of nitrogen are formed in internal combustion engines that can be deposited as nitrates that also contribute to fertilization of plant materials. It is clear that while there are temperature signals in tree rings, the temperature signals are confounded with many other factors including fertilization effects due to the use of fossil fuels in the 20th century. Wider rings are frequently produced during the early life of a tree. Thus, the tree rings frequently contain a low-frequency signal that is unrelated to climate or, at least, is confounded with climatic effects such as temperature. In order to use tree rings as a successful temperature signal, this low-frequency component must be removed. This is typically done by a non-linear parametric trend fit using a polynomial or modified exponential curve. Because the early history of tree rings confounds the climatic signal with low-frequency specimen-specific signals, tree rings are not usually effective for accurately determining low-frequency, longer term effects. Once there is reasonable confidence that the tree ring signal reflects a temperature signal, a calibration is performed using the derived tree ring data and instrumented temperature data over the (comparatively recent) period during which actual climatic temperature measurements were made. The assumption in this inference is that when the tree ring structure observed during the recent instrumented period is similar to the tree ring structure observed in the past, both will have correspondingly similar temperature profiles (Beckman and Mahoney, 1998).

However, as pointed out earlier, many different sets of climatic conditions can (and do) yield similar tree ring profiles. Thus, tree ring proxy data alone are unlikely to be sufficient to determine past climate variables (Mann, Bradley, and Hughes, 1998).

As Soon and Baliunas (2003a, b) pointed out:

> "Tree growth, and hence the width and density of tree rings, depends on many factors, including the tree species and age, the availability of stored food in the tree and nutrients in the soil, the full range of climatic variables (sunshine, precipitation, temperature, wind speed, humidity); and their distribution throughout the year. Of these factors, precipitation is probably the most important, since low water availability will lead to low tree growth, even at high temperature. Research has shown that the density of the wood in individual tree rings is a better indicator of average temperature in the growing season than the

width of the tree ring, and most recent proxy temperature studies use this approach ... Once tree ring width and/or density data have been collected, they have to be calibrated against climate variables, typically temperature and precipitation. Temperature and precipitation effects can be separated only if more than one measure of tree growth is available. In the typical situation, both tree ring width and density might be available for 500 years, but data for temperature and precipitation might be available for only 100 years. For the 100-year period, standard regression analysis techniques can be used to separate the effects of annual (or growing season) average temperature and precipitation on tree growth. The resulting information can be used to estimate annual (or growing season) average temperature and precipitation for the remaining 400 years. While this approach seems simple and mechanical, it is neither. Several problems arise. First, for the same weather conditions, young trees grow faster than older trees. The effects of this early growth must be removed statistically. The statistical approaches used to smooth the year-to-year variability due to weather from the growth record when the tree was young, and even the true year-to-year variability of weather may be lost through this procedure. Next, average values from the multiple samples per tree and multiple trees in the study must be calculated. This can further decrease the size of year-to-year variability in the final results. Also, the steady rise of atmospheric carbon dioxide (CO_2) concentration is a complicating factor in interpreting tree ring data. Plants grow better at higher CO_2 concentration, and there is growing evidence that this has already begun to affect trees growing in natural conditions. Since CO_2 concentration has been rising for the same period for which weather data are available to calibrate tree ring data, a non-linear error of unknown size has been introduced. Finally, since few trees yield good data for many centuries, it is usually necessary to combine data from several trees to get a multi-century record. The statistical techniques used to combine data filter out the century-scale climate variability. The effect of all of these problems is to make tree growth studies highly suspect as a continuous recorder of temperature histories over many centuries or as long as a millennium."

Despite these repeated warnings and cautions by a number of scientists, paleo-climatologists have used tree rings widely and repeatedly to infer past temperature variations, although the variations from investigator to investigator are large (Esper *et al.*, 2005a).

Anon. (N) provides further details on the use of tree ring proxies.

1.1.1.2 Ice cores

The accumulated past snowfall in the polar caps and ice sheets provide a basis for paleo-climate reconstruction. These are referred to as ice cores even though strictly speaking there is typically a combination of snow and ice. Somewhat compressed old snow is called firn. The transition from snow to firn to ice occurs as the weight of overlying material causes the snow crystals to compress, deform, and recrystallize in more compact form. When firn is buried beneath subsequent snowfalls, the density is increased as air spaces are compressed due to mechanical packing as well as plastic deformation. Interconnected air passages may then be sealed and appear as individual air bubbles. At this point the firn becomes ice. Paleo-climatic information derived from ice cores is obtained from four principal mechanisms: (1) analysis of stable isotopes of water and atmospheric oxygen; (2) analysis of other gases in the air bubbles in the ice; (3) analysis of dissolved and particulate matter in the firn and ice; and (4) analysis of other physical properties such as thickness of the firn and ice.

The mechanism by which stable isotopes of oxygen and hydrogen carry a temperature signal is as follows. The vapor pressure of normal water is higher than the heavier forms of water (containing either ^{18}O or D or both) because the lighter molecules have higher average velocities at the same temperature. When liquid water evaporates, the vapor is relatively poorer in the heavier forms of water. Conversely, the remaining liquid water will be enriched in water containing the heavier isotopes. In the inverse process, when condensation occurs, the lower vapor pressure of water containing the heavier isotopes will cause that water to condense more rapidly than lighter isotopes of water. The magnitude of this enrichment is temperature-dependent. Thus, the relative isotope concentrations in the condensate will be a direct indicator of the temperature at which condensation occurred. The ice presently buried at depth in polar caps and ice sheets long ago was water vapor that condensed out and became incorporated into the firn, and then the ice core of a polar cap or ice sheet. The isotope ratios contained in this buried ice contain an implicit historical record of the temperatures prevailing when precipitation occurred, perhaps thousands of years ago. In addition to the relative heavy/light isotope ratios, the trapped bubbles in ice cores provide a record of atmospheric concentrations of trace gases including greenhouse gases such as carbon dioxide, methane, and nitrous oxide. Furthermore, the ice cores contain a record of aerosols and dust content resulting from volcanic eruptions and other changes in particulate content in the atmosphere. The relative atmospheric concentrations of greenhouse gases as well as aerosol and particulate content coupled with other climate information gives insight into both the importance of these as drivers of temperature as well as how these drivers might couple in either a positive or negative feedback sense (Beckman and Mahoney, 1998).

According to Soon and Baliunas (2003a, b):

> "The ice sheets that cover Antarctica, Greenland, the islands north of Canada and Russia, and the tops of some mountainous areas, represent the accumulation of as much as several hundred thousand years of snowfall. In very cold, dry areas, such as the interior of Greenland and Antarctica, the record is particularly good because there is little year-to-year evaporation or melt, and snow compresses into annual layers of ice. The thickness of these layers is an indication of the amount of precipitation that fell at that location during the year the layer was deposited, and the isotopic make-up of the water in the ice can provide a proxy for temperature . . . Heavier HDO and H_2–^{18}O molecules will condense more quickly than H_2–^{16}O. The concentration of D and ^{18}O in the ice sample is a measure of the temperature at which the snow that formed that ice fell. However, as more

precipitation falls, the water vapor in the atmosphere becomes depleted in D and ^{18}O, so the last snow to fall will have a different D and ^{18}O concentration than the first snow that fell. In areas of heavy snowfall this can cause significant differences in proxy temperature estimates.''

However, the process by which precipitated snow is gradually compressed into firn, and then ice, entrapping gas bubbles and preserving isotope concentrations, may take hundreds of years or longer. As a result, ice core data typically represent averages smeared over several hundred (or more) years.

1.1.1.3 Ocean and stream sediments

A large number of proxies have been developed that rely on analysis of ocean and stream sediments. These tend to be very complex and difficult to describe simply. Two requirements are (1) measurements that provide dates at which layers were laid down (such as radiocarbon), and (2) measurements that provide indications of past temperatures (e.g., Cd/Ca ratios or isotope ratios found in the remains of foraminifera).

> ''Ocean sediments contain the skeletons of a variety of invertebrates. Variations in the ^{18}O content in their shells can be used to establish a proxy temperature record using many of the same techniques as are used for corals. There are, however, several additional complications. Corals grow at the ocean surface, but the invertebrates deposited in ocean sediments live at different depths in the oceans. Water temperature changes rapidly with depth in the first few hundred feet below the ocean surface, so the knowledge of the depth at which the invertebrate species lived is of critical importance. Also, not all families of invertebrates concentrate ^{18}O with the same efficiency, a fact that must be taken into account when calibrating ocean sediment proxy data'' (Soon and Baliunas (2003a, b).

A more complete description is given in Anon. (N).

1.1.1.4 Pollen

Plant pollen measurements can be used as a proxy for climate change in the past. Pollen measurements typically depend on radiocarbon dating of sediments, and pollen, grains, and spores that are counted under a microscope. From the number of pollen, and the types of plants represented, inferences on past climates can be made. Converting pollen counts to temperature is a complex subject that is beyond the scope of the present work (Davis *et al.*, 2003).

1.1.1.5 Boreholes

According to Pollack and Huang (2000), the fundamental concept behind subsurface temperatures as a climate proxy can be succinctly stated: If Earth's atmosphere experiences a warming or cooling, the soil and rock in contact with the atmosphere will feel this change. Such temperature changes at the Earth's solid surface then propagate into the subsurface by heat conduction through the soil and rock. The process is analogous to the warming of a cold ceramic cup after hot tea is poured into it. The interior surface of the cup experiences an increase in temperature, which then propagates through the wall of the cup and can be sensed a short time later on the exterior surface. Similarly, variations of temperature at the Earth's surface associated with climate change can be thought of as a time-varying boundary condition on the upper boundary of the solid Earth. But whereas heat conducts through a cup in just minutes, temperature fluctuations at the Earth's surface take several hundred years to penetrate the upper few hundred meters of the subsurface. The Earth filters out high-frequency energy fluctuations and retains only the long-term trends of surface energy imbalance, recording surface changes as perturbations of underground temperature as a function of depth. These changes in the energy balance at the Earth's surface are reflected in geothermal records whenever the underlying physical processes are sustained.

> "The spatial variation of temperature over the Earth's surface is set principally by the balance of incoming radiation (mainly solar) and outgoing terrestrial radiation, establishing a fundamental latitudinal variation. That simple distribution is modified by albedo variations between the land, sea, and ice, and by atmospheric and oceanic circulation that redistributes heat over the planetary surface. Because the energy flux reaching Earth from the Sun is some 4000 times greater than the energy flux from the Earth's interior, the surface temperature of the planet is dominated by external rather than internal forcings" (Pollack and Huang, 2000).

The present temperature distribution below the surface is the end product of variable surface temperature acting over past epochs of time to transfer heat by conduction down into the subsurface. The deeper that a temperature is measured the more it encompasses a longer duration of surface temperature effects.

> "Many thousands of boreholes around the world have been subjected to temperature logging in the course of determining the terrestrial heat flux. Thus, an abundance of observations exists, but because of the many investigators and different measurement practices and techniques, the data are heterogeneous. The heterogeneity arises from different borehole depths, different logging depth intervals, and variable information about thermo-physical properties, subsurface geological structure, and surface site characteristics. Even with such heterogeneity, however, quality data are sufficiently abundant and the analysis tools sufficiently flexible to allow credible climate reconstructions from these data at many sites around the world" (Pollack and Huang, 2000).

Anon. (C) attempted to superimpose the estimates of Holocene temperatures from a number of studies onto a single graph. However, the absolute calibration from study to study is complex, and it was not explained how they combined these results onto a single scale. Furthermore, some aspects of the graph appear strange. On top of everything else, the goal of Anon. (C) seems to have been to reassure us that the *hockey stick* is correct for the past 2,000 years, and that the temperature in 2004 is higher than at any time in the past 12,000 years—which seems to be a false assertion (see Section 2.2).

Kilty (1997) explains how borehole measurements are used to estimate the ground surface temperature (GST), say, over the past 1,000 years. The system involves circular reasoning because researchers begin with a model and use the observed borehole temperatures to find the parameters of the model.

> "However, a common problem with obtaining the history of surface temperature from borehole temperatures is that heat conduction destroys information regarding long past temperature quite completely, and, therefore, many different temperature histories explain the borehole data equally well. Quite a few of these histories oscillate in temperature wildly. By including a penalty for deviating from the initial model the program drives the final solution toward some unique result, and, if the initial model is smooth, the solution is also smooth" (Kilty, 1997).

One can either allow a loose or a tight constraint on variations from the original model.

Kilty (1997) describes the process of recovering past temperature from boreholes as an "ill-conditioned problem". Many doubts are raised about the veracity of borehole measurements in resolving past temperature variations. Only through circular reasoning by limiting variations from an assumed model can a unique result be obtained.

Ogilvie and Jonsson (2001) also mention the difficulties with borehole measurements, including the "uncertain relation between ground temperatures and atmosphere temperatures." It is stated:

> "The temporal resolution of the borehole temperature deteriorates very rapidly backwards in time as a consequence of the heat diffusion process. Information about surface temperature variations slowly diffuses downwards, but at the same time the amplitude of the variations attenuates" (Ogilvie and Jonsson, 2001).

1.1.1.6 Corals

Corals have hard calcium-based skeletons supporting softer tissues. An important subgroup for paleo-climate studies is the reef-building corals in which the coral polyp lives symbiotically with single-celled algae. These algae produce carbohydrates by means of photosynthesis and are affected by water depth, water turbidity, and cloudiness. Much of the carbohydrates diffuse away from the algae providing food to the coral polyp, which in turn provides a protective environment for the algae. Reef-building corals are strongly affected by temperature and, as the temperature drops, the rate of calcification drops with lower temperatures potentially presaging the death of the colony. Coral growth rates vary over a year and coral can be sectioned and X-rayed to reveal high and low-density bands. High-density layers are produced during times of higher sea surface temperatures. Thus, not unlike tree rings, data on corals also can be calibrated to estimate (sea) surface temperatures (Beckman and Mahoney, 1998).

> "Coral reefs do not exhibit the finely defined layers trees do, but their growth varies with sea water temperature; the higher the sea water temperature, the more dense the coral. As is the case with tree rings, many other factors also affect the density of coral reefs. However, several attempts have been made to develop a proxy record from the growth layers in coral reefs. A proxy temperature approach makes use of the fact that corals extract calcium carbonate ($CaCO_3$) from seawater to form their reefs. The calcium carbonate that corals extract is slightly enriched in ^{18}O compared with seawater, with the degree of enrichment decreasing as temperature increases. However, the relationship between the amount of ^{18}O in corals and temperature is not simple because the amount of ^{18}O in seawater is not constant. Rainwater is depleted in ^{18}O, so heavy rainfall will lower the concentration of ^{18}O at the surface of the ocean. Conversely, a long dry period, with high evaporation rates, can raise ^{18}O concentration at the ocean's surface. Despite these difficulties, several reconstructed temperature records have been developed based on ^{18}O in coral reefs" (Soon and Baliunas, 2003a, b).

1.1.2 Proxies and climate

1.1.2.1 Processing proxy data

The common approach to climate reconstruction from proxies is to use statistical regression to establish a relationship between recent temperature measurements and the variability of the proxy over this recent period of overlap (calibration period). This provides a transfer function that enables the proxies to be used as predictors of past climate where proxy data are available in the absence of direct temperature measurements. However, this requires speculative assumptions about the temporal and spatial stability of the relationship between proxy indicator and temperature represented in these proxy records (Jones, Osborn, and Briffa, 2001).

Over the past several decades, quite a number of scientists have analyzed data from one or several proxies and derived estimates of climate history in various localities and regions. Since much of the available data are from the northern hemisphere (NH), a good deal of this analysis pertains mainly to the NH. Several of these are described in the sections that follow. However, these are typically limited geographically and sometimes temporally.

Starting as early as the late 1970s and following through the 1980s and 1990s, culminating in a pair of very influential papers in 1998 and 1999 (Mann, Bradley, and Hughes, 1998, 1999), and continuing to this day, a loosely allied cadre of scientists has attempted to statistically combine large numbers of proxies (indeed, all the reliable proxies that were available) into a reconstruction of global (or at least NH) average temperatures for the past millennium. They have assembled as many as a thousand proxies into a database. These proxies include a variety of geographical locations, ranges of time, and degrees of credibility. A major question is how should these proxies be combined? Measurements at different locations, particularly different latitudes, will have different absolute temperatures and different temperature changes with time. Equally challenging is the question of how (or whether) to include documentary information that is typically discontinuous and often anecdotal in nature. This cadre of scientists has typically tended to avoid documentary information, and has employed sophisticated mathematical approaches for combining proxy data sets into reconstructions of past NH or global average temperatures. These are discussed in Section 2.2.1.

1.1.2.2 Challenges in using proxies

Soon and Baliunas (2003a, b) discussed the uncertainties involved in inferring past climate variations from proxies. The greatest sources of uncertainty appear to be

(i) Lack of timescale resolution for the longest term component of climate signals; for example, in tree ring and coral records, or the loss of short-term climate information in borehole temperature reconstructions.
(ii) Non-linearities of biological, chemical, and physical transfer functions necessary for temperature reconstruction (i.e., related to age, threshold, discontinuous or insufficient sampling, saturated response, limited dynamic range of proxy, etc.). The transfer function is the functional relation between the proxy measurement (e.g., tree ring density) and temperature.
(iii) Variability with time ("non-stationarity") of the climate–proxy calibration relationships. Here, the concern is that the transfer function derived for the calibration period may not work well for historical times.
(iv) Confounding by factors other than temperature producing the same net effect.

These uncertainties can be alarmingly large for most proxies, and Soon and Baliunas (2003a, b) quoted a 1998 paper by Jones *et al.* that said:

> "It requires considerable faith to compare, for example, the climate of the twelfth and twentieth centuries from tree ring proxies. To date, the goal of combining information from borehole and tree-ring proxies, or even between borehole and thermometer data, to arrive at a true proxy that simultaneously resolves timescales of years to centuries, has not been realized."

This is in contrast to the rather optimistic view of the validity of proxy reconstructions expressed, for example, in Mann, Bradley, and Hughes (1998, 1999).

Amplitudes of large-scale surface temperature change derived from tree ring proxies can be substantially underestimated, by a factor of 2 to 3 as compared with results from borehole thermometry. Soon and Baliunas (2003a, b) believe that:

> "Differing amplitudes resulting from borehole and tree ring climate proxies suggest that longer time scale (multi-decadal and century) variability is more

> faithfully captured by borehole results, while the same information can be irretrievably lost in tree ring records."

However, borehole measurements have serious problems of uniqueness (see Section 1.3.4).

Ogilvie and Jonsson (2001) have further noted that essentially all current calibrations of proxies to large-scale instrumental measurements have been made over periods of rising temperature. They raised the concern that a different calibration response might arise when the procedure is extended to an untested climate regime associated with a persistent cooling phase. Ogilvie and Jonsson also raised other issues as well.

Jones *et al.* (1998) presented an extensive review of proxies. The spatial and timescale constraints on proxies were described in some detail. Seventeen annually resolved proxies were reviewed and integrated. However, large areas, particularly in tropical regions, were not represented. Many of the reconstructions were also limited seasonally in that they were most representative of summer or the growing season. It was concluded that each reconstruction

> "... is probably limited in its ability to reproduce past temperature variations faithfully on the longest of timescales. This limitation varies from proxy to proxy and it is virtually impossible to quantify the degree to which this has occurred because instrumental series are not long enough."

It was found that for most proxies, the correlation with instrumental data during the calibration period was not as good as reported in the journal articles. It was concluded that tree ring proxies were more reliable than coral and ice core proxies. Average reconstructions were prepared (a) for the NH from ten NH proxy series, and (b) for the SH from seven SH proxy series, but more paleo-climate reconstructions are required. However, all evidence suggests the contrary. Since most proxies seem to be wildly different, combining multiple proxies merely tends to obfuscate regional differences. Much more is likely to be learned from an overview and comparison of individual proxies than by combining them into a single global average temperature that tends to flatten out local variations.

1.2 ICE AGES AND INTERGLACIAL PERIODS

As we peer back further in time, the variations that occurred in the Earth's climate become more profound. The Earth has gone through alternating periods of glaciation when huge ice sheets covered the higher latitudes, and warm periods, some of which extensively melted polar ice. The oceans have risen and fallen as much as a hundred meters through these changes. No sensible study of global climate change can completely ignore this history, even though we are presently in an interglacial period, because the forces that produced these oscillations are still there, however tentatively balanced or dormant they may be for the moment.

Climatic variability on the timescale of tens of thousands of years has turned out to be a predominant pattern in Earth history. The last two and a half million years have been marked by many global climate oscillations between warmer and cooler conditions. This trend of oscillations appears to be merely the continuation of a pattern of variability extending back well into the Tertiary period and possibly beyond. During the last few million years, the duration and the amplitude of these climate cycles have increased. Large global interglacial–glacial–interglacial climate oscillations have been recurring at approximately a 100,000-year periodicity for the last 900,000 years, though each individual cycle has had its own idiosyncrasies in terms of the timing and magnitude of changes (Adams, Maslin, and Thomas, 1999).

The Quaternary ice ages had a cyclic pattern. Ice sheets formed and then retreated roughly 25 times in the last 2.5 million years.

1.2.1 The Pleistocene

Over the past 425,000 years, the Earth has experienced four lengthy glacial periods as shown in Figure 1.1. The last glacial period is known as the Wisconsin Glacial period. During the coldest segment of the last glacial period, all of Canada, portions of the northern United States, and large portions of northern Europe and Russia were covered with ice sheets that were up to 3,000 m to 4,000 m thick.

The overall amplitude of the global surface temperature change in the glacial–interglacial transition has been estimated to be $\sim$12°C. The greatest amounts of ice reached during glaciation were quite repetitive from cycle to cycle as shown in Figure

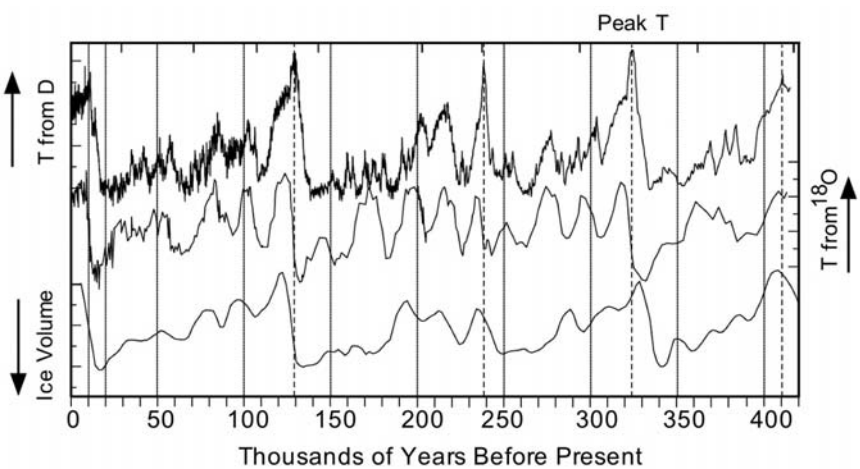

Figure 1.1. Vostok ice core data. The upper curve is the variation in deuterium content vs. depth of the ice core that is interpreted as a function of temperature vs. time. The middle curve is the ^{18}O profile in the atmosphere from gas bubbles. The lower curve is ice volume implied by ^{18}O in the ice core. Adapted from Petit *et al.* (1999).

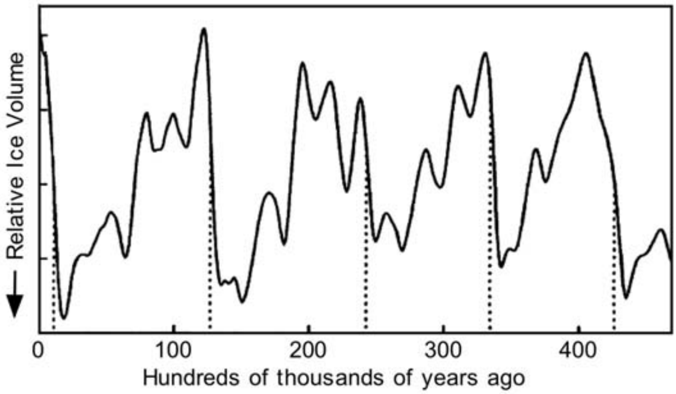

Figure 1.2. Four glacial periods of the Pleistocene showing slow buildup of ice followed by rapid warming and short interglacial periods. Adapted from de Blij (2005).

1.2. The highest temperatures reached during previous interglacial periods were slightly higher than we experience today.

Broecker's famous "Angry Beast" article (Broecker, 1995) likened the Earth's climate to an angry beast. He said:

> "... No one understands what is required to cool Greenland by 16°C and the tropics by 4 ± 1°C, to lower the mountain snowlines by 900 m, to create an ice sheet covering much of North America, to reduce ... CO_2 by 30%, or to raise the dust rain ... by an order of magnitude. If these changes were not documented in the climate record, they would never have entered the minds of the climate dynamics community. Models that purportedly simulate glacial climates do so only because key boundary conditions are prescribed (the size and elevation of ice sheets, sea ice extent, sea surface temperature, CO_2 content, etc.). The current climate models do not explain and cannot reproduce the severe and abrupt climate changes in the proxy climatic record."

It seems evident that these alternating periods of ice ages and interglacials must be driven by positive feedback processes. Simplistically, if high-latitude ice spreads for some reason, that would increase reflection of incident solar irradiance, thus cooling the area, and causing spreading of the ice, etc. A number of such feedback mechanisms have been discussed, but none are well understood (Bony *et al.*, 2006). Such feedback processes may proceed to an inordinate extent, once underway in earnest.

A number of conceptual triggers for initiating these extreme feedback processes have been proposed but none is entirely satisfactory. Noting the quasi-periodic nature of ice age episodes, a number of investigators have sought explanations based on periodic variations in the Earth's orbit about the Sun. Milankovitch spent a lifetime studying this problem. Three factors enter: (1) eccentricity (elongation of ellipse) of the Earth's orbit (period ~100,000 years), (2) tilt of the Earth's axis to the plane of its motion (period ~41,000 years), and (3) occurrence of seasons relative to the position along elliptical orbit ("precession of the equinoxes") (26,000 years). As these changes in the Earth's orbit occur independently, they create a history of changing solar inputs to the Earth. These changes are complex and involve variable inputs to different latitudes at different seasons. It is likely that the solar inputs to higher latitudes are most important in regard to ice ages, but it is not clear whether summer or winter is the dominant factor. A number of studies have attempted to carry out mathematical fitting of variations in solar intensity at higher latitudes resulting from variations of the above three orbital parameters to ice core data on historical global ice volume (e.g., Rial, 1999; Elkibbi and Rial, 2001).

But, there are many aspects of the ice core record that remain difficult to explain. The general trends that are observed are slow buildup of ice taking many tens of thousands of years followed by relatively sudden reductions over comparatively short periods (centuries or even decades), followed by thousands to tens of thousands of years of interglacial warmth, and then the whole process begins again. Is this part of a regular pattern induced by astronomical variations and abetted by feedback mechanisms, or is it the result of random triggers for feedback? We don't know.

1.2.2 The last ice age

Two old but still valuable treatises on the extent and manifestations of the most recent ice age are Dawson (1893) and Geikie (1882).

Adams (2002) pointed out:

> "The time span of the last 130,000 years has seen the global climate system switch from warm interglacial to cold glacial conditions, and back again. This broad interglacial–glacial–interglacial climate oscillation has been recurring on a similar periodicity for about the last 900,000 years, though each individual cycle has had its own idiosyncrasies in terms of the timing and magnitude of changes. As is usually the case with the study of the past, data are in short supply, and only a few sketchy outlines are known for the earliest cycles. Even for the most recent oscillation beginning around 130,000 years ago, there is still too much ambiguity in terms of the errors in geological dating techniques, in the gaps in the record, and in the slowness of responses by indicator species, to know precisely when certain events occurred and whether the climate changes were truly synchronous between different regions. The general picture summarized here roughly reflects the present consensus gained from ice cores, deep ocean cores, and terrestrial and lake sediments around the world"

Around 130,000–110,000 years ago (the "Eemian interglacial"), the Earth's climates are believed to have been generally much like those of today, though perhaps somewhat warmer and moister in many regions. The climate record derived from long ice cores taken through the Greenland ice cap suggests that the warm climate of the Eemian might have been punctuated by a number of sudden and fairly short-lived cold phases, but these results remain controversial.

Though the time at which the Eemian interglacial ended is subject to some uncertainty ($\sim$110,000 years ago), it appears to have been a relatively sudden event (perhaps a few hundred years) and not a gradual slide into colder conditions taking many thousands of years.

Following this initial cooling event, conditions often changed in sudden leaps and bounds followed by several thousand years of relatively stable climate or even a temporary reversal to warmth, but overall there was a decline in temperature. Northern forest zones retreated and fragmented as the summers and winters grew colder. Large ice sheets began to grow in the northern latitudes when the snow that fell in winter failed to melt in summer, and instead piled up from one year to the next until it reached thousands of meters in thickness.

As the cold grew more severe, the Earth's climate also became drier because the global *weather machine* that evaporates water from the oceans and drops it on the land operates less effectively at colder temperatures and when the polar sea ice is extensive. Even in areas that were not directly affected by the ice sheets, aridity began to cause forests to die and give way to dry grassland, which requires less water to survive. Eventually, much of the grassland retreated to give way to deserts and semi-deserts, as global conditions reached a cold, dry low point around 70,000 years ago. By this time, ice sheets covered most of northern Europe and Canada.

By around 60,000–55,000 years ago, conditions around the world had become warmer, though still generally colder than today. The ice melted back partially, and there followed a long *middling* phase in which the climate oscillated between warmer and colder conditions, often in sudden jumps. During some parts of this phase, conditions in the tropics may have been moister than they are at present, and at other times they were drier. Generally, the mid-latitude zones seem to have been drier than present, with cold steppe and wooded steppe instead of forests.

A summary of the sequence of events for the last 130,000 years is as follows (Adams, 2002):

(Phases about as warm or warmer than the present are shown in *italics*.)

1. 150,000 YBP (years before present)—cold, dry full glacial world.
2. $\sim$130,000 YBP—rapid warming initiates the Eemian interglacial.
3. *130,000–110,000* YBP—global climates generally warmer and moister than at present, but with progressive cooling to temperatures similar to present (except for possible global cold, dry event at 121,000 YBP).
4. 110,000? YBP—a strong cooling marks the end of the Eemian interglacial.
5. 105,000–95,000 YBP—climate warms slightly but still cooler and drier than present; strong fluctuations.
6. 95,000–93,000 YBP—another cooler phase similar to that at 110,000 YBP.
7. 93,000–75,000 YBP—a milder phase, resembling that at 105,000–95,000 YBP.
8. 75,000–60,000 YBP—full glacial world, cold and dry.

9. 60,000–25,000 YBP—"middling phase" of highly unstable but generally cooler and drier-than-present conditions.
10. 25,000–15,000 YBP—full glacial world, cold and dry (includes the "Last Glacial Maximum"). This period includes two "coldest phases" (Heinrich Events) at around 23,000–21,000 YBP and at 17,000–14,500 YBP.
11. 14,500 YBP—rapid warming and moistening of climates in some areas. Rapid deglaciation begins.
12. *13,500* YBP—nearly all areas with climates at least as warm and moist as today's.
13. 12,800 YBP (±200 years)—rapid onset of cool, dry Younger Dryas period in many areas.
14. 11,500 YBP (±200 years)—Younger Dryas ends suddenly, back to warmth and moist climates.
15. *9,000–8,200* YBP—climates warmer and often moister than today's.
16. ~8,200 YBP—sudden cool and dry phase in many areas.
17. *8,000–4,500* YBP—climates somewhat warmer and moister than today's.
18. Since 4,500 YBP—climates fairly similar to the present (except about 2,600 YBP—relatively wet/cold event (of unknown duration) in many areas).

The point at which the global ice extent was at its greatest, about 21,000 YBP, is known as the Last Glacial Maximum (LGM). During the Last Glacial Maximum, the Earth was much more arid than it is at present, with desert and semi-desert occupying huge regions of the continents and forests were shrunk back. But the greatest global aridity (rather than ice extent) may have been reached slightly after the Last Glacial Maximum, somewhere during the interval 19,000–17,000 YBP.

The extent and height of the North American ice sheets at the LGM in the most recent ice age was estimated by Dyke *et al.* (2002) to be as shown in Figure 1.3.

Several models have been developed to estimate the evolution of the ice sheets during the last ice age (Charbit *et al.*, 2007; Zweck and Huybrechts, 2003) but it is not clear to this writer that the models deal at all with why and how the ice sheets formed in the first place, or why and how they evolved the way that they did. Nevertheless they provide some interesting insights (see Figure 1.4, and Figure 1.5, color section).

Global sea level and marine isotope curves place the maximum ice volume in the most recent ice age at 18,000 YBP. The most pronounced oceanic changes occurred in middle latitudes of the North Atlantic where August surface temperatures were $\gtrsim 10^\circ$C lower than modern values. Even so, the global ocean surface was claimed to be, on average, only 2.3°C cooler (Andrews and Barry, 1978).

The development and expansion of the Laurentide Ice Sheet acted as a cold trap to prevent water vapor from reaching the highest polar latitudes. While this ice sheet peaked around 23,000 YBP, the Cordillera Ice Sheet began to develop around 20,000 YBP and reached its maximum around 14,000 YBP. It appears that the water vapor emanating from the Laurentide Ice Sheet as it warmed after 20,000 YBP may have provided the moisture needed to build the Cordillera Ice Sheet between 20,000 and 14,000 YBP (Dyke *et al.*, 2002).

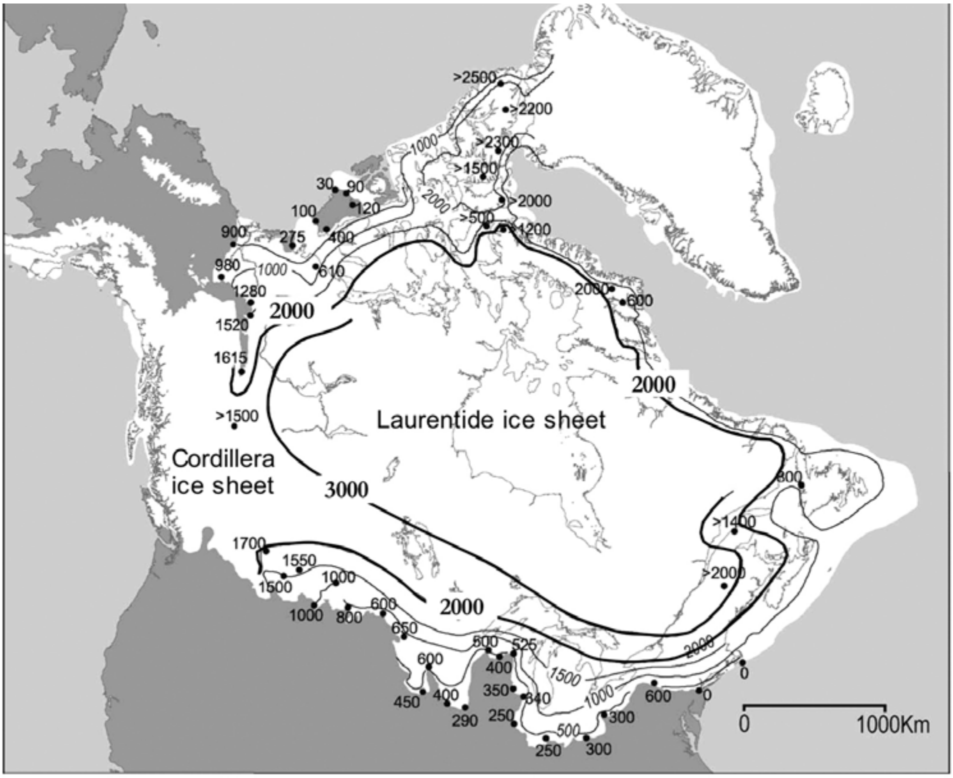

Figure 1.3. Extent and height of the North American ice sheets at the maximum in the most recent ice age. Height is measured in meters. Adapted from Dyke *et al.* (2002) by permission of Elsevier.

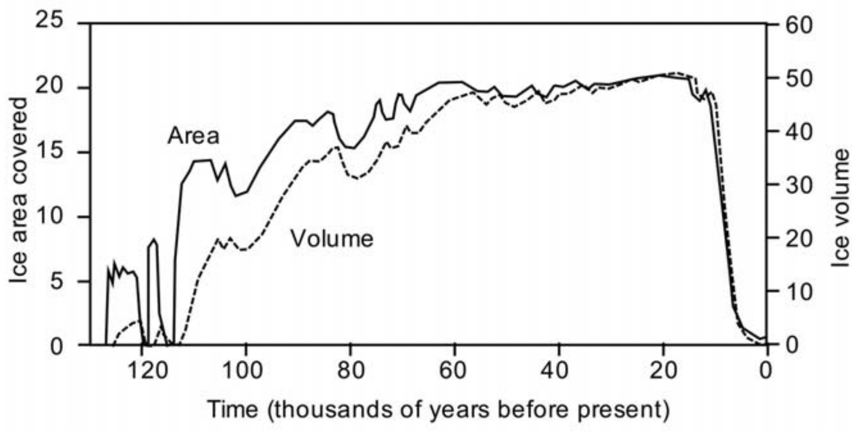

Figure 1.4. Build-up and decline of the Laurentide Ice Sheet. Area is in units of 10^{12} m^2. Volume is in 10^{15} m^3. Adapted from Charbit *et al.* (2007).

1.2.3 Proposed explanations for ice ages

1.2.3.1 Variations in the Earth's orbit and ice ages

Over millions of years, there have been many ice ages that have left their record in ice cores and other proxies. There is a periodicity to these ice ages, but that periodicity is not uniform or amenable to simple interpretation. The repeatable pattern is for slow buildup of ice sheets over many tens of thousands of years, followed by a rather abrupt deglaciation that may require just a few thousand years with significant warming over hundreds of years. This *sawtooth* pattern seems to be fairly repeatable, although there are typically many fluctuations during the cooling cycle, and often, violent fluctuations during the rapid deglaciation.

It is natural that scientists have sought a relationship between the periodicities of the ice ages and the periodic variations in the Earth's orbit around the Sun, assuming that the ice ages (and their terminations) are somehow tied to variability of solar irradiance, particularly at high latitudes. Although solar irradiance variations could not possibly account for the violent fluctuations that have occurred, it has been conjectured that solar irradiance variations may act as *triggers* to initiate trends that are further propagated by feedback mechanisms. Numerous articles and books support this view (e.g., Anon. (G); Berger and Loutre, 2002; Imbrie and Imbrie, 1979; Macdougall, 2004). However, the connection between variations in solar irradiance and ice ages may lie more in the eye of the beholder than in the actual data.

The three parameters of the Earth's orbit that are relevant here are (i) the eccentricity with a period of roughly 100,000 years but highly variable amplitude, (ii) the obliquity (angle that the Earth's spin axis makes with the plane of its motion) that varies between 22° and 24.5° with a ~41,000 yr period, and (iii) the longitude of perihelion (position along the Earth's orbit where closest approach to the Sun occurs) with a ~26,000 yr period. As the theory goes, when these three parameters happen to produce a minimum in solar irradiance at higher latitudes, the ice age is set in motion.

However, the small variations in the Earth's orbit do not appear to be large enough to produce the massive gyration in the Earth's climate in the past 400,000 years for which we have ample evidence. In particular, the glaciation that occurred in the most recent ice age (as illustrated in Figures 1.1–1.4, and in the color section Figure 1.5) do not seem to be associated with any solar "triggers". Figures 1.6–1.8 show the orbital parameters over the past 100,000 years, and Figure 1.9 shows the annual integrated summer solar irradiance on a horizontal surface (assuming 100% atmospheric transmission) for various latitudes. It is difficult to associate these changes in orbital parameters and solar irradiance with the massive changes in climate that took place during that period. Similar plots over the 400,000 yr span of the past four ice ages, lead to the same conclusion; solar irradiance variations are too small and much too gradual to produce or terminate the most recent ice ages. The rapidity of historical changes suggests that large heat flows are involved, which then suggests that ocean currents play a significant role.

There are many papers in the literature that have sought connections between the variation of parameters of the Earth's orbit and the occurrence of ice ages

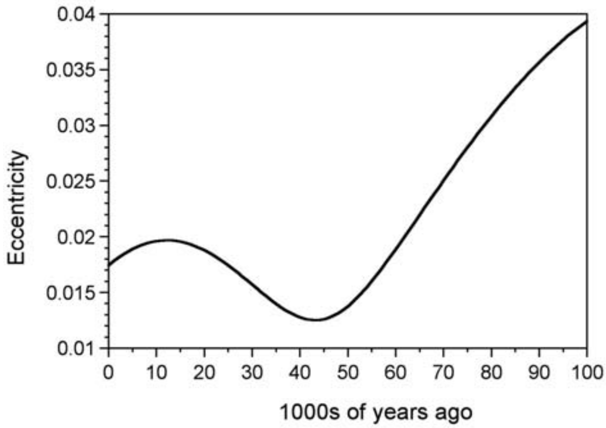

Figure 1.6. Variation of the eccentricity of the Earth's orbit during the past 100,000 years.

over various time periods. Rial (1999) and Elkibbi and Rial (2001) are examples of such studies.

Over the last million years, the Earth has experienced at least ten major glaciations, which according to the astronomical theory of the ice ages are the consequence of secular variations in irradiance caused by changes in Earth's orbital eccentricity, axial tilt, and longitude of perihelion (see Figure 1.10). However, a satisfactory explanation of how the changes in orbital eccentricity are transformed into the observed quasi-periodic fluctuations in global ice volume indicated by data has not yet been found (Rial, 1999).

Roe (2006) argued that we are not yet ready to explain how gigantic ice sheets form and dissipate. Instead, all one can seek is a correspondence in time of orbital-induced variations in solar irradiance with proxy evidence of ice sheet extent.

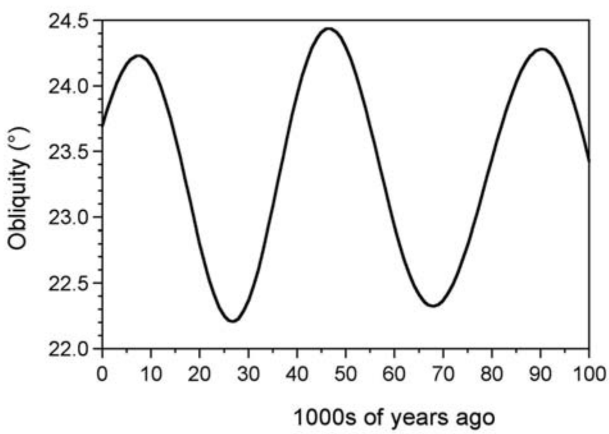

Figure 1.7. Variation of the obliquity of the Earth's orbit during the past 100,000 years.

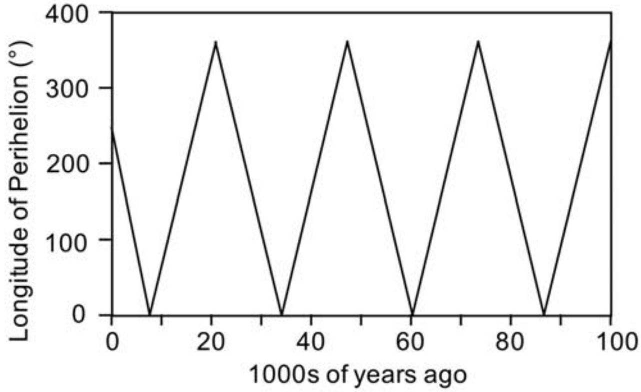

Figure 1.8. Variation of the longitude of perihelion of the Earth's orbit during the past 100,000 years.

Whether these solar variations are sufficient to cause the inferred variations in ice sheet extent, and the mechanisms by which these occur, remain to be clarified in future work.

Reconstructions of global ice volume during the Pleistocene rely on the measurement of oxygen isotopes incorporated into the shells of foraminifera, records of which are recovered from deep-sea sediment cores (Roe, 2006). Elkibbi and Rial (2001) provided a list of the "best known difficulties with the astronomical theory of the climate." There are a number of problems with these theories that remain unsolved. However, Elkibbi and Rial (2001) provided a figure that is at least suggestive of an astronomical origin, as shown in Figure 1.11.

Figure 1.11 compares the mid-summer (June 21) variation in solar irradiance at 65°N latitude with the measured variation in ^{18}O at such latitudes, which should be a

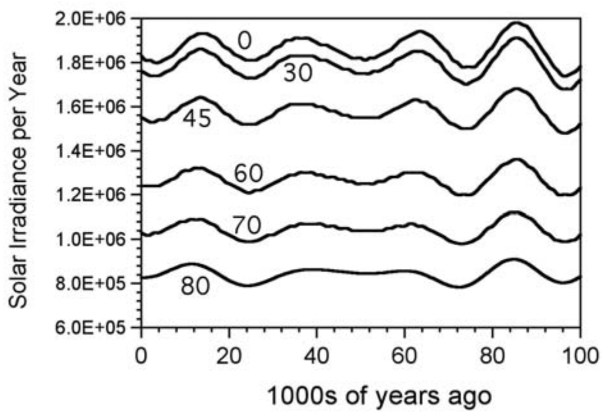

Figure 1.9. Variation of the integrated summer solar irradiance (W-h/m^2) at various latitudes in the NH over the past 100,000 years.

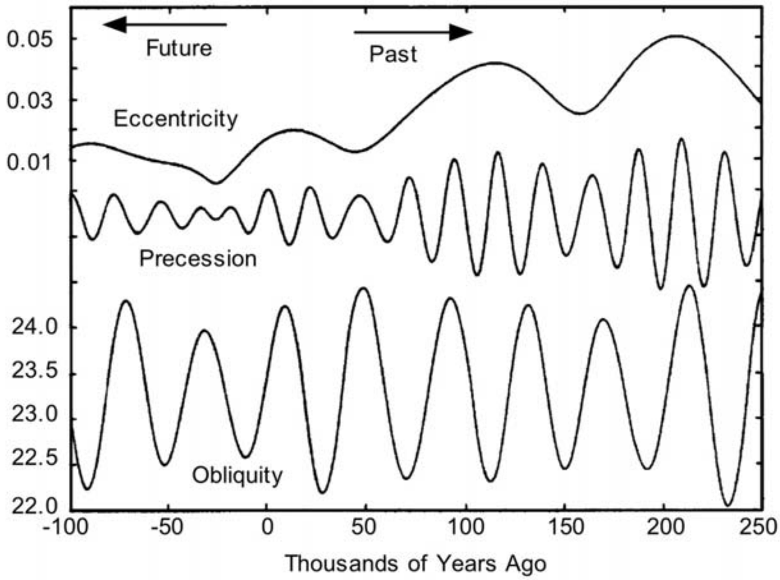

Figure 1.10. Variation of Earth orbit parameters over the past 250,000 years and into the future 100,000 years. Adapted from Elkibbi and Rial (2001).

proxy for ice sheet extent. While a weak case can be made that the onsets of deglaciation (dotted lines) coincide to some extent with increased irradiance, this requires considerable imagination to perceive. The arrows represent periods of low summer irradiance that seem to presage deglaciation (after a time lag of several tens of thousands of years). This time lag has been variously attributed to the dynamical response time of ice sheets, to the role of ocean circulation in the global transmission of the climate signal, or to the role of CO_2 or tropical sea surface temperatures in driving ice age cycles. However, it is evident that there is much greater variability at higher frequencies in the solar irradiance than in the ice volume (Roe, 2006).

Roe (2006) provided a new viewpoint to the orbital theory of ice ages:

> "While most studies have focused on the connection between solar irradiance and ice volume (V), there is a more direct physical connection between irradiance and the rate of change of ice volume (dV/dt). This distinction is crucial. First, the mass balance of ice sheets is acutely sensitive to summertime temperature: the characteristically convex profile of ice sheets means that the area of ablation at land-based margins varies strongly with summertime temperature. This effect renders the total ablation rate proportional to approximately the third power of the summertime temperature above some reference value. Second, while the convergence of atmospheric and oceanic heat fluxes plays a large role in wintertime climates, summertime climates in continental interiors are much more strongly controlled by the local radiation balance. Thus, there are strong physical

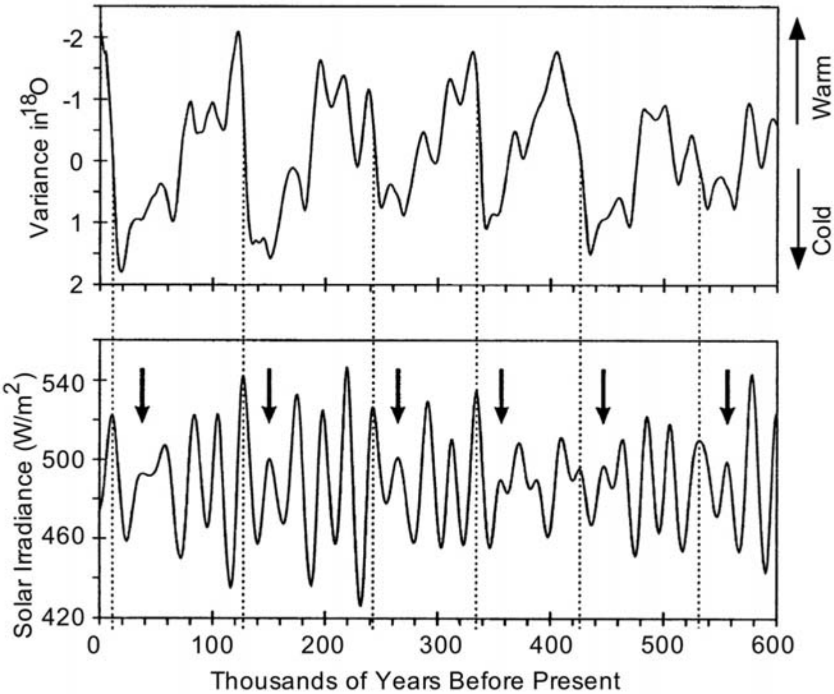

Figure 1.11. Comparison of past temperatures (from ice cores) with estimated solar irradiance in mid-summer (June 21) at 65°N latitude. The upper panel shows the record of change in ^{18}O that can be interpreted as a measure of ice sheet extent. The dotted lines show the onsets of deglaciation. The arrows in the lower panel show timing of low maxima in summer temperatures. Adapted from Elkibbi and Rial (2001).

> grounds, supported by model studies for expecting a direct response of summertime temperatures, and hence of ice sheet ablation rates and dV/dt, to local summertime irradiance variations.''

The comparison of solar irradiance with dV/dt shows much better correlation than the comparison of solar irradiance with V (see Figure 1.12 in color section).

However, this writer is unable to reproduce the large changes in solar irradiance in Figure 1.12, and particularly the huge sudden increase in irradiance shown at the far right of this figure does not seem to correlate with the small variations in orbital parameters during the past few tens of thousands of years as shown, for example, in Figures 1.6 and 1.7.

It has also been reported that the ice volume lags behind CO_2, and this has led to the suggestion that CO_2 variations drive ice age cycles. However, atmospheric CO_2 lags, or is at most synchronous with, dV/dt; the variations in ice sheet change rate precede variations in CO_2. According to Roe (2006), the variations in summertime solar irradiance forcing exceed the direct CO_2 radiative forcing by about a factor of 5, although the estimate of variance in irradiance seem high to this writer. Thus, Roe (2006) concluded: "CO_2 variations play a relatively weak role in driving changes in global ice volume compared to irradiance variations."

Roe (2006) also added: "The Milankovitch hypothesis as formulated here does not explain the large rapid deglaciations that occurred at the end of some of the ice age cycles."

1.2.3.2 Cosmos theory

Patterson (2007) asserted: "... I and the first-class scientists I work with are consistently finding excellent correlations between the regular fluctuations in the brightness of the sun and earthly climate." It was claimed that while there was a "clear and repeated correlation" of climate with brightness of the Sun,

> "The measured variations in incoming solar energy were, on their own, not sufficient to cause the climate changes we have observed in our proxies. In addition, even though the Sun is brighter now than at any time in the past 8,000 years, the increase in direct solar input is not calculated to be sufficient to cause the past century's modest warming on its own. There had to be an amplifier of some sort for the Sun to be a primary driver of climate change."

It was then claimed that such an amplifier (i.e., a factor that magnifies the effect of small variations of TSI on the Earth's climate) was discovered, and Patterson (2007) referred to several other studies for support. The theory here is that as small variations in TSI occur, the solar wind also changes, and the solar wind controls the number of galactic cosmic rays from deep space that enter our solar system and penetrate the Earth's atmosphere. The solar wind thus acts like a control grid on an old-fashioned triode vacuum tube where the cosmic rays are the current to the anode. The theory then claims that cosmic rays enhance cloud formation, and makes the further claim that this produces a cooling effect on the planet. So, it is claimed that the putative correlation of TSI with climate is an indicator of solar wind effects that in turn affect cosmic ray penetration, which affects cloud formation, which in turn produces cooling. Patterson (2007) asserts all of this wild speculation as if it were self-evident and a proven fact.

A number of papers were published on the putative relation between solar activity, cosmic ray flux, clouds, and climate. Most of these papers were concerned with multi-million year timescales and the question of whether solar variations or CO_2 variations was the dominant factor in past climate change. One example is Shaviv and Veizir (2003). Rahmstorf *et al.* (2004) took issue with a number of points in Shaviv and Veizir (2003) and a lively debate ensued. In the debate, Rahmstorf said:

> "We also fully agree with Shaviv and Veizir (2003) that their results, even if they were correct, apply only to the multi-million-year time scale and cannot be applied to shorter time scales. We are glad they have clarified this point. Their media releases as well as their paper, in which they compare their climate

> sensitivity with the range given by the Intergovernmental Panel on Climate Change (which applies to modern climate and centennial time scales), could have been misunderstood in this respect".

This writer agrees with Rahmstorf. It appears likely that Patterson (2007) made unsupportable claims. Nevertheless, this topic should alert us to the possibility that complex processes may be at work in the Earth's climate that depend on factors seemingly unrelated to our climate.

Another relevant paper is Shaviv (2005). This is a lengthy and very detailed paper that will not be discussed here except to note that it includes sections on warming since the last glacial maximum, and warming over the last century, which seem to be inappropriate based on the conclusions reached by Shaviv and Veizir (2004).

Kirkby, Mangini, and Muller (2004) continued the development of the concept but it remains somewhat far-fetched to this writer.

1.2.3.3 Atlantic Ocean circulation variation

If the Earth's rotation axis were not tilted relative to the plane of its orbit (obliquity = 0), the polar areas would be very cold because the maximum solar zenith angle at any latitude (measured up from the horizontal) would be the co-latitude, resulting in low glancing angles of the solar irradiance and very low solar input to the surface. This actually occurs on the Moon, where shaded areas in polar craters can have temperatures as low as $\sim$40 K. It is believed that any volatiles (water, ammonia, etc.) on the Moon will have migrated to cold traps in shaded craters near the poles, leaving almost all of the Moon desiccated.

On this hypothetical Earth with no obliquity, the polar areas would get very cold, and as water vapor carried by winds randomly approached the polar areas, it would condense out and, eventually, all the water on Earth would get trapped as snow and ice in the polar areas, while the remainder of the Earth would be desiccated.

The heat input to polar areas prevents this global cold trap catastrophe from happening, but during ice ages, significant capture of the Earth's water in polar areas will occur.

The total heat input to the north polar areas is the sum of contributions by solar irradiance, movements of air masses, and ocean currents. Above the Arctic Circle, there are long dark winters, during which ice could build up. It seems likely that if the polar areas depended solely of solar irradiance, they would freeze up and gradually acquire all of the world's water as ice sheets, thus desiccating the globe. The augmentation of solar irradiance by heat transfer from air masses, and more importantly from ocean currents provides a delicate balance between growth and depletion of the northerly ice sheets. The ocean currents have been suggested as major players because they convey large amounts of heat.

The circulation of the North Atlantic Ocean is discussed further in Section 1.2.4.

A number of clues point to variations in the Atlantic Ocean circulation as a cause of ice ages and sudden climate shifts. Rahmstorf and Alley (2002) argued that thermohaline circulation (i.e., temperature and salinity-driven) is a highly non-linear system and that at least two possible stable climatic states are possible: one with, and one without deep water forming in the north. The Atlantic Ocean would thus be a bi-stable system, like a ball in a double-well potential. Oscillations from one state to the other state could occur as a result of random variations in climate if the system behaves with *stochastic resonance*. In *stochastic resonance*, the system does not respond to signals below some threshold value, but amplifies signals that exceed the threshold. Thus, when random fluctuations exceed the threshold, it is hypothesized that the system can jump from one stable state to another. It is likely that these stable states involve changes in flow rate and/or geographical shifts in the location of the North Atlantic Deep Water (NADW) formation. In this model, the Atlantic Ocean currents can act like a threshold amplifier, turning a feeble signal into dramatic climate swings.

Rahmstorf (2002) extended the discussion of the role of ocean circulation in ice ages and sudden climate variations. Strong ocean currents carry warm and cold water at different levels along the coast of North America and up into the areas around Greenland and Iceland. This reference postulates warm and cold modes for the formation of the NADW. It is claimed that Earth orbit variations trigger a non-linear stochastic resonance that produces transfers between these modes, leading to climate change.

However, some data suggest that changes in ocean circulation may lag ice sheet growth, suggesting that changes in ocean circulation do not cause ice ages but are a result of ice sheet formation (Piotrowski *et al.*, 2005).

1.2.4 Sudden climate changes

Sudden warm and moist phases occurred at various times during the past 150,000 years, often rapidly taking Greenland and Europe from a full-glacial climate to conditions about as warm as at present. For the time period between 115,000 and 14,000 years ago, 24 significant short-lived warm events have been recognized from the Greenland ice core data, although many lesser warming events also occurred. From the speed of the climate changes recorded in the Greenland ice cap, it is believed that complete jumps in climate occurred over only a few decades. The intermittent warm periods lasted for varying spans of time, usually a few centuries to about 2,000 years, before equally rapid cooling periods returned conditions to their previous glacial state. Sudden intense cold and dry phases also occasionally affected Europe and the North Atlantic region, and possibly many other parts of the world. These so-called "Heinrich events" were first recognized as the traces of ice surges into the North Atlantic, but they show up in the Greenland ice cores and at least some are also detectable in the European pollen records and distant Antarctic ice cores (Taylor, 1999; Adams, 2002).

Around 14,000 years ago, a rapid global warming and moistening of climates began, perhaps occurring within the space of only a few years or decades. Conditions in many mid-latitude areas appear to have been roughly as warm as they are today, although many other areas—while warmer than during the Late Glacial Cold Stage—seem to have remained slightly cooler than at present. Forests began to spread back, and the ice sheets began to retreat. However, after a few thousand years of recovery, the Earth was suddenly plunged back into a new and very short-lived ice age known as the *Younger Dryas*, that led to a brief resurgence of the ice sheets. The main cooling event that marks the beginning of the Younger Dryas seems to have occurred within fewer than 100 years. After about 1,300 years of cold and aridity, the Younger Dryas seems to have ended in the space of only a few decades when conditions became roughly as warm as they are today (Adams, 2002).

The start of the present warm phase, the *Holocene*, followed the sudden ending of the Younger Dryas, about 11,500 years ago. Forests quickly regained the ground that they had lost to cold and aridity. Ice sheets again began melting, though because of their size they took about two thousand more years to disappear completely. The Earth entered several thousand years of conditions warmer and moister than today; the Saharan and Arabian deserts almost completely disappeared under vegetation cover, and in the northern latitudes forests grew slightly closer to the poles than they do at present. This phase, known as the *Holocene optimum* occurred between about 9,000 and 5,000 years ago, although the timing of the warmest and moistest conditions probably varied somewhat between different regions. Other fluctuations during the Holocene have been reported (Adams, 2002).

A number of sudden climate transitions occurred during the Younger Dryas-to-Holocene stepwise change around 11,500 years ago, which seems to have occurred over a few decades. The speed of this change is probably representative of similar but less well-studied climate transitions during the last few hundred thousand years. These events almost certainly did not take longer than a few centuries. Various mechanisms, involving changes in ocean circulation, changes in atmospheric concentrations of greenhouse gases or haze particles, and changes in snow and ice cover, have been invoked to explain these sudden regional and global transitions. We do not know whether such changes could occur in the near future as a result of human effects on climate. Phenomena such as the Younger Dryas and Heinrich events might only occur in a glacial world with much larger ice sheets and more extensive sea ice cover. All the evidence indicates that most long-term climate changes occur in relatively sudden jumps, rather than as incremental changes (Adams, Maslin, and Thomas, 1999).

The sudden onset and ending of the Younger Dryas has been studied in particular detail in the ice core and sediment records on land and in the sea and it might be representative of other analogous events in the more distant past. A detailed study of two Greenland ice cores suggests that the main Younger Dryas to Holocene warming took several decades in the Arctic, but was marked by a series of warming steps, each taking fewer than 5 years. About half of the warming was concentrated into a single period of less than 15 years. A rapid global rise in atmospheric methane concentration that occurred at the same time suggests that the warming and moistening of climate (causing more methane output from swamps and other biotic sources) was a globally synchronized change. According to data from the Greenland ice cores, conditions remained slightly cooler than present for a while after the main warming period; *normal* Holocene warmth was not reached for a further 1,500 years (until around 10,000 YBP; Adams, Maslin, and Thomas, 1999).

1.2.4.1 Mechanisms behind sudden climate transitions.

Adams, Maslin, and Thomas (1999) pointed out:

> "It is still unclear how the climate on a regional or even global scale can change as rapidly as present evidence suggests. It appears that the climate system is more delicately balanced than had previously been thought, linked by a cascade of powerful mechanisms that can amplify a small initial change into a much larger shift in temperature and aridity."

According to Adams, Maslin, and Thomas (1999), the thinking of climatologists tends to emphasize several key components, as discussed next.

1.2.4.2 North Atlantic circulation as a trigger or an amplifier in rapid climate changes

The circulation of the North Atlantic Ocean probably plays a major role in either triggering or amplifying rapid climate changes in the historical and recent geological record. The North Atlantic has a peculiar circulation pattern: the northeast-trending Gulf Stream carries warm and relatively salty surface water from the Gulf of Mexico up to the seas between Greenland, Iceland, and Norway. On reaching these regions, the surface waters cool off and (with the combination of being cooler and relatively salty because it mixes with mid-depth overflow water from the Mediterranean) become dense enough to sink into the deep ocean. The *pull* exerted by this dense sinking water is thought to help maintain the strength of the warm Gulf Stream, ensuring a current of warm tropical water into the North Atlantic that sends mild air masses across to the European continent (Adams, Maslin, and Thomas, 1999).

According to Adams, Maslin, and Thomas (1999):

> "If the sinking process in the North Atlantic were to diminish or cease, the weakening of the warm Gulf Stream would result in colder winters (but not warmer summers) in Europe. So, a shutting off of the mild Gulf Stream air masses does not in itself explain why summers also became colder during sudden cooling events (and why ice masses started to build up on land due to winter snows failing to melt during summer). In the North Atlantic itself, sea ice would form more readily in the cooler winter waters due to a shut-off of the Gulf Stream, and for a greater part of the year the ice would form a continuous lid over the North Atlantic. A lid of sea ice over the North Atlantic would last for a greater proportion of the year; this would reflect back solar heat, leading to cooler summers on the adjacent landmass as well as colder winters. With cooler summers, snow cover would last longer into the spring, further cooling the climate by reflecting back the sun's heat. The immediate result of all this would be a European and west Siberian climate that was substantially colder, and substantially drier because the air that reached Europe would carry less moisture, having come from a cold sea ice surface rather than the warm Gulf Stream waters. After an initial rapid cooling event, the colder summers would also tend to allow the snow

> to build up year-on-year into a Scandinavian ice sheet, and as the ice built up it would reflect more of the Sun's heat, further cooling the land surface, and giving a massive high pressure zone that would be even more effective at diverting Gulf Stream air and moisture away from the mid-latitudes of Europe. This would reinforce a much colder regional climate.''

Adams, Maslin, and Thomas (1999) went on to say:

> ''The trigger for a sudden 'switching off' or a strong decrease in deep water formation in the North Atlantic must be found in a decrease in density of surface waters in the areas of sinking in the northern Atlantic Ocean. Such a decrease in density would result from changes in salinity (addition of fresh water from rivers, precipitation, or melt water), and/or increased temperatures ... During glacial phases, the trigger for a shut-off or a decrease in deep water formation could be the sudden emptying into the northern seas of a lake formed along the edge of a large ice sheet on land (for instance, the very large ice-dammed lake that existed in western Siberia), or a diversion of a melt-water stream from the North American Laurentide ice sheet through the Gulf of St. Lawrence, as seems to have occurred as part of the trigger for the Younger Dryas cold. A pulse of fresh water would dilute the dense, salty Gulf Stream and float on top, forming a temporary lid that stopped the sinking of water that helps drive the Gulf Stream. The Gulf Stream could weaken and its northern end could switch off altogether, breaking the 'conveyer belt' and allowing an extensive sea ice cap to form across the North Atlantic, preventing the ocean current from starting up again at its previous strength. Theoretically, the whole process could occur very rapidly, in the space of just a few decades or even several years. The result could be a very sudden climate change to colder conditions, as has happened many times in the area around the North Atlantic during the last 100,000 years.
>
> The sudden switch could also occur in the opposite direction, for example if warmer summers caused the sea ice to melt back to a critical point where the sea ice lid vanished and the Gulf Stream was able to start up again. Indeed, following an initial cooling event the evaporation of water vapor in the tropical Atlantic could result in an 'oscillator' whereby the salinity of Atlantic Ocean surface water (unable to sink into the North Atlantic because of the lid of sea ice) built up to a point where strong sinking began to occur anyway at the edges of the sea ice zone. The onset of sinking could result in a renewed northward flux of warm water and air to the North Atlantic, giving a sudden switch to warmer climates, as is observed many times within the record of the last 130,000 years or so.''

According to Adams, Maslin, and Thomas (1999), the process of switching off or greatly diminishing the flow of the Gulf Stream would not affect Europe alone. Antarctica would be even colder than it is now, because much of the heat that it receives now ultimately comes from Gulf Stream water that sinks in the North Atlantic, and travels down the western side of the deep Atlantic Basin and then partially resurfaces just off the bays of the Antarctic coastline.

The idea is widespread that the Gulf Stream is responsible for Europe's mild winters; if this transport of heat did not take place, the soft climates of both France and England would be like that of Labrador, severe in the extreme, and ice-bound. However, Seager (2006) emphasized the role of the Gulf Stream in ocean circulation but debunked the role of the Gulf Stream in warming Europe. According to Seager (2006):

> "The Gulf Stream carries with it considerable heat when it flows out from the Gulf of Mexico and then north along the East Coast before departing U.S. waters at Cape Hatteras and heading northeast toward Europe. All along the way, it warms the overlying atmosphere. In the seas between Norway and Newfoundland, the current has lost so much of its heat, and the water has become so salty (through evaporation), that it is dense enough to sink. The return flow occurs at the bottom of the North Atlantic, also along the eastern flank of North America. This overturning is frequently referred to as the North Atlantic thermo-haline circulation, or simply the *Atlantic conveyor*. It is part of the global pattern of ocean circulation, which is driven by winds and the exchange of heat and water vapor at the sea surface."

No mechanism could be found by which the Gulf Stream could warm Europe in the winter. Instead, Seager (2006) pointed out that the same type of climatological difference between Europe and North America (warmer winters in Europe for the same latitude) also occur in the Pacific Northwest (Seattle/Vancouver is warmer than comparable latitudes in East Asia). A main contributor to this is simply that the ocean is a vast thermal reservoir that reduces thermal excursions, and the prevailing winds in both the Atlantic and the Pacific are easterly, providing climates to the Pacific Northwest and to Europe that are regulated by the flow of air over oceans, whereas on the opposite sides of the oceans, the climates are regulated by the flow of air over land which undergoes much greater thermal variation. In fact, global climate models indicate that Europe does not cool down even when the Gulf Stream is turned off. Seager (2006) claimed that topographically forced atmospheric waves also contribute significantly to the large difference in winter temperature across the Atlantic. This is a complex topic that will not be discussed further here.

Seager (2006) claimed:

> "Evidence from ocean sediments suggests that at times during the last ice age the North Atlantic thermo-haline circulation was considerably weaker than it is today, or perhaps it even shut down entirely. One such event took place about 12,900 years ago, during the last deglaciation, and is called the Younger Dryas. The Younger Dryas began with a dramatic reversal in what was a general warming trend, bringing near-glacial cold to the North Atlantic region. This episode ended with an even more dramatic warming about 1,000 years later. In Greenland and Western Europe, the beginning and end of the Younger Dryas involved changes in winter temperature as large as 20 degrees taking place in little more than a decade. But the Younger Dryas was not a purely North Atlantic

phenomenon: Manifestations of it also appeared in the tropical and southern Atlantic, in South America and in Asia. For many years, the leading theory for what caused the Younger Dryas was a release of water from glacial Lake Agassiz, a huge, ice-dammed lake that was once situated near Lake Superior. This sudden outwash of glacial melt-water flooded into the North Atlantic, it was said, lowering the salinity and density of surface waters enough to prevent them from sinking, thus switching off the conveyor. The North Atlantic Drift then ceased flowing north, and, consequently, the northward transport of heat in the ocean diminished. The North Atlantic region was then plunged back into near-glacial conditions. Or so the prevailing reasoning went. Recently, however, evidence has emerged that the Younger Dryas began long before the breach that allowed freshwater to flood the North Atlantic. What is more, the temperature changes induced by a shutdown in the conveyor are too small to explain what went on during the Younger Dryas. Some climatologists appeal to a large expansion in sea ice to explain the severe winter cooling. I agree that something of this sort probably happened, but it's not at all clear to me how stopping the Atlantic conveyor could cause a sufficient redistribution of heat to bring on this vast a change. In any event, the still-tentative connections investigators have made between thermo-haline circulation and abrupt climate change during glacial times have combined with the popular perception that it is the Gulf Stream that keeps European climate mild to create a doomsday scenario: Global warming might shut down the Gulf Stream, which could 'plunge western Europe into a mini–ice age,' making winters 'as harsh as those in Newfoundland,' or so claims, for example, a recent article in *New Scientist*. This general idea has been rehashed in hundreds of sensational news stories. The germ of truth on which such hype is based is that most atmosphere–ocean models show a slowdown of thermo-haline circulation in simulations of the 21st century with the expected rise in greenhouse gases. The conveyer slows because the surface waters of the sub-polar North Atlantic warm and because the increased transport of water vapor from the subtropics to the sub-polar regions (where it falls as rain and snow) freshens the sub-polar North Atlantic and reduces the density of surface waters, which makes it harder for them to sink. These processes could be augmented by the melting of freshwater reserves (glaciers, permafrost and sea ice) around the North Atlantic and the Arctic. But from what specialists have long known, I would expect that any slowdown in thermo-haline circulation would have a noticeable but not catastrophic effect on climate. The temperature difference between Europe and Labrador should remain. Temperatures will not drop to ice-age levels, not even to the levels of the LIA, the relatively cold period that Europe suffered a few centuries ago. The North Atlantic will not freeze over, and English Channel ferries will not have to plow their way through sea ice. A slowdown in thermo-haline circulation should bring on a cooling tendency of at most a few degrees across the North Atlantic one that would most likely be overwhelmed by the warming caused by rising concentrations of greenhouse gases. This moderating influence is indeed what the climate models show for the 21st century and what has been stated in reports of the Intergovernmental Panel on Climate Change.

> Instead of creating catastrophe in the North Atlantic region, a slowdown in thermo-haline circulation would serve to mitigate the expected anthropogenic warming!"

The role of ocean circulation and variations in salinity as a cause for sudden changes in glaciation is also discussed by Schmidt, Vautravers, and Spero (2006).

1.2.4.3 Carbon dioxide as a feedback in sudden changes

According to Adams, Maslin, and Thomas (1999), analysis of bubbles in ice cores shows that at the peak of glacial phases, the atmospheric concentration of CO_2 was about 30% lower than during interglacial conditions. Adams, Maslin, and Thomas (1999) said: "We do not at present know whether the lower glacial CO_2 levels were a cause or merely an effect of the ice ages." The lower carbon dioxide concentrations resulting from greater ocean carbon storage would cool the atmosphere, and allow more snow and ice to accumulate on land. Relatively rapid changes in climate, occurring over a few thousand years, could have resulted from changes in the atmospheric CO_2 concentration. It was also stated that a problem with invoking atmospheric carbon dioxide levels as a causal factor in sudden climate changes is that CO_2 seems to have varied too slowly, following on the timescale of millennia what often occurred on the timescale of decades—"but the resolution of our records may not be good enough to resolve this question now." Petit *et al.* (1999) showed that the atmospheric concentrations of CO_2 rose from $\sim$180 ppm during glaciation to 280 ppm to 300 ppm during interglacial periods.

However, there is considerable evidence that the CO_2 concentration rise (or fall) lags the temperature rise (or fall) that occurs during periods of increased glaciation or warming at Antarctica. The time lag was estimated to be $\sim$500 years by Roper (2006), 800 ± 200 years by Caillon *et al.* (2003), 1,300–5,000 years by Mudelsee (2001), "several thousand years" by Petit *et al.* (1999), 800 years by Monnin *et al.* (2001), and 400–1,000 years by Fischer *et al.* (1999). That would seem to imply that increased CO_2 is an effect—not a cause—of temperature change. A number of naysayers have used this fact to argue against rising CO_2 concentration as a cause (rather than an effect) of global warming. However, the rise (or fall) of CO_2 actually preceded temperature changes in the far north, so the situation is more complicated.

1.2.4.4 Surface reflectivity (albedo) of ice, snow, and vegetation.

According to Adams, Maslin, and Thomas (1999):

> "The intensely white surface of sea ice and snow reflects back much of the Sun's heat, hence keeping the surface cool. Presently, about a third of the heat received from the Sun is reflected back into space, and changes in this proportion thus have the potential to strongly influence global climate. In general the ice cover on the sea, and the snow cover on the land, have the potential to set off rapid climate changes because they can either appear or disappear rapidly given the right circumstances. Ice sheets are more permanent objects that, whilst they reflect

a large proportion of the sunlight that falls upon them, take hundreds of years to melt or build up because of their sheer size. When present, sea ice or snow can have a major effect in cooling regional and global climates, but with a slight change in conditions (e.g. just a slightly warmer summer) they will each disappear rapidly, giving a much greater warming effect because sunlight is now absorbed by the much darker sea or land cover underneath. In an unusually cold year, the opposite could happen, with snow staying on the ground throughout the summer, itself resulting in a cooler summer climate. A runaway change in snow or sea ice (positive feedback) could thus be an important amplifier or trigger for a major change in global temperature. It is possible that by slow changes over millennia or centuries, the climate could be brought to a break point involving a runaway change in snow and ice reflectivity over a few decades. These slow background changes might include variations in the Earth's orbit (affecting summer sunlight intensity), or gradual changes in carbon dioxide concentration, or in the northern forest cover which affects the amount of snow that is exposed to sunlight."

"It is possible that the relatively long-lived ice sheets might occasionally help bring about very rapid changes in climate, by rapidly 'surging' outwards into the sea and giving rise to large numbers of icebergs that would reflect back the Sun's heat and rapidly cool the climate."

"Another, possibly neglected, factor in rapid regional or global climate changes may be the shifts in the albedo of the land surface that result from changes in vegetation or algal cover on desert and polar desert surfaces. An initial spreading of dark-colored soil surface algae or lichens following a particularly warm or moist year might provide a 'kick' to the climate system by absorbing more sunlight and thus warming the climate, and also reducing the dust flux from the soil surface to the atmosphere."

1.3 HOLOCENE TEMPERATURE HISTORY

1.3.1 Introduction

Temperatures over the last 8,000 years have been unusually stable compared with earlier epochs. In fact, as judged from Vostok and Greenland records, this long stable period in the "Holocene" is a unique feature of climate during the past 420,000 years. It has been suggested that this had profound implications for the development of civilizations (Houghton, 2004).

de Blij (2005) describes the end of the last ice age and the evolution of the Holocene. As the ice sheets were melting about 12,000 YBP, it is hypothesized that a very large ice sheet (the size of a Canadian province?) slid into the North Atlantic, chilling the ocean back to glacial temperatures. This so-called "Younger Dryas" event (see Section 1.2.4) lasted about 2,000 years and by about 10,000 YBP, the warming trend continued, as shown in Figure 1.13.

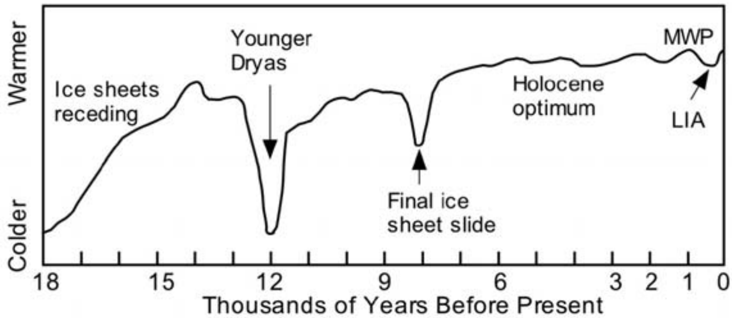

Figure 1.13. A concept of post-glaciation temperatures. Adapted from de Blij (2005).

As the post-glaciation period progressed, there was one more large slide of an ice sheet into the sea around 8,000 YBP, sending a wall of water through the Mediterranean that filled the Black Sea with "the force of 200 Niagara Falls" (de Blij, 2005). The "Medieval Warm Period" (MWP) and "Little Ice Age" (LIA) appear as small wrinkles on this broad background.

1.3.2 Glacial sediments

Matthews and Briffa (2005) reported on measurements of glacier fluvial sediments from stream bank mires subject to episodic overbank deposition of suspended sediment in sediment cores in Norway. For the glacier at Bjørnbreen, Jotunheimen, in southern Norway, the history of glacier expansion and contraction is shown in Figure 1.14.

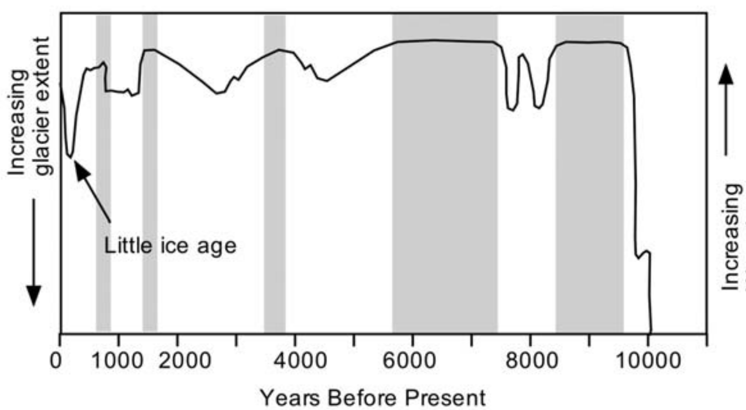

Figure 1.14. Historical expansion and contraction of Bjørnbreen glacier. Gray areas represent disappearance of the glacier. Adapted from Matthews and Briffa (2005).

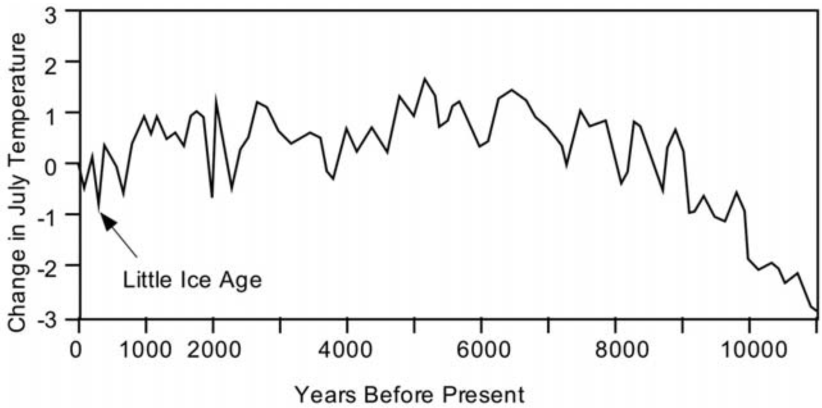

Figure 1.15. Holocene climatic variations (relative to modern values) at Bjørnbreen, Jotunheimen, in southern Norway. The mean July temperatures were based on an independent pollen-based proxy. Adapted from Matthews and Briffa (2005).

An estimate of Holocene temperatures at the Bjørnbreen glacier is shown in Figure 1.15. This figure suggests that the LIA was colder than almost all of the 9,000 years that preceded it and despite the recent rise in temperature ("global warming") temperatures in 2007 are lower than they were for about 8,000 years prior to the last millennium. A mid-range warm period around 6,500 YBP is evident. This figure also suggests that any warming taking place in the early 21st century is minor compared with the past 8,000 years.

1.3.3 Plant pollen proxies

Plant pollen measurements can be used as a proxy for climate change in the past. (Proxies are covered in detail in Section 1.1.) Converting pollen counts to temperature is a complex subject that is beyond the scope of the present work. Davis *et al.* (2003) reported on an extensive study of Holocene temperatures in Europe based on pollen measurements. They divided Europe into six regions and used an extensive network of 510 cores spread widely over Europe. The pollen–temperature transfer function was calibrated with 2,363 samples from throughout North Africa and Europe west of the Urals. The results are shown in Figures 1.16 to 1.18.

As might be expected, the northern regions show the warming at the end of the last ice age. The ice sheets in the ice age were centered near Scandinavia and thus the western region displays a more classical recovery from glaciation than the eastern region. The southern region never endured glaciation. Peak temperatures occurred in the north around 6,000 YBP.

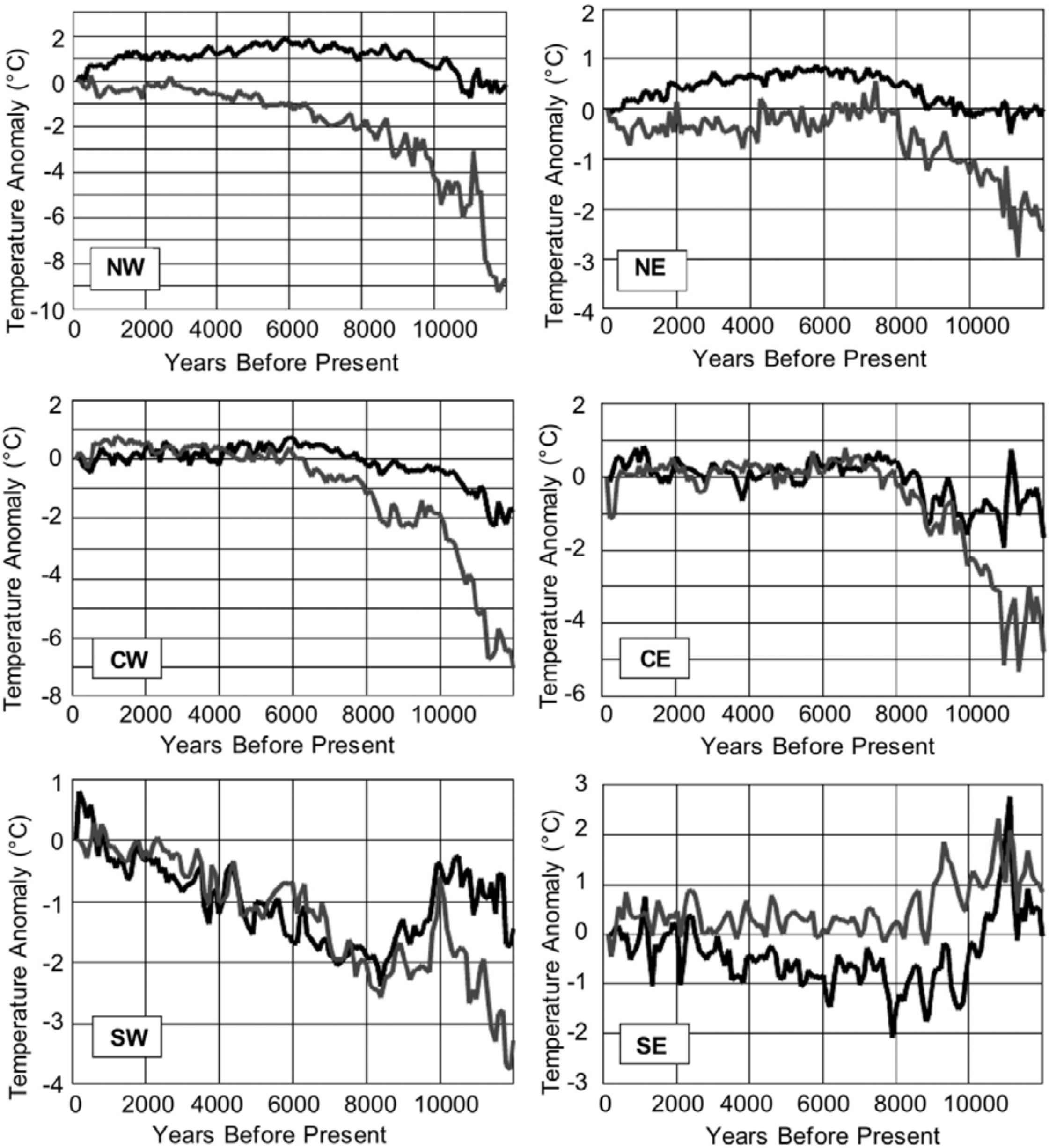

Figure 1.16. Holocene temperatures in six regions of Europe. Black lines are maximum summer temperatures and gray lines are minimum winter temperatures. All temperatures measured as deviations from a baseline of 120 years centered on 1890. Adapted from Davis *et al.* (2003).

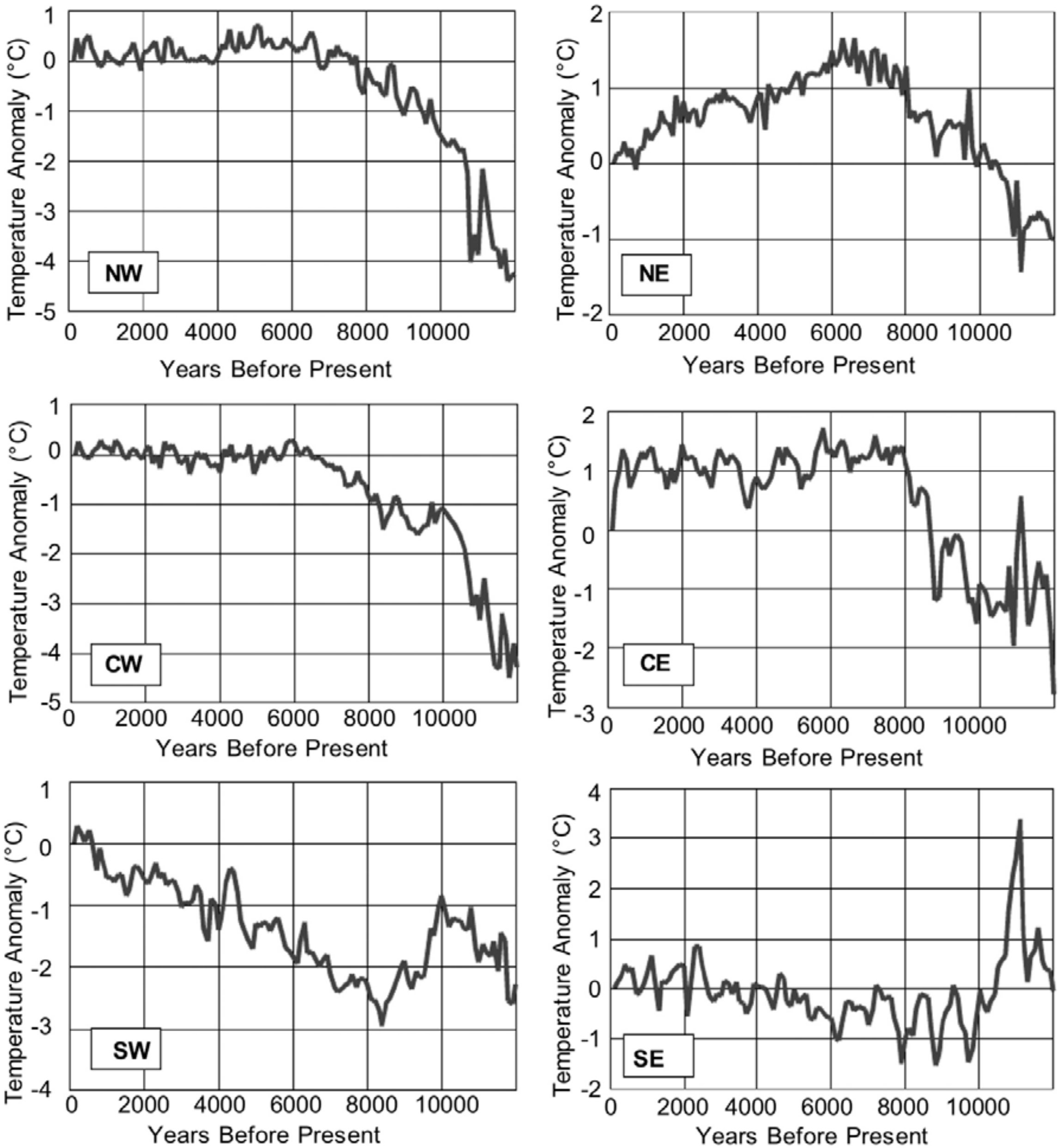

Figure 1.17. Holocene annual temperatures in six regions of Europe. All temperatures are deviations from a baseline of 120 years centered on 1890. Adapted from Davis *et al.* (2003).

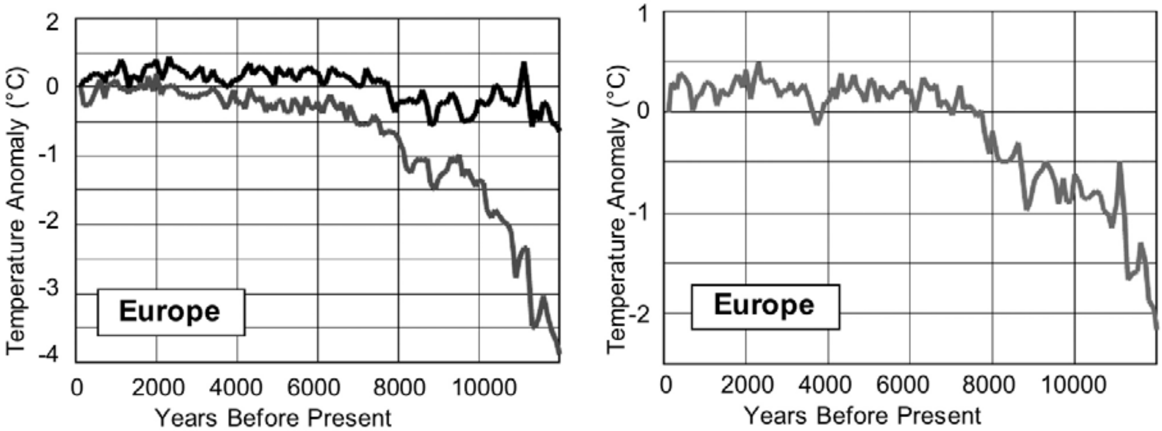

Figure 1.18. Holocene annual temperatures for Europe as a whole. (a) Left panel: black line = summer maximum and gray line = winter minimum. (b) Right panel: annual temperatures. All temperatures are deviations from a baseline of 120 years centered on 1890. Adapted from Davis *et al.* (2003).

1.3.4 Borehole measurements

The results of a comprehensive borehole analysis encompassing over 6,000 borehole measurements at depths of 100 m to 2,000 m are shown in Figure 1.19. Although the majority of the boreholes are concentrated in mid-latitudes of the Northern

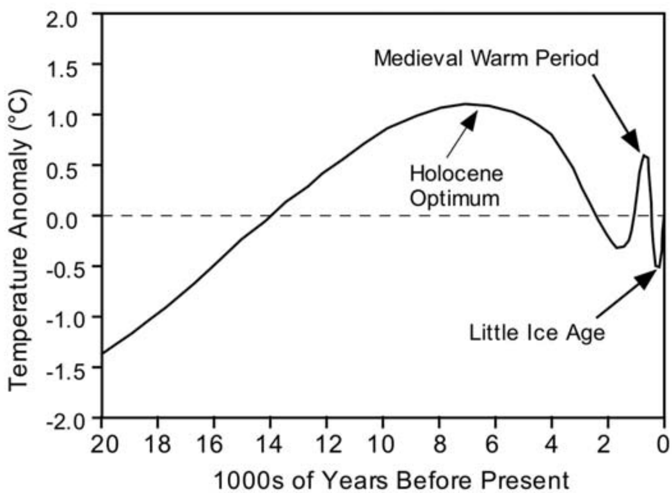

Figure 1.19. Result of borehole interpretations of past surface temperature. Depending on assumptions made in data analysis, the amplitude of the oscillations can increase or decrease, but the overall shape remains the same. Adapted from Huang, Pollack, and Shen (1997).

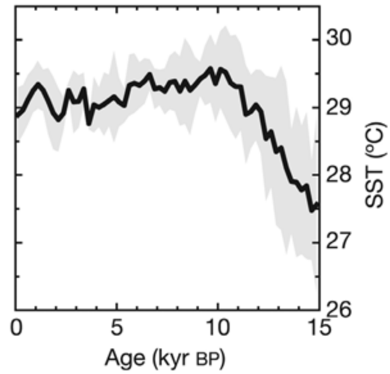

Figure 1.20. Average sea surface temperature during the Holocene. Adapted from Stott *et al.* (2004).

Hemisphere, the data set has some representation from every continent (Huang, Pollack, and Shen (1997).

1.3.5 Ocean sediment cores

Stott *et al.* (2004) combined oxygen isotope and Mg/Ca data from foraminifers retrieved from three sediment cores in the western tropical Pacific Ocean to reconstruct Holocene sea surface temperatures and salinities in the region. The average of several sites is shown in Figure 1.20. A relatively flat maximum is observed around 10,000 YBP.

Briner *et al.* (2006) examined lake sediments from northeastern Baffin Island, Arctic Canada and found a pronounced maximum temperature from around 10,000 to 8,500 YBP that was as much as 5°C warmer than today. They did not observe any "Holocene optimum" at 5,500 YBP. Caseldine, Langdon, and Holmes (2006) found peak warmth of about 2°C higher than present at Iceland around 8,000 YBP, which they indicated was a later date than for Greenland and Eastern Canada. Darby *et al.* (2001) developed a new 10,000-year multi-parameter environmental record from a thick sequence of post-glacial sediments obtained from cores retrieved from the upper continental slope off the Chukchi Sea shelf in the Arctic Ocean. Their data reveal "previously unrecognized millennial-scale variability in Arctic Ocean circulation and climate," along with evidence that "in the recent past, the western Arctic Ocean was much warmer than it is today."

1.3.6 Other Holocene results

Although there is some variation from proxy to proxy, it appears that the Holocene has been a relatively benign period of relative warmth, following the last ice age. On the other hand, O'Brien *et al.* (1995) found some significant fluctuations in the Holocene climate. deMenocal *et al.* (2000) found significant variations that correlated between tropical and polar trends. Some measurements suggest a 1,500-year cycle in the Holocene (see Section 7.2) but this remains uncertain. Keigwin and Boyle (2000) studied cores taken from the "Bermuda Rise" and concluded:

> "Throughout the last glacial cycle, reorganizations of deep ocean water masses were coincident with rapid millennial-scale changes in climate. Climate changes have been less severe during the present interglacial, but evidence for concurrent deep ocean circulation change is ambiguous. The Medieval Warm Period and Little Ice Age appear as minor fluctuations in a slowly downward trending temperature over the past two millennia."

Section 6.1.3 describes estimates of variation of CO_2 concentration during the Holocene.

2

Temperatures in the past millennium

2.1 THE LITTLE ICE AGE AND THE MEDIEVAL WARM PERIOD

Historic proxy studies have distinguished two periods of particular interest in the past millennium. One is the putative *Medieval Warm Period* (MWP) centered near 900–1000, that was supposedly an unusually mild climate. The other was the *Little Ice Age* (LIA) from perhaps 1400 (or 1600) to about 1850 when temperatures were unusually cold. The nature of proxies is such that a considerable amount of variability in results derives from various proxies even if the underlying data are uniform spatially and temporally. Compounding this is the fact that, apparently, the MWP and LIA represented trends that varied spatially and temporally, so the net result of proxy measurements for these periods is typically not clear-cut.

In the past several years, global warming alarmists, with a vested interest in the *hockey stick* model of past temperatures (see Section 2.2.1), have pointed out the lack of uniformity in evidence for the MWP and the LIA, and thereby attacked the very notions of the MWP and the LIA, arguing either that they were regional, minor, and variable, or in some cases they were claimed to be non-existent.

However, as Soon and Baliunas (2003a, b) pointed out:

> "The term Medieval Warm Period has been the subject of considerable controversy. Its nature and even its existence has been questioned . . . as has that of the Little Ice Age . . . They were not periods of unbroken cold and warmth respectively. Climate varied on small scales both spatially and temporally, as it has also in the twentieth century. Nevertheless, climatic conditions were such during the Little Ice Age that mass balances were sufficiently predominant for the glaciers to remain enlarged, although their fronts oscillated. Similarly during the Medieval Warm Period climatic conditions caused mass balances to be negative, and volumes of glaciers to be reduced, so that they retracted substantially, though

> their fronts no doubt fluctuated, as they have been observed to do during the warming of the twentieth century.''

One can deal with the MWP and the LIA in various ways. Grove (2001) reduced the difficulty in deciphering the nature of the MWP and the LIA by not directly referring to climate, but rather by limiting the definition to the extent to which glaciers extended globally and remained primarily enlarged or primarily retracted, while their fronts fluctuated about these forward or backward positions.

Various proxy studies have derived different time periods, and different spatial extents of the putative LIA. Ogilvie and Jonsson (2001) pointed out ''the difficulty in defining exactly the onset of the LIA.'' However, it is widely agreed that the end of the LIA was either late in the 19th century or early in the 20th century. They emphasized the many discrepancies and lack of coherence in data purporting to define the temporal extent of the LIA (and the MWP as well). However, it is not clear how much of the variability in the observed timing of the LIA is due to true variability and how much is due to difficulty in interpreting proxy data. Ogilvie and Jonsson (2001) said:

> ''This lack of agreement could be due in part to uneven distribution and character of the evidence available, to the dating techniques used, and their resolution, and possibly due to differing degrees of effort devoted to unraveling glacial history.''

There is no precise onset and there is no way to define the LIA except as a multi-century period when temperatures were predominantly (but certainly not exclusively) relatively low compared with the eras that preceded and followed the LIA.

Soon and Baliunas (2003a, b) investigated the putative MWP and LIA by posing three important questions:

(1) Was there an objectively discernible climatic anomaly during the LIA, defined as 1300–1900?
(2) Was there an objectively discernible climatic anomaly during the MWP, defined as 800–1300?
(3) Was there an objectively discernible climatic anomaly within the 20th century that may validly be considered the most extreme (i.e., the warmest) period in the record? (An important consideration in answering this question is to distinguish the case in which the 20th century warming began early in the century vs. after the 1970s, as recorded by surface thermometers. This criterion is necessary in order to judge the influence of 20th century warming by anthropogenic forcing inputs such as increased atmospheric carbon dioxide content.)

It is understood that neither the LIA nor the MWP were periods of unbroken cold and warmth, respectively. Climate varied on small scales both spatially and temporally, as it has also in the 20th century. Nevertheless, climatic conditions may have been such during the LIA that mass balances were sufficient for the glaciers to remain predominantly enlarged, although their fronts oscillated. Similarly, during the MWP climatic conditions would have caused the volumes of glaciers to be reduced, so that they retracted substantially, though their fronts no doubt fluctuated, as they have been observed to do during the warming of the 20th century.

In the context of Soon and Baliunas (2003a, b), a *climatic anomaly* was defined as a period of 50 or more years of predominantly sustained warmth, wetness, or dryness within the MWP, or a 50-year or longer period of predominantly cold, dryness, or wetness during the LIA. Definition of the 20th century anomaly is more difficult to establish. The 20th century surface instrumental temperature record contains three distinct, multi-decadal trends: early-century warming, mid-century cooling, and late-century warming. Soon and Baliunas compared the 20th century objectively with extended proxy-based temperature and precipitation histories and answered Question 3 by asking if, within each proxy record, there was an earlier (pre–20th century) 50-year interval that was warmer (or more extreme, in the case of precipitation) than any 50-year average within the 20th century.

Climate indicators that were considered included information obtained from documentary and cultural sources, ice cores, glaciers, boreholes, speleothems, tree growth limits, lake fossils, mammalian fauna, coral and tree ring growth, peat cellulose, pollen, phenomenological data, and seafloor sediments. In its own way, each proxy provides a unique view of climate variability in terms of its relative sensitivity to the planet's thermal and hydrological fields, as well as non-climatic factors. Thus, the three questions were addressed within the context of local or regional sensitivity of the proxies to relevant climatic variables, including air temperature, sea surface temperature, precipitation, and any combination of large-scale patterns of pressure, wind, and oceanic circulation.

Soon and Baliunas (2003a, b) argued that the procedure (used, for example, by Mann, Bradley, and Hughes, 1998) of mathematical decomposition techniques to the reconstruction of a global 1,000-year temperature history is limited by both the inhomogeneous spatio-temporal sampling gaps in proxy records and the very short length of surface thermometer record available for calibration–verification purposes. The classification of proxies using local proxy data is complementary to the mathematical decomposition process but avoids some of their difficulties (albeit at the expense of quantitative results).

The different sensitivities of proxies to climate variables and the potential time dependence of the proxy–climate correlation require careful calibration and verification on a location-by-location basis; the emphasis on local results by Soon and Baliunas (2003a, b) avoided the difficulty of inter-comparing disparate proxies but did not generate a synoptic global view. Thus, Soon and Baliunas (2003a, b) gave up on quantitative synthesis of many proxies into global or NH average temperatures, because even for the same location, different proxies may yield different climate expressions simply because of their different sensitivities to local climatic variables. Soon and Baliunas (2003a, b) suggested that a compact mathematical representation of individual proxy variations (e.g., Mann, Bradley, and Hughes, 1998), without full understanding of proxy–climate calibration relations, may yield overconfident results.

Soon and Baliunas (2003a, b) provided a very long table listing the various proxies used in the study. For each proxy, they provided the spatial extent, latitude, and longitude (where applicable), type of proxy, reference, and three "yes" or "no" entries as to whether the proxy provided answers to Questions 1, 2, and 3. These included 14 worldwide proxies, and >100 proxies that are regional or local. The answers to the three questions were provided in several figures accompanied by a lengthy discussion (about 25 pages) of detailed information regarding specific proxy results that led to these figures. These results indicated that

- The proxy data suggest that the LIA existed as a distinguishable climatic anomaly in almost all regions of the world that were assessed. Only two records, tree ring growth from western Tasmania and isotopic measurements from ice cores at Siple Dome, Antarctica, do not exhibit any persistent or unusual climatic change over this period (although the western Tasmanian reconstruction contains an exceptionally cold decade).
- The MWP is a distinguishable climatic anomaly with only two unambiguous negative results.
- Most of the proxy records do not suggest the 20th century to be the warmest or the most extreme in its local representations. There are only three unambiguous findings favoring the 20th century as the warmest of the last 1,000 years: the records from the Dyer Plateau, Antarctica, the Himalayas, and Mongolia. An important feature of this result is the large number of uncertain answers compared with the two prior questions. Another interesting feature is that the warmest or most extreme climatic anomalies in the proxy indicators often occurred in the early to mid-20th century, rather than throughout the century.

2.1.1 Anecdotal inferences on the MWP and the LIA

Fagan (2000) provided many anecdotal descriptions of the climate during the MWP and the LIA. How accurate or general these may be remains an open question.

Fagan described the mild period prior to the LIA. The overseas conquests of the Norse from about 800–1200 took place in "unusually mild and stable weather". He went on at length to describe the reduced pack ice around Iceland when "winter and summer temperatures were usually higher than today." By contrast, during the great cold of 1350–1380, sea ice came so close to land that Greenland polar bears came ashore on Iceland. He said: "For five centuries [9th through 13th centuries], Europe basked in warm, settled weather ... Compared with what was to follow, these centuries were a climatic golden age."

Fagan said: "In the 13th century, Greenland and Iceland experienced increasing cold. Sea ice spread southward around Greenland and in the northern Atlantic, creating difficulties for Norse ships ..." Icelandic recollections of the Little Ice Age are typified by: "In the extreme winter of 1695, ice blocked the entire coast in January and stayed all summer."

He also described changes in weather patterns other than temperature: drought and excessive rainfall. There was a deluge seven weeks after Easter in 1315. Rain fell essentially continuously from May through August, followed by a cold September, resulting in widespread famine and dislocation.

Fagan said:

> "The medieval warm period saw long successions of warm, settled summers. Then, starting around 1310, and continuing for about five and a half centuries, the climate became more unpredictable, cooler, occasionally stormy, and subject to sporadic extremes—the LIA. Anecdotal accounts of the cold during the little ice age abound in paintings of the period, showing skaters on frozen lakes and streams that do not presently freeze."
>
> "Between 1680 and 1730, the coldest cycle of the little ice age, temperatures plummeted, the growing season in England was about five weeks shorter than it was during the twentieth century's warmest decades. The number of days each winter with snow on the ground in Britain and the Netherlands rose to between twenty and thirty, as opposed to two to ten days through most of the twentieth century. The winter of 1683/84 was so cold that the ground froze to a depth of more than a meter in parts of southwestern England and belts of sea ice appeared along the coasts of southeastern England and northern France. The ice lay thirty to forty kilometers offshore along parts of the Dutch coast. Many harbors were so choked with ice that shipping halted throughout the North Sea. Conditions around Iceland were now exceptionally severe. Sea ice often blocked the Denmark Strait throughout the summer. In 1695, ice surrounded the entire coast of Iceland for much of the year, halting all ship traffic. The inshore cod fishery failed completely, partly because the fish may have moved offshore into slightly warmer water, but also because of the islanders' primitive fishing technology and open boats. On several occasions between 1695 and 1728, inhabitants of the Orkney Islands off northern Scotland were startled to see an Inuit in his kayak paddling off their coasts. On one memorable occasion, a kayaker came as far south as the River Don near Aberdeen. These solitary Arctic hunters had probably spent weeks marooned on large ice floes. As late as 1756, sea ice surrounded much of Iceland for as many as thirty weeks a year ... The cold polar water spread southward toward the British Isles. The cod fishery off the Faeroe Islands failed completely, as the sea surface temperature of the surrounding ocean became 5°C cooler than today. Just as it had in the 1580s, a steep thermal gradient developed between latitudes 50° and 61–65° north, which fostered occasional cyclonic windstorms far stronger than those experienced in northern Europe today. The effects of colder little ice age climate were felt over enormous areas, not only of Europe but the world" (Fagan, 2000).

An interesting paper (Varekamp, 2006) claims: "the removal of hundreds of thousands of beavers [to make furs for the cold middle and upper classes of Europe] during early Dutch and English colonial rule led to the extensive desiccation of wetlands in New England." Presumably the removal of beaver-created dams on a large scale had a significant climatic effect.

However, Crowley (2002) claims that historical written reports cannot always be taken at face value. An example is cited regarding the often-misused freezing of the River Thames. Between 1408 and 1914 the Thames in London froze over 22 times. Century counts are: 1400s (two times), 1500s (five), 1600s (nine), 1700s (five), and 1800s (one). Taken at face value, this would seem to imply that the 1600s and 1700s were coldest. However, there were a number of modifications to this bridge, including reductions in the number of piers of London Bridge in 1756 that reduced ponding effects. Replacement of the bridge between 1825 and 1835 widened the piers further and removed the small weir, enabling the tide to encroach farther upstream. No complete freezes have occurred since then. Changes to the river and its channel are important factors that must be considered alongside cooler winters as causes of freeze-over. For example, in the winter of 1962 to 1963, the third coldest since 1659 in the Central England Temperature (CET) record, the river only froze upstream of the modern tidal limit (20 km upstream of central London). In the two coldest CET winters in 1683 to 1684 and 1739 to 1740 the Thames froze, but it also froze during nine other winters between 1659 and 1820.

2.1.2 The Medieval Warm Period

There are anecdotal indications that the so-called Medieval Warm Period (MWP) from about 800 to perhaps 1200 was warmer than any period that followed it (e.g., grapes suitable for wine-making were reportedly grown in England, and the tree line in Scandinavia was 100 m–200 m higher than it is at present (Crowley and Lowery, 2000), although some believe that the late 20th century was warmer than the MWP. The degree of warmth in the MWP remains uncertain. There is considerably better anecdotal evidence that the so-called Little Ice Age (LIA) that followed the MWP (approximately 1400 to 1850) was considerably colder than the MWP, although there are uncertainties as to how consistently cold and how widespread the LIA was. The warmth of the MWP has been estimated by two means: (1) global climate models based on rather uncertain forcings, or (2) proxy analysis based on relatively few proxies available of uncertain veracity.

2.1.2.1 Climate models for the MWP: effects of changes in land use

Several analyses of the MWP were carried out with climate models. Unfortunately, we don't know much about differences in solar irradiance between the MWP and the LIA, although some solar irradiance models suggest that the solar irradiance was higher during the MWP (see, e.g., Figure 4.38, color section). Greenhouse gases were not an issue for the MWP and the LIA. Two forcings that have been modeled by several investigators are volcanic emissions and changes in land use (large-scale deforestation and conversion to farmland). While volcanic emissions provided several important short-term fluctuations, an important long-term difference between the MWP and the LIA that can be modeled is the change in land use. Cropland has a higher albedo than forest, and this can make a significant difference in the heat

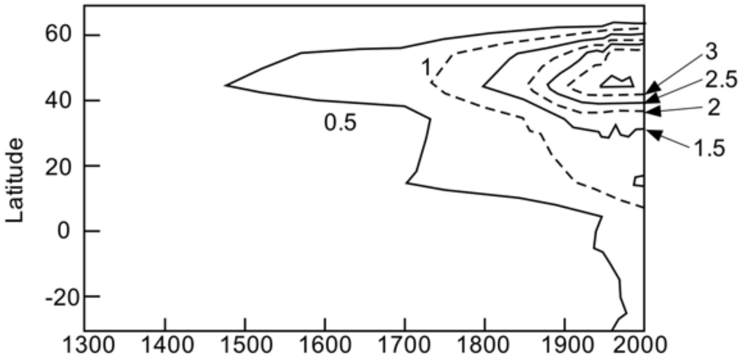

Figure 2.1. Deforested area shown as time-varying isolines in steps of units of 10^6 km^2 given for ten latitude bands. Adapted from Bauer, Claussen, and Brovkin (2003).

absorbed over a region. During the period after 1000, the conversion of forest to cropland accelerated, particularly in Europe.

According to Bauer, Claussen, and Brovkin (2003), global forest cover diminished over the period 1000 to 1992 by 30%, from 57×10^6 km^2 to 41.5×10^6 km^2. Before 1900, forest was mainly removed in the northern subtropical and temperate regions. In the second half of the 20th century, agriculture in these regions stopped expanding and even reversed while tropical deforestation was intensified. Figure 2.1 shows the deforestation model used by Bauer, Claussen, and Brovkin (2003).

Goosse *et al.* (2006) assumed a linear increase of crop area from zero in 1000 to the value reconstructed for 1700. However, they note that in a large number of regions of France, Belgium, the Netherlands, Germany, deforestation was particularly intense between 1000 and 1250 and weaker during the two following centuries. Their estimate of deforestation is shown in Figure 2.2. The forcing due to changes in land use was applied through modifications in the surface albedo, which is the primary effect of land cover change.

Brovkin *et al.* (2006) modeled the effect of land clearing changes and CO_2 emissions over the past millennium. The model used for land clearing is shown in Figure 2.3.

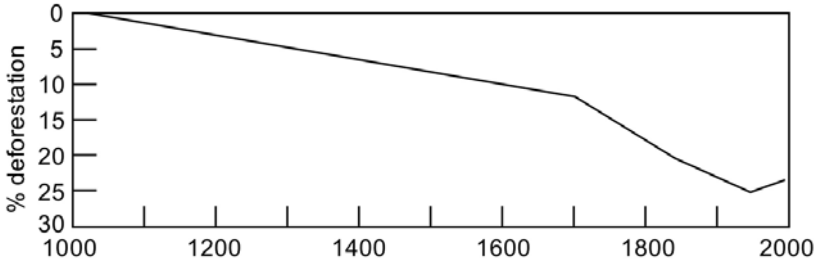

Figure 2.2. Estimate of deforestation. Adapted from Goosse *et al.* (2006).

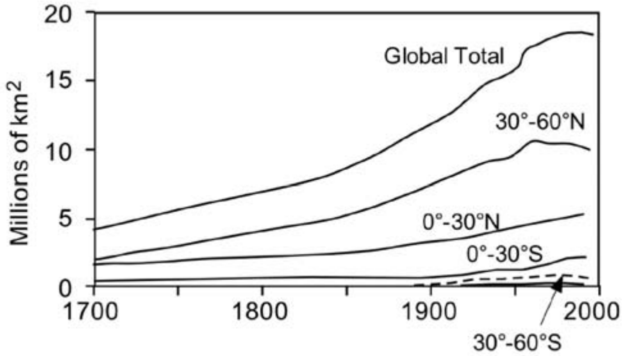

Figure 2.3. Cumulative area of land cleared by latitude and year. Adapted from Brovkin *et al.* (2006).

Bauer, Claussen, and Brovkin (2003) and Goosse *et al.* (2006) used global climate models to investigate the expected temperature variations over the past millennium, and compared the beginning of the millennium (the MWP) with the middle (the LIA) and later parts of the millennium (present day) to examine whether the putative MWP and LIA could be distinguished.

Starting in year 1000 as a baseline, Bauer, Claussen, and Brovkin (2003) examined the effect of various assumed forcings (solar, volcano, CO_2, and deforestation) on temperatures thereafter. Their model for solar irradiance was relatively flat with variances of about 0.1% from 1000 to 1900, and a greater increase after 1900. Therefore, the major forcing prior to the industrial era in their model was the change in land cover. A comparison of their estimated NH temperatures in the millennium based on all forcings (solar, volcano, CO_2, and deforestation) or only deforestation, is shown in Figure 2.4. Deforestation induces a slow and weak cooling in the NH from 1000 to 1850. The cooling accelerates after 1850 and reaches about 0.35°C by the end of the millennium. In this model, most of the difference between the MWP and the

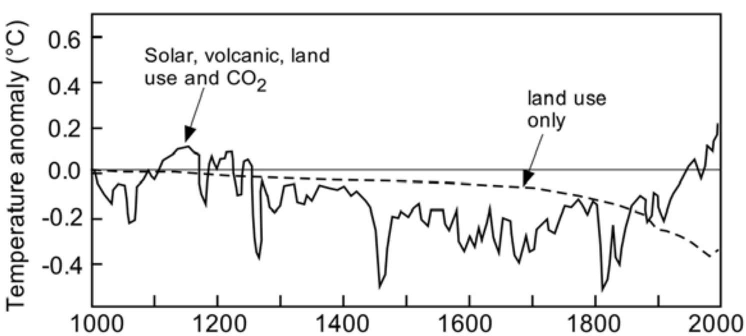

Figure 2.4. Modeled NH temperatures based on all forcings, or only deforestation. Adapted from Bauer, Claussen, and Brovkin (2003).

LIA appears to be solar-induced—and not due to deforestation. However, this would seem to contradict the assumption that variations in the solar irradiance were minor.

Goosse *et al.* (2006) also estimated millennium temperatures using models that accounted for deforestation. The results show a summer NH temperature drop of about 0.3°C from the MWP to the LIA, but it is not clear how much of this is due to the assumed pattern for solar irradiance, and how much is due to deforestation. Overall, from 1000 to 2000, temperatures dipped in the LIA and returned in 2000 to levels near those of the MWP. However, the effect of deforestation in the late 20th century was significant. As Goosse *et al.* (2006) said:

> "... there is no compelling evidence from either empirical proxy evidence or model simulation results that the European summer temperature during the last 25 years of the 20th century were the highest of the past millennium. This is largely due to the local negative radiative forcing caused by land-cover changes. The impact of this forcing at hemispheric scale has been underlined in recent studies. However, because of the large deforestation in Europe, land-use changes imply a larger negative temperature anomaly over Europe than on a global scale."

Unfortunately, our lack of knowledge of solar irradiance over the past millennium adds considerable uncertainty to any conclusion (see Section 4.7).

Brovkin *et al.* (2006) estimated global temperatures using climate models based on 1000 as the starting point. When land clearing alone was used for forcing, the resultant global temperature decreased (relative to 1000) as shown in Table 2.1 (average of several models). Results are also shown for the case where land use and CO_2 forcing were both included.

Matthews *et al.* (2004) focused on the role of historical land cover change in forcing the climate of the last 300 years. In a detailed sensitivity analysis using different data sets of land cover change and varying model configurations and

Table 2.1. Estimated temperature change in the NH due to CO_2 and land clearing. Brovkin *et al.* (2006).

Year	CO_2 (ppm)	ΔT (°C) (land use forcing only)	ΔT (°C) (CO_2 forcing only)	ΔT (°C) (CO_2 and land use forcing)
1000	280	0.00	0.00	0.00
1600	280	−0.05	0.00	−0.05
1800	280	−0.10	0.00	−0.10
1900	300	−0.15	+0.20	+0.05
1990	355	−0.20	+0.40	+0.20

parameters, they found that the primary biogeophysical effect of historical land cover change was to increase local surface albedos, resulting in a cooling of 0.1°C to 0.3°C from 1700 to the present day, depending on the model. It was estimated that changes in land cover from 1700 to 1990 reduced the NH temperature by about 0.2°C, mitigating some global warming from other factors. However, local reductions were much greater, reaching ~0.8°C over the Midwestern U.S. and Eastern Europe where large-scale farming is widespread.

2.1.2.2 Proxy analysis

Crowley and Lowery (2000) argued that anecdotal reports as well as studies of individual records from MWP suggest that the present warmth of the 20th century is not unusual and therefore cannot be taken as an indication of forced climate change from greenhouse gas emissions. But Crowley and Lowery then asked the question: "Were all of these changes synchronous, with hemispheric amplitudes comparable to or warmer than present?" However, this question seems to imply that present warming is spatially universal and synchronous—which it is not. Crowley and Lowery revisited the controversy regarding the existence of the putative MWP by carrying out another proxy analysis, incorporating additional time series not used in previous hemispheric compilations. The 15 proxies used in the study are shown in Figure 2.5. It is to the credit of Crowley and Lowery that the individual proxies are shown; this is not often the case when assemblages of multiple proxies are analyzed. They combined the various proxies to obtain Figure 2.6. The process used to combine proxies is not clear to this writer.

Based on this result, Crowley and Lowery (2000) reached the rather incredible conclusions:

> "Despite clear evidence for medieval warmth greater than present in some individual records, the new hemispheric composite supports the principal conclusion of earlier hemispheric reconstructions and, furthermore, indicates that maximum medieval warmth was restricted to two–three 20–30 year intervals, with composite values during these times being only comparable to the mid-20th century warm time interval. Failure to substantiate hemispheric warmth greater than the present consistently occurs in composites because there are significant offsets in timing of warmth in different regions; ignoring these offsets can lead to serious errors concerning inferences about the magnitude of Medieval warmth and its relevance to interpretation of late 20th century warming."
>
> "Because of uncertainties in the proxy-instrumental temperature calibration, it is still difficult to unequivocably [*sic*] assert that the late 20th century warming is significantly greater than the peak warmth of the Medieval Warm Period. But there is even less justification to assert the opposite—it is not possible to make a robust statement that the Medieval Warm Period was warmer than the last two decades."

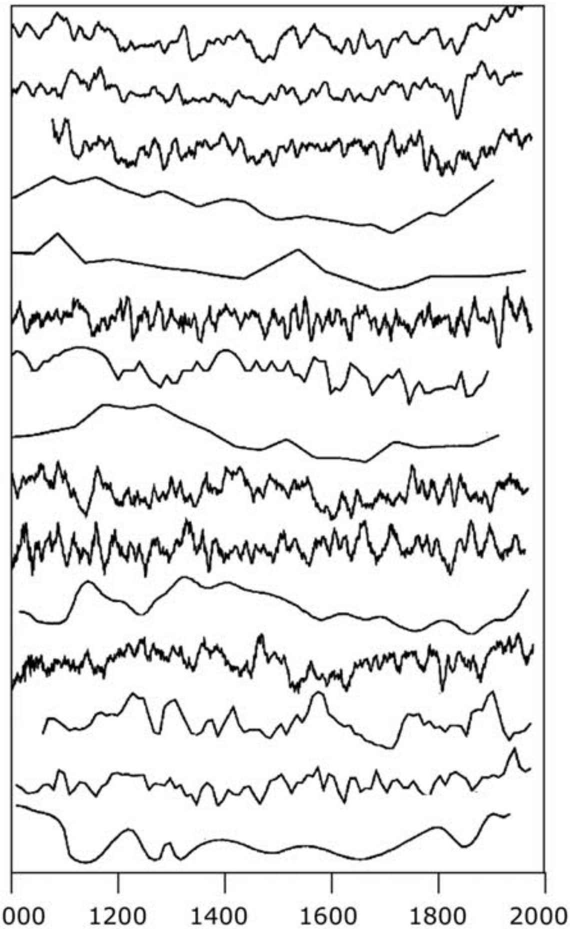

Figure 2.5. Fifteen individual proxies from various locations. Adapted from Crowley and Lowery (2000). Vertical scales are temperature anomalies.

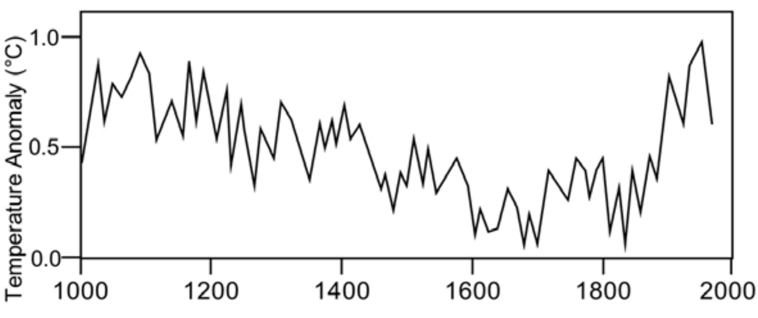

Figure 2.6. Derived NH temperature anomalies. Adapted from Crowley and Lowery (2000).

These conclusions seem far-fetched to this writer because:

1. The huge variation from proxy to proxy suggests that these divergences may not represent true differences in climate from place to place, but rather, noise and error in the proxies themselves.
2. Taking averages of highly divergent individual proxies must add uncertainty and large error bars to the resultant average.
3. The belief that the averages shown in Figure 2.6 can be trusted to the extent that differences between 20-year periods can be affirmed seems unwarranted by the lack of precision and consistency of the underlying data.
4. The insistence that the MWP must perforce involve uniformly high temperatures at all locations for the entire period is unreasonable. The issue is not whether such uniform warmth occurred, but rather, allowing for spatial and temporal variations, the preponderance of evidence favors relative warmth compared with other eras. Furthermore, even the current warming is far from uniform, spatially and temporally.

McIntyre (2007) examined the results of Crowley and Lowery (2000) in some detail. McIntyre prepared a new figure, similar to Figure 2.6, except that it showed contributions from each of the 15 individual proxies with color-coding. McIntyre pointed out:

> "Although Crowley and Lowery (2000) argued [based on Figure 2.5] that there is relatively little synchroneity [*sic*] between proxies from different regions (and thus no MWP or LIA), the color-coded graphic of their actual data could also be construed as showing a certain amount of coherence between the proxies."

McIntyre went on to say:

> "A distinctive 'hockey-stick' shape can be discerned in the 4 lowest records. Indeed, whatever 'hockey stickiness' exists in Crowley and Lowery (2000) is entirely due to these 4 series, which consist of 2 bristlecone pine series, Briffa's Polar Urals series and Thompson's Dunde series ... The bristlecone pine series are prominent in the MBH99 reconstruction and the Polar Urals series in the Jones *et al.* (1998) series. Both series have problems (as discussed elsewhere in McIntyre, 2007)."

McIntyre (2007) then modified the color-coded version of Figure 2.6 by omitting four suspect proxy series. Instead of deleting the Sargasso Sea and Central Michigan proxies, both of which are claimed by McIntyre to be well linked to temperature, the two bristlecone pine series were excluded (as not being good temperature proxies) and the first century of the Polar Urals series was excluded on quality control grounds. Without the contribution of the bristlecones and Polar Urals, the MWP peak is comparable with the 20th century peak.

Esper, Cook, and Schweingruber (2002) started out by repeating the mantra of the global warming alarmists:

> "... the MBH reconstruction indicates that the 20th century warming is abrupt and truly exceptional. It shows an almost linear temperature decrease from the year 1000 to the late 19th century, followed by a dramatic and unprecedented temperature increase to the present time. The magnitude of warmth indicated in the MBH reconstruction for the MWP, 1000–1300 is uniformly less than that for most of the 20th century."

However, Esper, Cook, and Schweingruber (2002) admitted: "the MBH reconstruction has been criticized for its lack of a clear MWP." It was claimed that critics doubt that tree-ring records can preserve long-term, multi-centennial temperature trends. However, as usual in papers written by the *paleo-climate group* (see Section 2.2.3.7), no mention is made of the devastating criticism of the MBH reconstruction made by McIntyre (2007).

Esper, Cook, and Schweingruber (2002) then went on to present a defense of tree ring reconstructions using centuries-long ring width trends in 1,205 radial tree ring series from 14 high-elevation and middle to high-latitude sites distributed over a large part of the NH extra-tropics. Their final result is shown in Figure 2.7.

Esper, Cook, and Schweingruber (2002) concluded that MBH did not miss an MWP but rather, "it had a reduced expression of the LIA." They took comfort from the fact that some of the short-term "bumps" in the RCS and MBH curves were synchronous but there are significant differences between the two reconstructions. While Esper, Cook, and Schweingruber (2002) intended to support Mann, Bradley, and Hughes (1999), the large differences between their results lead this writer to the opposite conclusion. This raises the question whether any reconstruction based on proxies is credible. Furthermore, note that the anomalies in Figure 2.7 are mostly

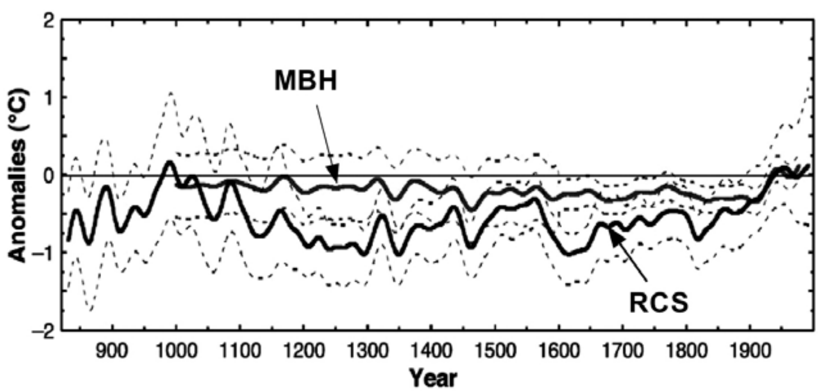

Figure 2.7. Comparison of temperature reconstructions by Esper, Cook, and Schweingruber (2002) ("RCS") with that of MBH (Mann, Bradley, and Hughes, 1999). Adapted from Esper, Cook, and Schweingruber (2002).

negative, suggesting that the mean used for data processing was not the mean for the entire time period, and as is shown in Section 2.2, this introduces significant doubt about the veracity of the results.

Nevertheless, based on their result, Esper, Cook, and Schweingruber (2002) reached the following conclusions:

1. Multi-centennial temperature variability in long tree ring records can be preserved if the appropriate tree ring data and proper methods of analysis are used.
2. The MWP appears to be more temporally variable than the warming trend of the last century and may have begun in the early 900s.
3. The warmest period covers the interval 950–1045, with the peak occurring around 990.
4. Past comparisons of the MWP with the 20th-century warming back to the year 1000 may not have included all of the MWP and, perhaps, not even its warmest interval.

McIntyre (2007) examined the data in Esper, Cook, and Schweingruber (2002) in considerable detail and wrote at length on their analysis. The issues are intricate and detailed and beyond the scope of the present write-up. McIntyre commented on the difficulty in obtaining the original data: "It's obviously been pulling teeth to get data from Esper. After only two years of trying, I've recently obtained all but one site chronology ... and gobbledy-gook about methodology." Using the 13 site chronologies that he had available, McIntyre plotted the individual proxies as shown in Figure 2.8.

McIntyre pointed out that only 2 of the 13 series have strongly elevated closing values. They both entail foxtail pines (interbreeding cousins of bristlecone pines) both from sites very close to Sheep Mountain, California. McIntyre (2007) casts considerable doubt on the validity of these two proxy sites.

McIntyre then went on to present individual plots for each proxy, and perform a simple average. The results are shown in Figure 2.9a (color section). These results show that the proxies vary widely, and cast doubt on the consistency and credibility of the various proxies. While Esper, Cook, and Schweingruber (2002) provides us

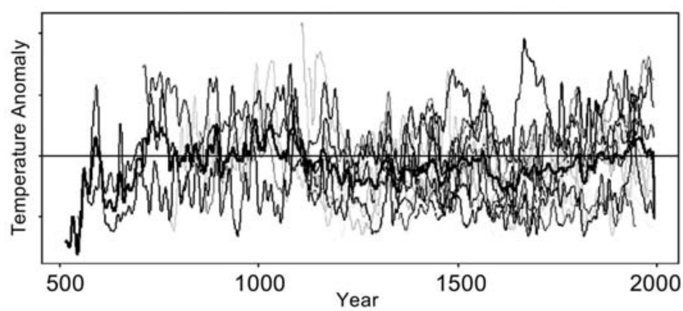

Figure 2.8. Plot of individual proxies (except Mongolia). Adapted from McIntyre (2007).

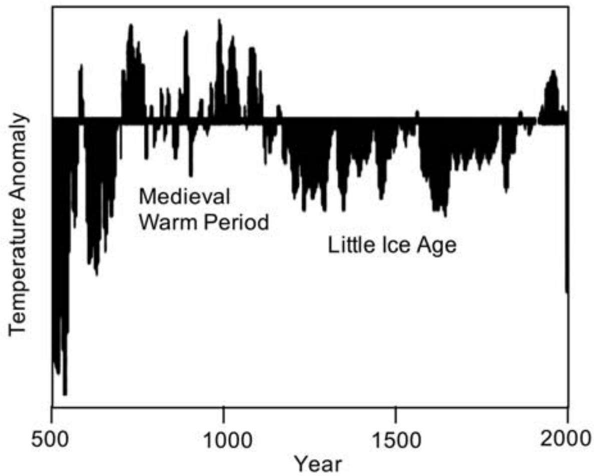

Figure 2.9b. Simple average of proxy data from Esper, Cook, and Schweingruber (2002). Adapted from McIntyre (2007).

with assurance that "multi-centennial temperature variability in long tree-ring records can be preserved if the appropriate tree-ring data and proper methods of analysis are used," Figure 2.8, and Figure 2.9a in the color section, suggest otherwise.

Finally, in Figure 2.9b, McIntyre (2007) presented a simple average of all the proxies. The result suggests an MWP and an LIA. Nevertheless, it seems evident that Esper, Cook, and Schweingruber (2002) used statistical data manipulation that unreasonably and illegitimately overemphasized the weighting of the two suspect proxies with high closing values.

Weckström *et al.* (2006) studied temperature patterns over the past eight centuries in Northern Fennoscandia inferred from sedimentary diatoms. Although temperature is not necessarily regarded as the strongest environmental variable affecting the distribution of diatoms it was claimed that temperature has been shown to be a relatively powerful variable in this study area. The results show a pronounced MWP prior to 1200 and a wide flat bottom temperature from 1650 to 1900, representing the LIA. The temperature rise after 1900 is significant, but does not reach the temperatures of the MWP. Tree ring data do not show this behavior.

2.1.3 The Little Ice Age

The term "Little Ice Age" (LIA) has been widely used to describe a period from roughly 1300 (or later) to about 1850 that evidence indicates was, on average, colder than the preceding or following eras, particularly in the NH. Matthews and Briffa (2005) discussed the LIA in some detail. It is believed that there was no uninterrupted, centuries-long cold phase following a similar, uninterrupted, centuries-long Medieval Warm Period (MWP). While the LIA was marked by prevailing cold temperatures, there were fluctuations within the LIA both spatially and temporally, and this has provided ammunition for some purists to debate whether there actually was an LIA. Matthews and Briffa (2005) indicated that the term "Little Ice Age" (LIA) has been defined in various ways according to the context and there is no single widely accepted interpretation of the term. In particular, depending on whether the emphasis is on glacierization or climate, some differences will inevitably result. Some authors suggest that the term should be used cautiously, some say it should not be used at all, and some say it should be allowed to disappear from use or should be avoided because of its limited utility. However, the existence of the LIA is a barrier of sorts to those who subscribe to the *hockey stick* version of global temperature history (see Section 2.2.3), and those who disparage the LIA seem to have an alarmist view of global warming.

One serious problem with Matthews and Briffa (2005) is that temperatures for the LIA are compared with a standard based on the average for 1961–1990. Since LIA temperatures are clearly lower than 1961–1990 temperatures, this serves to unduly emphasize the temperature rise of the 20th century. But the thing that makes the LIA unique is that temperatures during the LIA were lower than the long period that preceded it as well as the 20th century that followed it, and that is why it is colloquially called an LIA. From the perspective of global warming, the important point is how 20th century temperatures compare with the warm period prior to the LIA—not how they compare with temperatures during the LIA.

As Matthews and Briffa (2005) pointed out:

> "The expanded state of glaciers, relative to today, during the last few hundred years is an incontrovertible fact ... glaciers on all continents, from the tropics to the polar regions, were characterized by glacier expansion and subsequent retreat. However, beyond the European Alps, and to a lesser degree in Scandinavia and North America, data on the precise timing of variations in glacier size during this broad time interval are still patchy. Consequently, several controversial issues remain, including: (1) the timing of the onset (and end) of the LIA; (2) the amplitude and timing of glacier variations within the LIA; (3) the degree of synchroneity [*sic*] between glaciers from the different regions; and (4) the attribution of cause(s) in terms of large-scale climate forcing ... Greatest reliance must ... be placed on the geographically restricted evidence available from the European Alps, where the historical sources are sufficient in quality and quantity to answer not only the question of onset but also questions about when the 'Little Ice Age' glaciers reached their maximum extent and what amplitude of glacier variations occurred within the LIA period."

Grove (2001) asserted that the greatest amount of information about the LIA can be gleaned from the Swiss Alps where historical records are unusually rich and moraine dating is good. Many ice fronts extended below the tree line and were in full view of settlements for hundreds of years, or even abutted onto farmland. Written records, paintings, and drawings made by both local observers and visitors are plentiful. Identification of the calendar dates at which many *in situ* trees were killed by

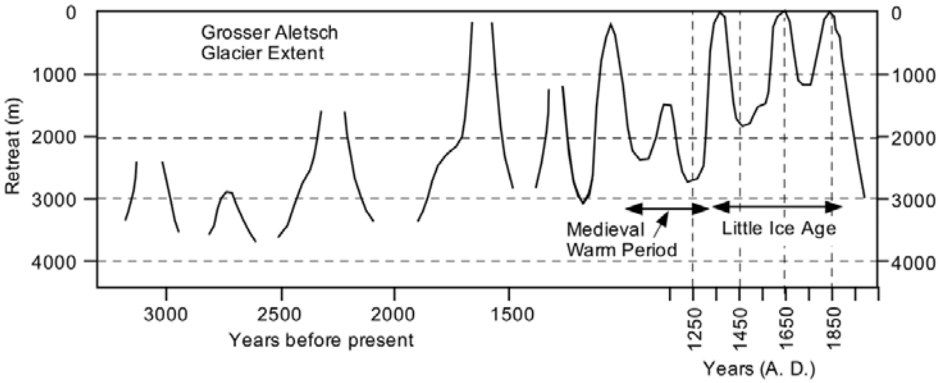

Figure 2.10. Variations in the size of the Grosser Aletsch Glacier, Swiss Alps, over the last 3,000 years based on documentary and proxy evidence. Adapted from Matthews and Briffa (2005).

advancing ice, together with their ages at death, has been made possible by multiple dendrochronological analyses.

The following paragraph is excerpted from Grove (2001):

> "The most complete record of the Late Holocene fluctuation history of any glacier in the world comes from intensive investigations of the deposits of the Grosser Aletsch [Figure 2.10]. This reconstruction was based on a great variety of evidence. Some samples were taken from the outer rings of trees overrun by the advancing ice, which could be absolutely dated by reference to dendrochronological series. This chronology is accordingly more accurate than one based only on radiocarbon samples. Retraction during the MWP was ended by rapid advance, starting after 1250 and culminating around 1350. Although the MWP here was fragmented by a marked glacial advance between 1050 and 1150, this was not comparable in scale with those of later centuries and therefore has to be considered an interruption of medieval warmth rather than part of the LIA. The Grosser Aletsch advanced about 40 m per year after 1300, to reach its greatest extension around 1370–80. This fourteenth-century advance brought the front as far forward as did those in the seventeenth and nineteenth centuries. The major extension phases were separated by withdrawals that were insufficient to return the front to positions comparable with those of the warm period. It is evidently reasonable to view the whole period between the start of expansion in the thirteenth century and the great retreat of the late nineteenth and twentieth centuries as one complex LIA with each century scale fluctuation itself made up of smaller scale oscillations, such as those recorded during monitoring of the positions of glacier fronts.

Several aspects of Figure 2.10 are critical when using it to define the LIA in the Swiss Alps (Matthews and Briffa, 2005). First, the three glacier high stands of around 1350, 1650, and 1850 were remarkably similar in extent. Second, previous glacier maxima, including those in the 3rd, 7th, 9th, and 12th centuries, were less extensive. Third, the size of the glacier during the retreat phases between the LIA high stands remained much greater than in the earlier retreat phases. The data support the notion of a change toward a more glacierized region at the end of the 12th century, and so marking the onset of the central European LIA. This change has also been interpreted as marking the end of the "Medieval Warm Period", and a similar pattern and timing is supported on a centennial timescale by the somewhat less complete records from other Alpine glaciers. It must nevertheless be concluded that, even in the Swiss Alps, differences between the glacier variations during the LIA and those before the LIA were a matter of degree rather than of kind.

It can be seen from Figure 2.10 that since the mid-19th century, mountain glaciers have been in a fairly steady retreat. This is illustrated in greater detail in Figure A.1 where it is shown that the retreat of the glaciers preceded large-scale buildup of CO_2 in the atmosphere by about a century. Anon. (N) confirms that the retreat of the glaciers preceded large-scale buildup of CO_2.

Polissar *et al.* (2006) also noted three major glacial advances from Andes lake sediments from the period 1300 to $\sim$1750.

Grove (2001) pointed out that the Gorner Glacier has advanced and retreated in harmony with the Grosser Aletsch, showing only very minor differences. Grove also mentions that other large Alpine glaciers have been shown to have been similarly affected by early LIA advances. The Grindelwald was advancing around 1338. The Rhone Glacier advanced to a maximum between 1350 and 1400, which was slightly more extensive than any occurring later. Farther east the Gurgl reached a maximum about 1300. In the Austrian Alps, the Gepatschferner, Gurglerfemer, and Simony-kees glaciers are also known to have advanced during this period.

Grove (2001) concluded that the LIA started in the second half of the 13th century and its three culminations, including the first in the 14th century, were very similar in scale. The LIA was not a unique event with a discrete beginning and a discrete end. Several phases of glacial expansion during the Holocene, comparable in scale with those of the LIA, have been traced in both the Swiss and Austrian Alps.

Grove (2001) attempted to estimate the degree to which the LIA was applicable to regions other than the Swiss Alps. An extensive survey of available data for Canada, Greenland, Iceland, and Scandinavia provided fragmentary insights. It was concluded:

> "Though no reconstructions of the glacial history of the last millennium are as complete as the most detailed from Switzerland, evidence that the LIA had begun in the thirteenth century, with the first culmination in the fourteenth century, is widespread."

Joerin, Stocker, and Schluchter (2006) studied sub-fossil remains of wood and peat from six Swiss glaciers found in pro-glacial fluvial sediments. They discovered 12 phases of glacier recessions during the Holocene. Trees and mires grew where glaciers exist at present and, therefore, glaciers were smaller at that time than the present. The 12 major recession periods occurred at 9850–9600, 9300–8650, 8550–8050,

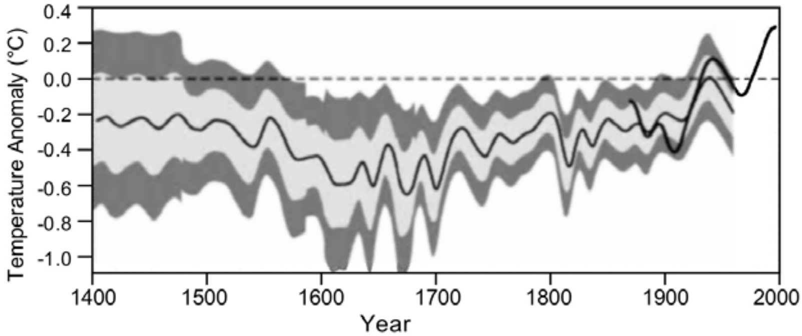

Figure 2.11. Tree-ring density reconstruction of Northern Hemisphere (land areas north of 20°N) summer temperatures (April to September) since AD 1400 (thin continuous line). Units are °C anomalies with reference to the 1961–1990 mean (dashed line). Shaded areas show 68% and 95% confidence intervals. Measured temperatures (thick line) are also shown. Adapted from Matthews and Briffa (2005).

7700–7550, 7450–6550, 6150–5950, 5700–5500, 5200–4400, 4300–3400, 2800–2700, 2150–1850, and 1400–1200 YBP. They emphasized that "this natural variability of glacier extent, which occurs on a centennial timescale, is superimposed on a much longer term ... trend towards increased glacier extent culminating in the 'Little Ice Age'."

A reconstruction covering the last 600 years based on selected tree ring density series mainly from high-latitude land areas is shown in Figure 2.11. However, it is not clear how the tree ring data were scaled. It appears to this writer that the data from tree rings might fit the measured temperatures if the entire tree ring curve is lifted about 0.1°C.

According to Matthews and Briffa (2005), Figure 2.11 demonstrates a distinct LIA climate from about 1570 to 1900 when Northern Hemisphere summer temperatures (April to September) fell significantly below the 1961–1990 mean. Matthews and Briffa said:

> "It would appear that there is a tenable statistical basis for belief in at least the main phase of the 'Little Ice Age' as at least a hemispherical cold period ... and that, in terms of summer temperature, most of the seventeenth century was of the order of 0.5°C below the 1961–1990 mean. The question of whether the event was global remains more open."

In a later passage, Matthews and Briffa said:

> "Indeed, we show here, for the first time in map form, that the majority of the northern hemisphere experienced a relatively low mean summer temperature for more than three centuries (1570 to 1900), and that the LIA was not merely or even mainly a European phenomenon."

But perhaps more importantly, Figure 2.11 is somewhat misleading because temperatures for the LIA are compared with a standard as the average for 1961–1990. As we previously pointed out, since LIA temperatures are lower than 1961–1990 temperatures, this serves to unduly emphasize the temperature rise of the 20th century. But the thing that makes the LIA unique is that temperatures during the LIA were lower than the long period that preceded it, and that is why it is colloquially called an LIA. From the perspective of global warming, the important point is how 20th century temperatures compare with the period prior to the LIA—not how they compare with temperatures during the LIA. As long as we use 1880 as a base year for comparison, 20th century temperatures will show an increase. But is this a departure from the *normalcy* of the LIA, or was the LIA an aberration, with the 20th century rise in temperature being a return to *normalcy*?

2.1.4 Sea surface temperatures in the Sargasso Sea

Keigwin (1996) estimated sea surface temperatures in the Sargasso Sea over the past few thousand years from isotope ratios of marine organism remains in sediments at the bottom of the sea. His results, as presented by Robinson, Robinson, and Soon (2007) are shown in Figure 2.12.

2.1.5 Other proxy studies

2.1.5.1 China

Esper, Schweingruber, and Winiger (2002) reported results on more than 200,000 ring-width measurements from 384 trees obtained from 20 individual sites that were analyzed to reconstruct regional climatic variation patterns in western Central Asia

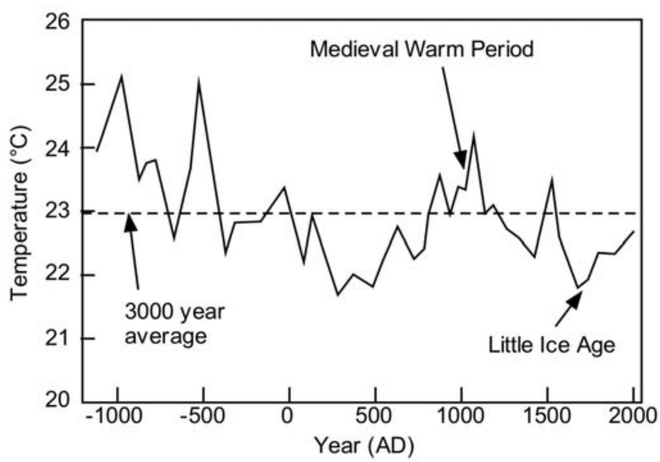

Figure 2.12. Sea surface temperatures in the Sargasso Sea (Keigwin, 1996) as presented by Robinson, Robinson, and Soon (2007).

since 618. A prolonged centennial trend toward better growing conditions was observed over the last ~300 years (1700–2000) in the western Central Asia tree ring records. This trend is of a lesser magnitude compared with conditions before ~1100 and indicates the existence of an MWP. These early and recent benign periods were separated by a prolonged period of poor growth, which presumably reflects the LIA in western Central Asia. These results support the hypothesis of the existence of the MWP and the LIA. The warmest decades since 618 appear to be between 800 and 1000, whereas the coldest periods were recorded in the first half of the 17th century.

Zhang *et al.* (2003) reported on a 2,326-year tree ring chronology that is currently the longest annually resolved climate proxy record on the Qinghai–Tibetan Plateau and in China. Their results indicate that the climate on the plateau has undergone oscillations and, sometimes, very rapid swings during the last two millennia.

Liu *et al.* (2005) carried out a study of historical temperatures in China since 1550. China was divided into ten districts that are relatively homogeneous. With proxy data from historical documents, tree rings, and ice cores, reconstructions of the temperature series were made for eight of these regions. The reconstructions of 10-year mean temperature anomalies were based on proxies via statistical techniques that rely on establishing empirical relationships between modern observations and environments during the calibration period (1880–1979). However, Liu *et al.* (2005) reports: "Unfortunately, this evidence is very uncertain." The basic data for one of the Chinese regions (Region 3) is shown in Figure 2.13. Note how the "simulated" data accentuate the rise during the 20th century. However, it is difficult to understand how the "simulated data" were derived.

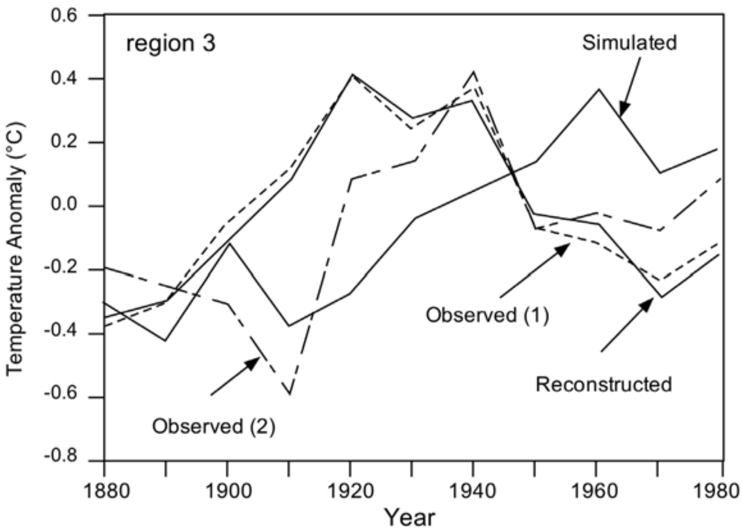

Figure 2.13. Basic data for the calibration period for Region 3 (south China). Adapted from Liu *et al.* (2005).

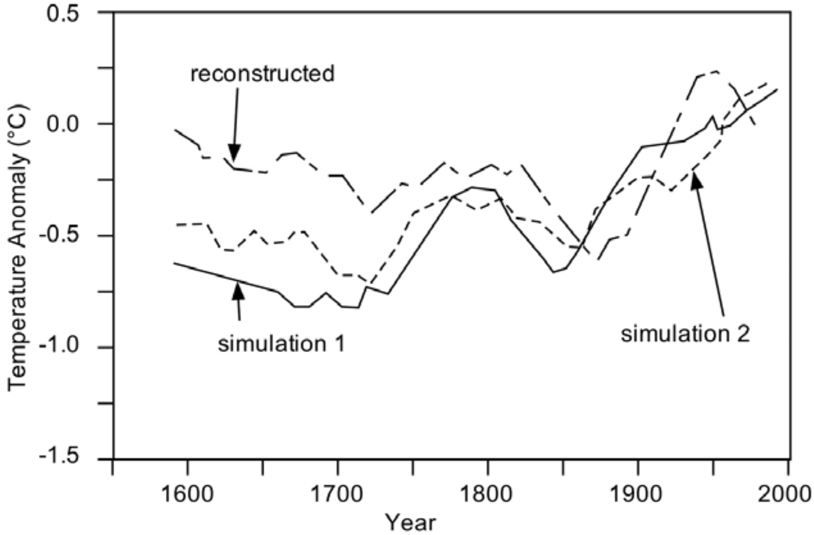

Figure 2.14. Longer term data for Region 3. Adapted from Liu *et al.* (2005).

Liu *et al.* (2005) provided "reconstructed" and "simulated" data from 1590 to 1980 for each of the eight regions. It is not clear to this writer how these were derived. Interestingly, when these data are compared with Figure 2.14 for Region 3, there doesn't seem to be much correlation.

Liu *et al.* then went through an *empirical orthogonal analysis* (EOF) that is a form of principal component analysis (PCA)[1] (see Section 2.2), and ended up with Figure 2.14. The connection of this figure to Figure 2.13 appears to be "lost in translation".

The final result for the eight regions of China is given in Figure 2.15, showing a moderate *hockey stick* form. However, there is some evidence of a significant LIA, particularly between 1650 and 1750. Furthermore, the absolute values of the temperature anomalies seem very high in this figure. Without access to the original temperature data (1880–1980) from which the fundamental proxy relations were (presumably) derived, it is difficult to evaluate the veracity of this result. In particular, a concern is that in statistical processing, they may have used the mean for the 1880–1980 period as the basis for calculating anomalies for the entire period 1590–1980, which could lead to exaggeration of the *hockey stick* syndrome. This writer is unable to penetrate the methodology enough to resolve this issue.

Yang *et al.* (2002) established three alternate China-wide temperature composites covering the last 2,000 years by combining multiple paleo-climate proxy records obtained from ice cores, tree rings, lake sediments, and historical documents.

[1] But the analysis was unintelligible to this author.

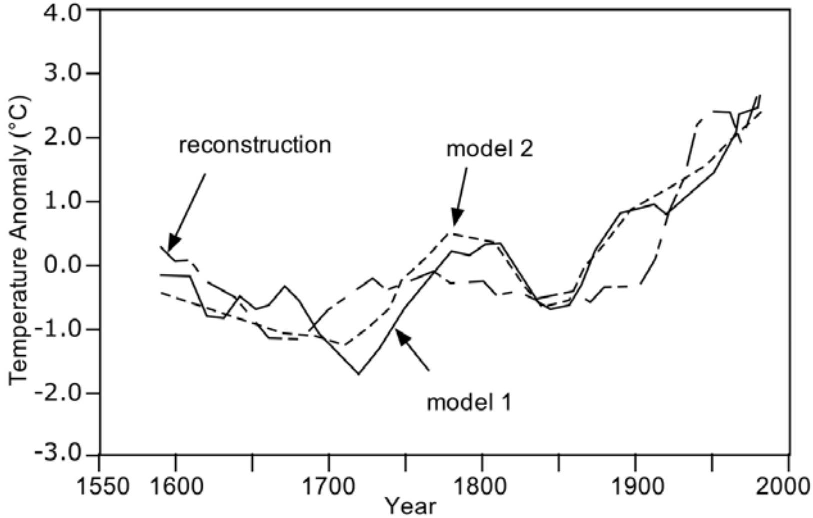

Figure 2.15. Estimated temperature profiles for all China. Adapted from Liu *et al.* (2005).

The basic proxy records are shown in Figure 2.16 for nine regions in and around China. As is usual with proxy data, there is considerable variation from region to region. Some of this could be real, while some could be the result of "noise" in the signal. There is a tendency for the time period around 1000 to be warm, but this is not uniform across all proxies. Similarly, there is a dip in temperature after 1600 in some of the proxies.

Yang *et al.* (2002) tried several methods to reconstruct regional paleo-temperature series from the nine data sets. One approach was to simply average all nine data sets with equal weighting. This was referred to as "Complete" China. A second approach ("Weighted" China) weighted the seven Chinese data sets in proportion to the implied areas covered by the data. A third approach ("H-res" China) averaged only the higher resolution Chinese data sets. These are shown in Figure 2.17.

There is good correlation between the three reconstructions. A cool period occurred between about 300 and 800. A medieval warm period occurred between 800 and 1100. A little ice age was pronounced from 1400 to 1700. A relatively flat neutral environment occurred from 1700 to 1900. The temperature rose again after 1900. Although the 20th century temperature appeared to reach (or exceed) medieval levels around 2000, the number of temperature series dropped off sharply in the 20th century.

Yang *et al.* (2002) compared their results for China with several global temperature reconstructions, as shown in Figure 2.18. Yang *et al.* claimed good correlation with the global reconstructions, but the Chinese data show a much more pronounced LIA, a slightly more suggestive MWP, and a lesser *hockey stick* rise after 1900. This is exactly what one would expect, considering that the global studies used means for the

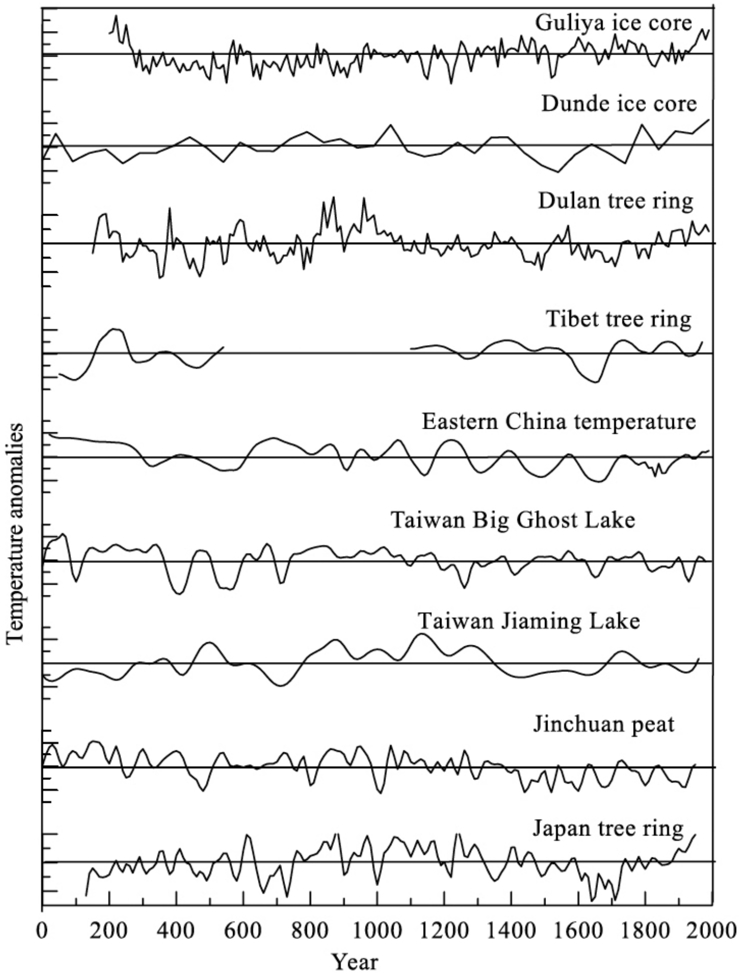

Figure 2.16. 2000-year temperature histories for Chinese and vicinity areas. Big Ghost Lake, Jiaming Lake, and Jinchuan had 20-year resolution and Dunde had 50-year resolution. Resolution of other series was probably decadal. Adapted from Yang *et al.* (2002).

20th century (rather than for the whole data set) which skews the result and generates a *hockey stick* artifice (see Section 2.2.3).

2.1.5.2 Borehole measurements

The basis for borehole measurements for the Holocene is discussed in Section 1.3.4. Borehole measurements have also been made for the past few hundred years. Beltrami, Gosselin, and Mareschal (2003) reconstructed ground surface temperature histories from temperature vs. depth profiles measured at 246 sites distributed across Canada. They found that the ground has warmed about 0.7°C in the last 100 years.

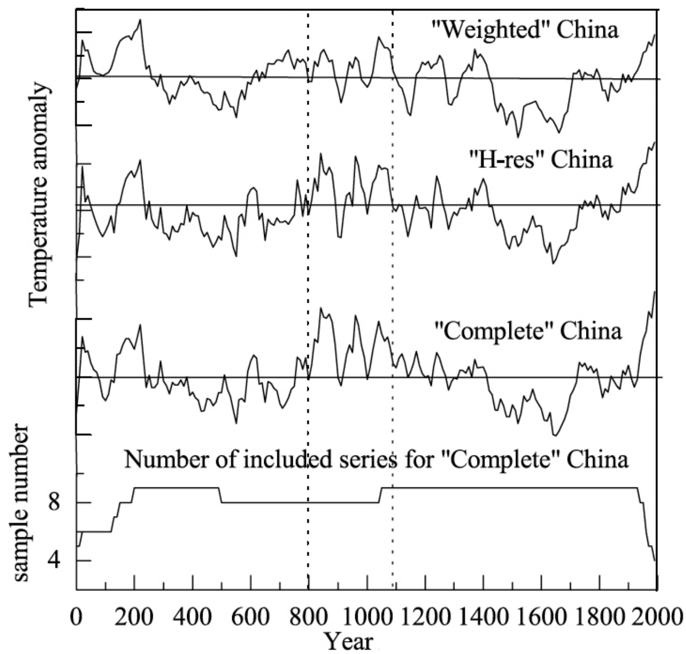

Figure 2.17. Comparison of several temperature reconstructions for China. Adapted from Yang *et al.* (2002).

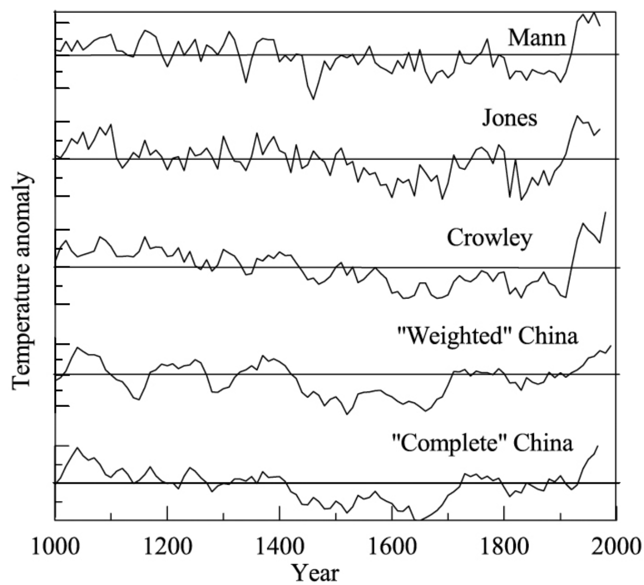

Figure 2.18. Comparison of several temperature reconstructions for China and the Northern Hemisphere. Adapted from Yang *et al.* (2002). Mann = Mann, Bradley, and Hughes (1999); Jones = Jones *et al.* (1998); Crowley = Crowley and Lowery (2000).

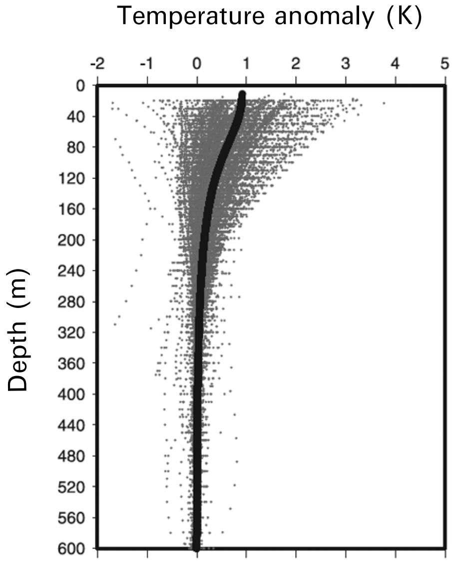

Figure 2.20. Data from 826 boreholes. The thick black line is the average used to infer historical surface temperatures. However, the large amount of variability is worrisome. Adapted from Beltrami, Gosselin, and Mareschal (2003).

This is expected from Figures 2.19a, b (color section) which show that Canadian temperatures have in the main been rising in the 20th century.

Beltrami, Gosselin, and Mareschal (2003) utilized 826 temperature–depth profiles distributed worldwide, in order to reconstruct ground surface temperature histories and surface heat flux histories at these sites. However, the distribution was uneven and roughly half of the boreholes were in Canada. The actual borehole data are shown in Figure 2.20. There was a large amount of variability in the data. The result obtained by Beltrami, Gosselin, and Mareschal is that the ground temperature has increased monotonically and roughly linearly over the past 500 years amounting to an increase of about 0.9°C from 1500 to 2000. They estimated the variation in heat flux into the continental lithosphere over the past 500 years. They found a monotonic increase over that period but the functionality was roughly exponential, increasing continuously from 1500 to 2000. This result seems incredible to this writer, considering the evidence from other proxies for temperature fluctuations including the LIA.

2.1.5.3 Arctic environment change of the last four centuries

Overpeck *et al.* (1997) presented a compilation of paleo-climate records from lake sediments, trees, glaciers, and marine sediments that provided a view of circum-Arctic environmental variability over the last 400 years. However, the instrumental record of Arctic climate change is brief and geographically sparse. In their article, the authors used the paleo-environmental record to assess the climate events of this century from the perspective of the last four centuries. They compiled a variety of complementary paleo-environmental indicators of climate from around the entire Arctic. This perspective permits the visualization of natural sub-decadal to century-scale climate variability in the circum-Arctic region. The results are shown in Figures 2.19a, b (color section). It can be seen that, in general, the period from 1600 to 1925 was cold, although some intermittent warm periods were interspersed in some of these time series (2, 5, 9, 13, 14, 20, 26). Nevertheless, 22 out of 29 series were predominantly cold in this era, and the other 7 were variable. Therefore, there is clear evidence of a little ice age.

The data after 1925 vary with the time series as follows:

(i) Strong warming: series 4, 7, 14, 16, 17, 18, 22, 24, 25, 26, 28, 29 (i.e., 12 series).
(ii) Warming followed by moderate cooling (or variable): series 1, 2, 3, 5, 8, 9, 10, 12, 13, 19, 20, 21, 23 (i.e., 13 series).
(iii) Warming followed by strong cooling: series 6, 11, 15, 27 (i.e., 4 series).

In 17 out of 29 series, the predominant trend in the late 20th century was cooling. In 4 of the 17, the cooling was strong. We may therefore conclude that in Arctic areas

(i) the era 1600–1925 was relatively cold;
(ii) compared with 1600–1925, the era that followed showed considerable warming;
(iii) warming after 1925 was not consistent, and the majority of Arctic sites late in the 20th century were either in a cooling trend or were variable.

Overpeck *et al.* (1997) seem to have been biased toward emphasizing global warming. They report:

> "From 1840 to the mid-20th century, the Arctic warmed to the highest temperatures in four centuries. This warming ended the Little Ice Age in the Arctic and has caused retreats of glaciers, melting of permafrost and sea ice, and alteration of terrestrial and lake ecosystems."

However, they admitted that peak temperatures occurred around 1945, but did not discuss the cooling that occurred after that date. The data do not seem to support their conclusions.[2]

[2] Recently, I was watching a boxing match on television. The announcer was enamored with the favorite and kept emphasizing how well he was doing, whereas my view indicated quite the opposite. Then there is the story of the boxer who returned to his corner between rounds and his trainer told him that his opponent never laid a glove on him. He complained that the referee must be hitting him because someone was administering a beating to him. Sometimes preconceived viewpoints affect what we perceive.

Overpeck *et al.* (1997) said: "Half of the post-1840 warming (about 0.75°C) took place from 1840 to 1920 ..." Overpeck *et al.* struggled to find a rationale for this warming. The cooling trend from 1950 to 1970 was also a concern. They suggested: "the observed slowdown in warming from 1950 to 1970 may have been influenced by the increase in Arctic tropospheric aerosols that occurred after 1950." Aerosols have been proposed after the fact to deal with recent cooling (see Section 3.2.4).

2.1.5.4 Iceland perspective

In the discussion of historical climate in Iceland, Ogilvie and Jonsson (2001) defined three separate viewpoints regarding Icelandic climatic change. One may be termed the *uniformitarian* view. As this name implies, it suggests a fairly constant climate, with only minor variations. A second may be called the "deterioration" view. This involves a transition from a relatively favorable early climate to an unfavorable later climate (i.e., an LIA). A third may be termed the "relative" view. This emphasizes that climate is constantly changing and suggests that even if there were relatively long cold or warm time periods, they nevertheless encompass large annual to decadal variability. Ogilvie and Jonsson provide an extensive review of journals written by Icelanders or Europeans from 1790 through the 1920s. One 1914 book was definitely *uniformitarian* and claimed that "the climate of Iceland did not change markedly from Iceland's settlement to ~1914." If that were true, it would cast significant doubt on the applicability of the LIA to Iceland.

Another 1914 book by a different author reached the opposite conclusion. For example, it was claimed that the first inhabitants of Iceland were able to grow grain but this later became impossible as the climate worsened. Several others (from Denmark and Norway) at a later date reached the uniformitarian conclusion. The sources of information become increasingly diffuse as one goes back in time. Ogilvie and Jonsson (2001) provide historical data on various aspects of Iceland. The sea ice index was plotted from 1600 to 1850, and from 1850 to 1990. Over the period 1600–1850, the sea ice index was a minimum during the 17th century and was highest from 1750 to 1850. Over the period 1850–1990, the sea ice index was highest before 1920, dropped to near zero from 1920 to 1967, and increased after 1967. The decrease starting around 1920 can hardly be due to greenhouse gases. The increases after 1967 are contrary to the expectation from greenhouse alarmists.

As in most studies of climate, Ogilvie and Jonsson (2001) provide many crosscurrents and conflicting indications that are highly stimulating but not fully revealing.

Figure 2.21 shows the variation of Iceland temperatures since 1830. Temperatures after 1855 were measured. Prior to that date proxies were used. There was a rise around 1920, but after 1950, temperatures fell. The rise around 1920 can hardly be due to greenhouse gases.

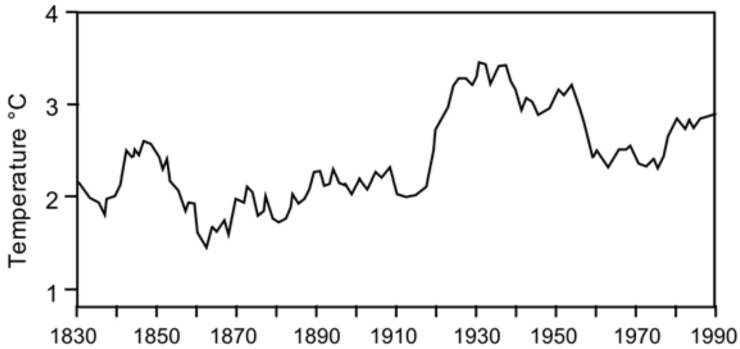

Figure 2.21. 10-year running average Iceland temperatures. Adapted from Ogilvie and Jonsson (2001).

2.2 AVERAGE GLOBAL AND HEMISPHERIC TEMPERATURES IN THE PAST MILLENNIUM

2.2.1 The "MBH" model

Realizing that there exist many local, regional, and hemispheric proxies, with variable spatial and temporal extent, Mann, Bradley, and Hughes (1998, 1999) attempted a comprehensive analysis of the history of global average temperatures using a multi-proxy network consisting of "widely distributed high-quality annual-resolution proxy climate indicators, individually collected and formerly analyzed by many paleo-climate researchers." The network included annual resolution dendro-climatic, ice core, ice melt, and long historical records previously assembled, combined with other coral, ice core, dendro-climatic, and long instrumental records. This was intended to integrate as many proxy sources as possible into a single comprehensive view of how a single global average temperature (or NH average temperature) varied over the past millennium. A number of subsequent related studies have also been published by the same group, as well as other allied groups. The final result is a reconstruction of a single NH or global average temperature over the past one or two millennia with a so-called *hockey stick* structure: a rather flat profile for most of the millennium, prior to the 20th century, with a significant rise in the 20th century.

As stated previously, Mann, Bradley, and Hughes (1998) attempted a comprehensive analysis of the history of global temperatures using a multi-proxy network consisting of "widely distributed high-quality annual-resolution proxy climate indicators, individually collected and formerly analyzed by many paleo-climate researchers." This work has been referred to as the "MBH" model after the names of the three authors of the principal paper. Subsequently, Mann, Bradley, and Hughes (1999) extended the period of analysis from 1400 back to 1000, and Mann and Jones (2003) added an additional millennium back to 200.

Mann, Bradley, and Hughes (1998) wrote a compact paper, full of jargon, and difficult to follow. However, this is a characteristic shared by many papers that deal with large data sets for historic Earth temperatures. Wegman, Scott, and Said (2006) said:

> "The papers of Mann *et al.* in themselves are written in a confusing manner, making it difficult for the reader to discern the actual methodology and what uncertainty is actually associated with these reconstructions. Vague terms such as 'moderate certainty' give no guidance to the reader as to how such conclusions should be weighed. While the works do have supplementary websites, they rely heavily on the reader's ability to piece together the work and methodology from raw data. This is especially unsettling when the findings of these works are said to have global impact, yet only a small population could truly understand them."

Wegman, Scott, and Said (2006) also said: "The description of the work in Mann, Bradley, and Hughes (1998) is both somewhat obscure and as others have noted, incomplete."

The reference period for calibration of proxies with actual temperature data was 1902 to 1980. The various proxies tended to become more numerous in recent times and less numerous in the more distant past. The number of proxies vs. earliest date is shown in Table 2.2.

Each of the proxy data sets had variable geographical distribution. The task was to combine these into a uniform function that best expresses the putative single global average temperature over a long time span. The process used for data reduction is too complex to discuss in any detail here. As is usual in such studies, these references worked with variances from the mean, rather than actual temperatures. However, a

Table 2.2. Number of proxies vs. earliest date according to Mann, Bradley, and Hughes (1998, 1999).

Earliest date	Number of proxies
1000	12
1400	22
1450	24
1600	57
1700	74
1763	93
1820	112
1854	219
1902	1,082

crucial factor was that they chose the mean during the calibration period (1902–1980) rather than the mean for the entire data set. As we shall see, this had major repercussions regarding the form and credibility of the result. Another key aspect was the use of *principal components analysis* (PCA) to identify the primary trends in data containing scatter and noise.

McKitrick (2005) summarized PCA as follows:

> "Principal components analysis involves replacing a group of data series with a weighted average of those series, where the weights are chosen so that the new vector (called the principal component or PC) explains as much of the variance of the original series as possible. This leaves a matrix of unexplained residuals, but this matrix can be reduced to a PC as well. In that case the original PC is called the first PC (PC1), and the PC of the residuals is called the second PC, or PC2. And there will be residuals from it too, yielding PC3, PC4, etc. The higher the number of the PC, the less important is the pattern it explains in the original data. PC1 is the dominant pattern, PC2 is the secondary pattern, etc. In many cases a large number of data series can be summarized with relatively few PCs."

It was noted that PCA operates in terms of deviations from the mean—not the primary data. However, it is essential that the mean used in the PCA must be the mean for the entire data set. Unfortunately, Mann, Bradley, and Hughes (1998, 1999) did not do this.

The final result from Mann, Bradley, and Hughes (1998) is shown in Figure 2.22. Note that the mean is the mean only for the period 1902–1980, and therefore most of the data (1400–1920) lie below the mean. We will have more to say about this in the following sections. This figure is the first rendition of a series of so-called *hockey stick* figures with a relatively flat profile prior to 1900 and a sudden rise after 1900.

The final result from Mann, Bradley, and Hughes (1999) is shown in Figure 2.23. This extended their (1998) model back to 1000.

Mann and Jones (2003) extended the work of Mann, Bradley, and Hughes (1998, 1999) back to 200. Their result is shown in Figure 2.24. These figures suggest that (1) there was no medieval warm period, (2) there was hardly any little ice age, (3) Earth temperatures have been remarkably stable for 2,000 years, and (4) the only significant change in Earth temperature took place in the 20th century with a sudden and decisive sharp rise after 1900.

Interestingly, Mann and Jones (2003) claims that Soon and Baliunas (2003a, b) was a "flawed study", which is only natural since Soon and Baliunas (2003a, b) reached a similar opinion of Mann and Jones (2003). There was a major difference in philosophies between the two studies. Mann and Jones (2003) insisted on combining all regional anomalies, which because of their variable occurrences in time, tended to cancel out and lead to a flat result, except for the 20th century. By contrast, Soon and Baliunas (2003a, b) sought to identify a preponderance of local and regional occurrences, which, though not necessarily simultaneous, added up in total to preponderant but vacillating cold or warm periods. Ultimate averaging would not detect such trends.

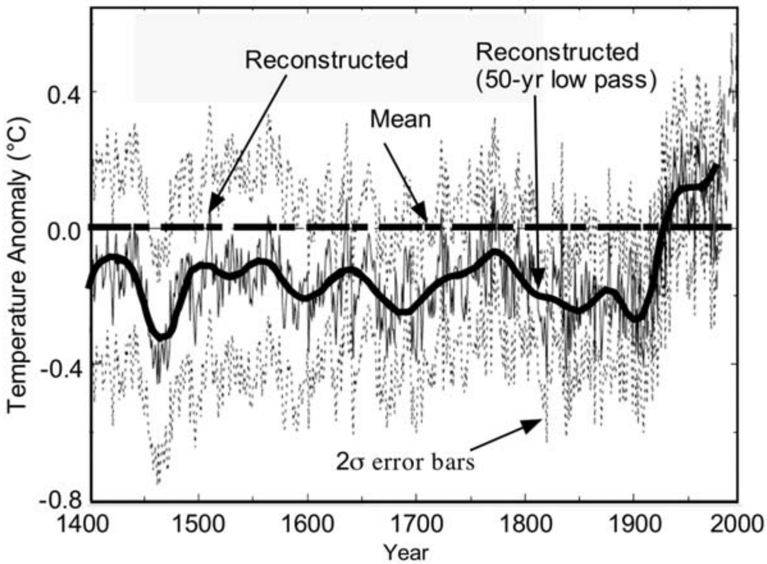

Figure 2.22. The original *hockey stick*. Adapted from Mann, Bradley, and Hughes (1998). Note that the mean is for 1902–1980. Also note that the 2σ error bars are so wide that they could hide almost any imaginable temperature curve.

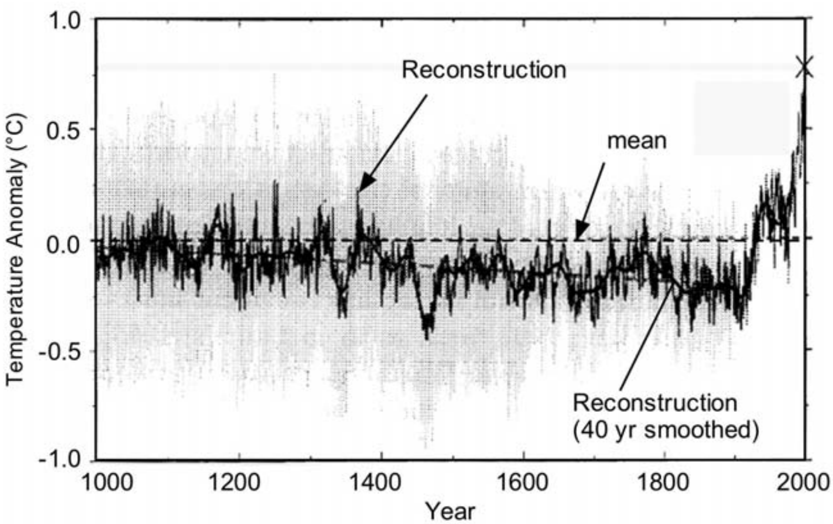

Figure 2.23. Final result for temperature anomaly vs. year since AD 1000. Adapted from Mann, Bradley, and Hughes (1999). The X at the far right is their estimate for 1998. Note that the mean is for 1902–1980. The gray bars represent 2σ error bars.

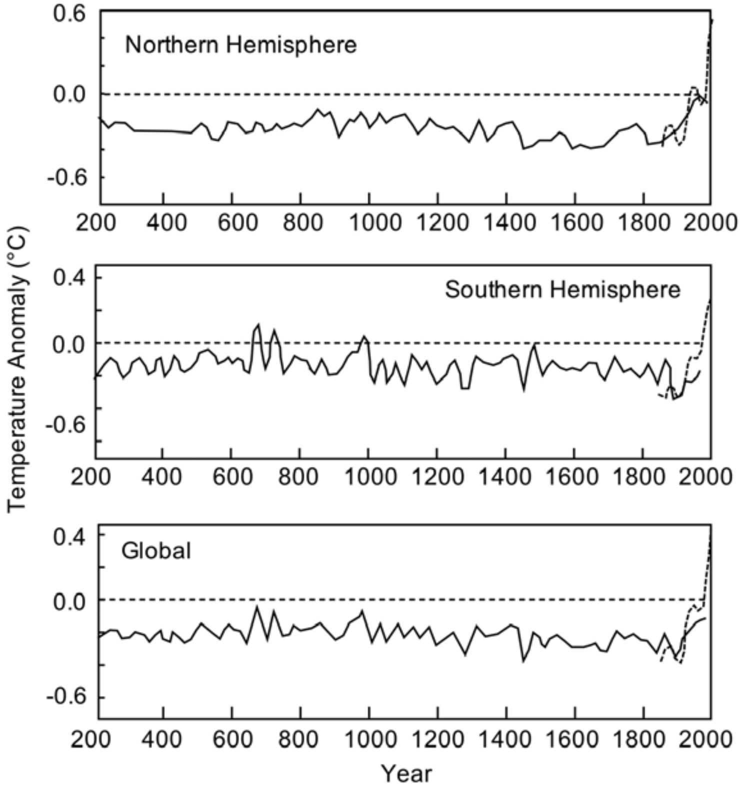

Figure 2.24. Temperature reconstructions based on area and local correlation weighting. Measured data shown as dashed line. Note that the anomalies prior to recent times are all negative, showing that the data were standardized against the mean for the calibration period. Adapted from Mann and Jones (2003).

2.2.2 Other reconstructions of historical temperature

A number of papers have published reconstructions of historical temperatures. Only a few will be mentioned here.

Jones, Osborn, and Briffa (2001), for example, support the MBH findings:

> "Relatively widespread instrumental [temperature] data exist for the land and marine regions of the Northern Hemisphere (NH) back to the mid-1850s. These data show that since 1861, annual average temperatures have warmed by 0.6°C, but with a marked seasonal contrast: winters have warmed by nearly 0.8°C and summers by only 0.4°C. The warming has occurred in two pronounced phases, from about 1920 to 1945 and from 1975 to the present."

They went on to say:

> "Several attempts have been made recently to extend this record of temperature variations across the NH to cover the last 1000 years. All are based on the rationale that large-scale temperature variability can be represented sufficiently well by integrating data from a limited number of geographically scattered indicators or 'proxies' of variability of past climate."

The most numerous of the proxy data are derived from trees (ring density, ring width, and wood isotopes), followed by ice cores (isotope ratios, accumulation rates, and melt layers) and corals (isotopes, cation ratios, and growth thicknesses). The result is shown in Figure 2.25 (color section), which parallels the results of Mann, Bradley, and Hughes (1998, 1999) and Mann and Jones (2003) shown previously. This figure shows (1) the mean (dotted line); (2) annual mean land and marine temperature from instrumental observations (black, 1856 to 1999); (3) estimated mean by Mann, Bradley, and Hughes (1999) (red, 1000 to 1980); (4) estimated mean by Crowley and Lowery (orange, 1000 to 1987); (5) April to September mean temperature from land north of 20°N (green, 1402 to 1960); and (6) estimated mean by re-calibrating (blue, 1000 to 1991) the Jones, Osborn, and Briffa NH summer temperature estimate. All series were smoothed with a 30-year Gaussian-weighted filter. Once again, the *hockey stick* shows up very clearly. Note that the mean was chosen for the short calibration period, and not for the extent of the full data set, so that most of the anomalies are <0.

It is particularly noteworthy that Jones, Osborn, and Briffa (2001) apparently decided not to show some of the data (particularly the green curve) late in the 20th century because it ticks sharply downward and conflicts with the desire to emphasize recent global warming (see Section 2.2.3.1 for more details).

Esper *et al.* (2005a, b) discussed differences between various reconstructions based primarily on tree rings and presented a comparison as shown in Figure 2.26 (color section). There is considerable variation in amplitude from study to study.

Moberg *et al.* (2005) indicated that although differences in the amplitude of centennial temperature variability have been discussed in the literature, the picture with relatively small variability (i.e., the *hockey stick* results) "is arguably best known by a wider audience. One reason for this is the prominent role that the multi-proxy reconstruction by MBH had in the latest IPCC report and in public media." However, they went on to point out that recent findings suggest that considerable underestimation of centennial Northern Hemisphere temperature variability may result when regression-based methods (like those used by MBH) are applied to noisy proxy data with insufficient spatial representation. Moberg *et al.* (2005) also referred to well-documented difficulties in reliably reproducing multi-centennial temperature variability based on tree ring proxies.

Moberg *et al.* (2005) further studied the use of low-resolution proxy data in order to preserve multi-centennial variability in climate reconstructions. They used lake and ocean sediment cores, which tend to have a less favorable time resolution, but provide climate information at multi-centennial timescales that may not be captured by tree ring data. They used seven tree ring series and eleven low-resolution proxy series in order to derive a 2,000-year long Northern Hemisphere temperature reconstruction in which they claimed that they avoided using each proxy type at timescales where they were least reliable. However, they indicated that the "number of available 2,000-yr-long local-to-regional scale temperature proxy series is very limited." Their result is shown in Figure 2.27 (color section). Note that the zero on the vertical scale is the mean of measured values—not the mean for the entire time period. Most of the proxy data lie below the mean. The results show a weak MWP but a pronounced LIA. Their reconstruction shows a larger multi-centennial variability than most previous multi-proxy reconstructions. Furthermore, their reconstruction depicted high temperatures in the period 1000–1100 that are comparable with the 20th century temperatures, and minimum temperatures occurred around 1600 that are about 0.7°C below the average of 1961–1990. This large natural variability in the past (prior to large-scale human impact) suggests an important role of natural multi-centennial variability that is likely to continue.

von Storch *et al.* (2004) used a coupled atmosphere–ocean model simulation of the past 1,000 years to test empirical reconstructions of historical temperatures, specifically those of MBH. They found that centennial variability of the NH temperature is underestimated by the MBH regression-based methods. Their results also suggest that actual variability may have been at least twice as large as the variability obtained in the MBH studies. von Storch *et al.* (2004) surmised that this conclusion probably applies to most regression-based methods of analysis, but other methods that estimate past temperatures with physical (instead of statistical) methods or regression methods that address retention of low-frequency variability in proxies may be free from this critique.

Juckes *et al.* (2006) provided an extensive survey of a number of recent temperature reconstructions based on proxies. However, a glance at the authors of this paper suggests that they may be closely allied to the *paleo-climate group* (see Section 2.2.3.7) and therefore it is not surprising that they found relatively small temperature fluctuations over the past thousand years, with a steep rise in the 20th century and they claimed:

> "Two recent years (1998 and 2005) have exceeded the estimated pre-industrial maximum by more than 4 standard errors."

They found: "clear evidence of a cool period from 1500 to 1900, but no strong MWP (though the second warmest century in the Northern Hemisphere reconstruction was the 11th)." While all of the reconstructions of the 11th century temperature considered by Juckes *et al.* (2006) estimate the 11th century to have been warmer than most of the past millennium, the question raised by Juckes *et al.* (2006) "of more practical importance" is not "whether the 11th century was warmer than the 12th to 19th centuries, which is generally accepted, but whether it was a period of comparable warmth to the late 20th century." Mann, Bradley, and Hughes (1999) concluded, with 95% confidence, that this was not so.

Juckes *et al.* (2006) presented a number of graphs of reconstructions of historical temperatures. However, all of these were based on MBH-type models in which the mean was chosen only for the calibration period (20th century) and as a result, almost all of the temperature data for the past millennium (except for the 20th century) lie below the mean. Clearly, these results are faulty, as shown in Section 2.2.3. Juckes *et al.* (2006) attempted to deal with the criticisms of Section 2.2.5, referring to McIntyre and McKitrick (2003) as claiming: "... the deficiencies in the description of the data used and possible irregularities in the data itself. These issues have been largely resolved in [Mann, Bradley, and Hughes (2004)]." However, aside from deficiencies in the data, which Mann, Bradley, and Hughes (2004) did not resolve except to obfuscate the matter, the critical issue of using the wrong mean, resulting in mining for *hockey stick* results (see Section 2.2.5) was not even mentioned. Juckes *et al.* (2006) is just another in a series of papers by the *paleo-climate group* using flawed statistics in a feeble effort to provide a pseudo-basis for their contention that we are in a state of unprecedented runaway global warming. There is no great point in reproducing their graphs here since they all display *hockey sticks* of one form or another.

In the course of discussion, Juckes *et al.* (2006) could not resist taking a poke at Soon and Baliunas (2003a, b), calling this work "problematic", which is more charitable than Mann and Jones (2003) who called it "flawed". This seems to be a case of "the pot calling the kettle black" considering how flawed the *hockey stick* turns out to be (see next section).

2.2.3 Criticisms of the MBH model

2.2.3.1 McIntyre and McKitrick

Two Canadian professionals, Stephen McIntyre and Ross McKitrick (M&M) have maintained a steady barrage of criticism of the MBH model and the *hockey stick* result over the past several years (e.g., McKitrick, 2005; McIntyre and McKitrick, 2005, 2006, 2007). Both are very knowledgeable in regard to statistical processing of large noisy data sets in general, and PCA in particular.

McKitrick (2005) said:

> "The *hockey stick* debate is thus about two things. At a technical level it is about flaws in methodology and erroneous results in a scientific paper. But at the political level the debate is about whether the Inter-government Panel on Climate Change (IPCC) betrayed the trust of governments around the world."

Although McKitrick (2005) didn't come right out and say it, the implication is clear (and credible to this writer) that there exists an international conspiracy of scientists determined to (in their belief) save the world from putative overheating, who have seized on the *hockey stick* (rightly or wrongly) as a means of furthering their goals.

The computational process involved in MBH models is quite complex. M&M attempted to reproduce this process and ran into a number of roadblocks. After much perseverance, they succeeded to a considerable degree. In the course of doing this, they uncovered several major errors in the MBH model. The principal problem was summarized by McKitrick (2005) and his summary is paraphrased below.

In a conventional PCA, if the data are in different units it is common to *standardize* them by subtracting the mean of each column and dividing by the standard deviation. This re-centers and re-scales all the data to a mean of 0 and a variance of 1. In the MBH program, a scaling was applied, but rather than subtract the mean of the entire series length, they subtracted the mean of the 20th-century portion used for calibration, and then divided by the standard error of the 20th-century portion. The overwhelming majority of individual proxy series do not have the form of *hockey sticks*, but appear as random noise, and since they don't change in the 20th century, this procedure did not make much difference for them. The mean of the calibration period is roughly the same as the mean of the whole series (as is the standard error) so either way of standardizing yields more or less the same result. But a few of the proxy series trend upward in the 20th century. For these, the MBH method has a huge effect. Since the mean of the 20th century portion is higher than the mean of the whole series, subtracting the 20th-century mean *de-centers* the series, shifting it off a zero mean. This, in turn, inflates the variance of these series with increases in the 20th century. PC algorithms inflate the weights of data series with the highest variance. If one series in the group has a relatively high variance, its weight in the PC1 gets inflated. The MBH algorithm did just this. The PCA procedure would, in effect, sift through a data set and identify series with a 20th-century up-trend, and then load almost all the weight on these series. In effect, it data-mines for *hockey sticks*.

Figure 2.28 provides an example of the effect. It shows 2 of the 90 full-length series in the MBH database. The top panel is a tree ring chronology from a stand of bristlecone pines at Sheep Mountain, California. The bottom panel is a tree ring chronology from Mayberry Slough, Arkansas. In the bottom panel, the mean over the last 80 years is roughly equal to the mean for the previous 500 years, but in the top panel the post-1900 mean is above that for the pre-1900 portion. The MBH algorithm attributes 390 times as much weight to the top series as it does to the bottom series in the first principal component (PC1).

As it turns out, of 1,082 proxies used by MBH, only a handful exhibit the form shown in the upper panel of Figure 2.28, and all of these suffer from the potential CO_2 fertilization problem in the 20th century.

To test the MBH data-mining algorithm, M&M ran an experiment in which they input only trendless random *red noise*, simulating the data one would obtain from trees in a climate that is only subject to random fluctuations with no warming trend. In 10,000 repetitions, they found that a conventional PC algorithm almost never yielded a *hockey stick*–shaped PC1, but the MBH algorithm yielded a pronounced *hockey stick*–shaped PC1 more than 99% of the time. The MBH algorithm efficiently looks for those kinds of series and flags them for maximum weighting. It concludes that a *hockey stick* is the dominant pattern even when pure noise is the input!

M&M extended their study in two ways. First, they showed that the MBH data-mining procedure did not just pull out a random group of proxies—it pulled out an eccentric group of bristlecone pine chronologies. These trees (the Sheep Mountain

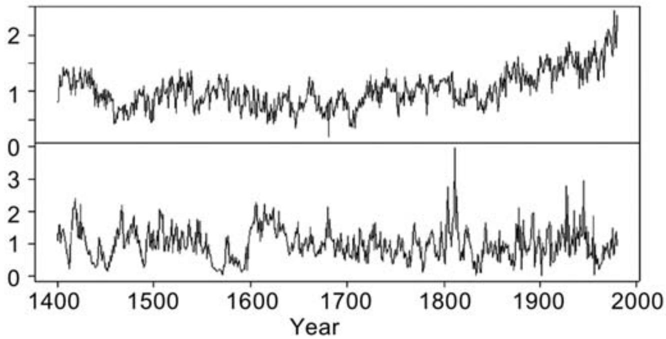

Figure 2.28. Two tree-ring chronologies from the MBH data set. Top: Sheep Mountain, CA. Bottom: Mayberry Slough, AR. Both series are the same length, but due to the 20th century trend in the top panel, the MBH algorithm gives it 390 times the weight of the bottom series in the PC1. Adapted from McKitrick (2005).

series in Figure 2.28 is an example) all turned out to exhibit a 20th-century growth spurt that has not been fully explained, but is likely to be at least partly due to CO_2 fertilization and is known not to be a temperature signal since it does not match nearby temperature records. The original authors (and others) have stressed that these series do not constitute proper climate proxies. So, M&M examined the consequences to the MBH results if these 20 bristlecone pine proxies were excluded. The result showed no *hockey stick* at all. Without these proxies with their rising shapes in the 20th century to mine for, the MBH method generates a result just like that from a conventional PC algorithm, and shows the dominant pattern is not *hockey stick*–shaped at all. In other words, without the bristlecone pines, even the flawed procedure of MBH would not have a *hockey stick* shape.

Of crucial importance here is the fact that this result is contained in a folder marked CENSORED on Mann's FTP site. Apparently, he did this very experiment himself and discovered that the PCs lose their *hockey stick* shape when the 20 bristlecone pine proxies are removed. In so doing he discovered that the *hockey stick* is not a global pattern, it is driven by a flawed group of U.S. proxies that experts do not consider valid as climate indicators. But he did not disclose this fatal weakness of his results, and it only came to light because of Stephen McIntyre's laborious efforts. Yet, Mann has testified that the *hockey stick* result is independent of whether these proxies are included or not.

In addition, M&M found other problems with the MBH procedure that enhanced the *hockey stick* result. Finally, McKitrick (2005) estimated what the temperature history would look like if they used a proper procedure and made appropriate corrections for the bristlecone pines as well as other factors. The result is shown in Figure 2.29.

Although Figure 2.29 still shows a significant warming trend in the late 20th century, the important point is that the solid curve indicates that this warming trend may not be any greater than temperature excursions in the past, prior to the MM.

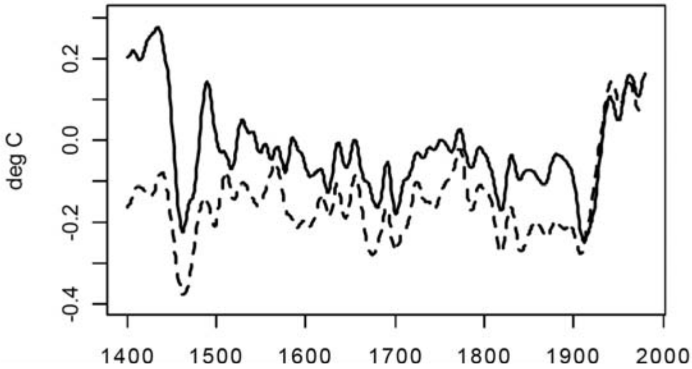

Figure 2.29. Comparison of temperature reconstructions. Dashed line is *hockey stick* result of MBH. Solid line is corrected by M&M. Vertical scale is temperature anomaly. Adapted from McKitrick (2005).

However, the vertical scale in this figure appears to be unduly compressed. A wider range of variation is likely. M&M (McIntyre and McKitrick, 2006) pointed out that other reconstructions of historical Earth temperatures based on smaller numbers of proxies than MBH, also suffer from problems due to the inclusion of bristlecone pines and other proxies that unreasonably increase the rise in the 20th century, providing unjustified support for the *hockey stick* result. They also pointed out that most of the crucial studies of historical Earth temperatures cannot be reproduced by an independent observer based on published materials—which is not in keeping with the scientific method.

2.2.3.2 Bürger and Cubasch

Bürger and Cubasch (2005) is a difficult paper to read. It is full of jargon and uses a number of acronyms that are not defined. It is likely that only a reader who is intimately connected to statistical processing of long-term historical climate data could follow this paper in detail. Nevertheless, it appears to be an important paper and must be considered here. Bürger and Cubasch (2005) examined the mathematical procedure used by MBH for the NH temperature reconstruction and noted that there were six key junctures where a fork in the road occurred, and MBH had to choose one or the other pathway for the ensuing computations. Since any one choice of path at one juncture could be combined with any other choice of path at another juncture, and there are six junctures, there must be a total of $2^6 = 64$ possible pathways to carry out the entire calculation.

We will not describe all of the junctures and choices here, but it is important to mention that one of the junctures was the choice of alternatives: (1) the MBH calculation of temperature anomalies based on the mean over the calibration period vs. (2) calculation of the mean for the entire time span of the data. As M&M have shown, use of only the calibration period mines for *hockey stick* results.

The various pathways can be described by means of six-digit binary numbers. The MBH method is described by one of these 64 binary numbers. Bürger and Cubasch (2005) said: "No a priori, purely theoretical argument allows us to select one out of the 64 as being the 'true' reconstruction." Bürger and Cubasch (2005) also argued that the alternate paths at each juncture are "a priori sound, with numerous applications elsewhere, and can hardly be dismissed purely on theoretical grounds." However, in regard to the juncture where one chooses the mean as a basis for calculating anomalies, it appears from the results of M&M that use of the mean for only the 20th century is fundamentally wrong *a priori*, and therefore the assertion by Bürger and Cubasch (2005) is incorrect in this specific instance. The choice of the time period for the mean is *not* one of reasonable alternatives, but rather a choice of right vs. wrong.

The results of Bürger and Cubasch (2005) are shown in Figure 2.30. Unfortunately, there is no key given to identify which of the 64 pathways correspond to the various temperature reconstructions. A worrisome feature is that the zero line appears to be the mean of the 20th century data and most anomalies are negative. This leads one to wonder whether they actually did calculations with the mean for the whole time period, and if they did, why are the anomalies (for non-MBH options) not centered vertically on the zero line? Bürger and Cubasch (2005) concluded:

> "Any robust, regression-based method of deriving past climatic variations from proxies is therefore inherently trapped by variations seen at the training stage, that is, in the instrumental period. The more one leaves that scale and the farther the estimated regression laws are extrapolated the less robust the method is. The described error growth is particularly critical for parameter-intensive, multi-proxy climate field reconstructions of the MBH type. Here, for example, co-linearity and over-fitting induce considerable error already in the estimation phase."

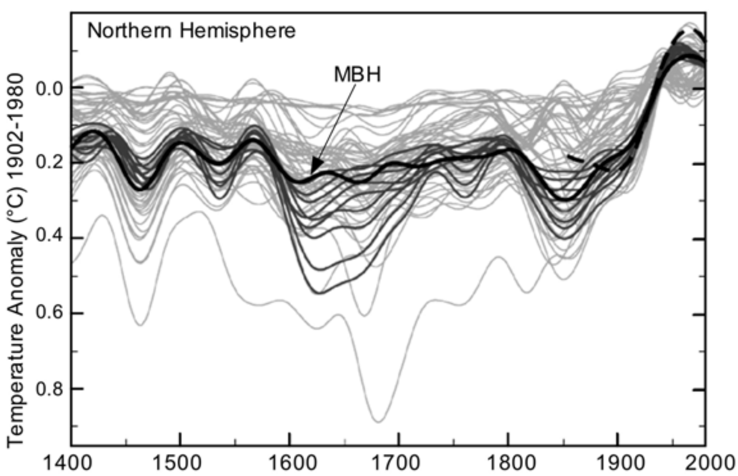

Figure 2.30. Temperature reconstructions. Adapted from Bürger and Cubasch (2005).

It appears that almost any result can follow from an integration of proxies, and no proxy result can be trusted.

Esper *et al.* (2005a, b) concluded:

> "Our understanding of the shape of long-term fluctuations is better than commonly perceived, but the absolute amplitude of temperature variations is poorly understood ... Overall, amplitude discrepancies are of the order of the total variability estimated over the past millennium ..."

Even this conclusion seems optimistic.

2.2.3.3 The Wegman Report

A team led by Professor Edward J. Wegman performed an independent examination of the *hockey stick* controversy (Wegman, Scott, and Said, 2006). They produced a lengthy report, full of details.

According to Wegman, Scott, and Said (2006):

> "The controversy of Mann's methods lies in that the proxies are centered on the mean of the period 1902–1995, rather than on the whole time period ... Principal component methods are normally structured so that each of the proxy data series are centered on their respective means and appropriately scaled. The first principal component attempts to discover the composite series that explains the maximum amount of variance. The second principal component is another composite series that is uncorrelated with the first and that seeks to explain as much of the remaining variance as possible. The third, fourth, and so on follow in a similar way. In the MBH approach the authors make a simple seemingly innocuous and somewhat obscure calibration assumption. Because the instrumental temperature records are only available for a limited window, they use instrumental temperature data from 1902–1995 to calibrate the proxy data set. This would seem reasonable except for the fact that temperatures were rising during this period, so that centering on this period has the effect of making the mean value for any proxy series exhibiting the same increasing trend to be de-centered low. Because the proxy series exhibiting the rising trend are de-centered, their calculated variance will be larger than their normal variance when calculated based on centered data, and hence they will tend to be selected preferentially as the first principal component. Thus, in effect, any proxy series that exhibits a rising trend in the calibration period will be preferentially added to the first principal component."

Wegman, Scott, and Said (2006) went on to say:

> "The centering of the proxy series is a critical factor in using principal components methodology properly. It is not clear that the MBH Team even realized that their methodology was faulty at the time of writing the MBH paper. The net

effect of the de-centering is to preferentially choose the so-called *hockey stick* shapes. While this error would have been less critical had the paper been overlooked like many academic papers, the fact that their paper fit some policy agendas has greatly enhanced their paper's visibility. Specifically, global warming and its potentially negative consequences have been central concerns of both governments and individuals. The *hockey stick* reconstruction of temperature graphic dramatically illustrated the global warming issue and was adopted by the IPCC and many governments as the poster graphic. The graphic's prominence together with the fact that it is based on incorrect use of PCA puts Dr. Mann and his co-authors in a difficult face-saving position. We have been to Michael Mann's University of Virginia website and downloaded the materials there. Unfortunately, we did not find adequate material to reproduce the MBH materials."

Wegman, Scott, and Said (2006) performed a calculation similar to that of M&M by comparing the results of an analysis of the North American tree network PC1 using the MBH data with centering based either on the calibration period mean or the mean for the whole time span of the data set. The result is shown in Figure 2.31. In addition to the *hockey stick* shape of the upper panel it is worth noting that the lower panel exhibits considerably more variability. PCA seeks to identify the largest contributor to the variance. The MBH offset of the mean value shifts the main variance from the bulk of the data set to the 20th century data.

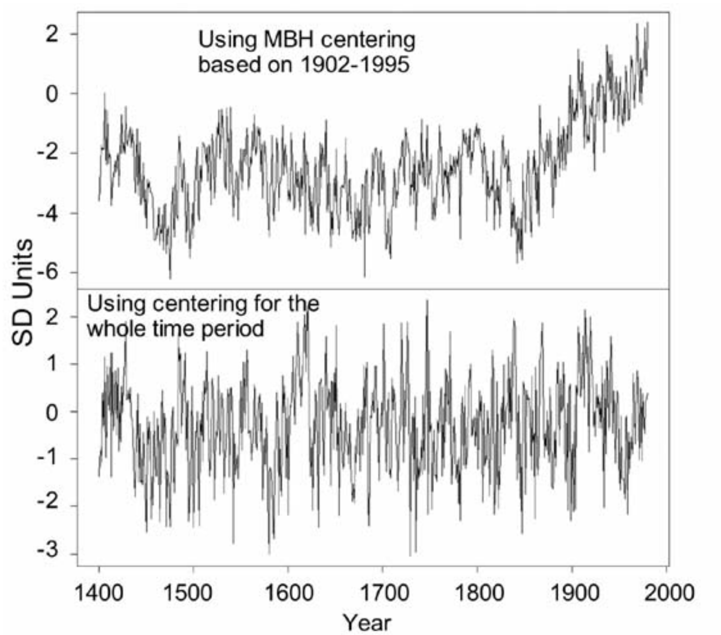

Figure 2.31. Comparison of re-work of the North American tree network PC1 using MBH centering vs. using centering across the whole time span of the data set. The *hockey stick* is shown to be an artifice. Adapted from Wegman, Scott, and Said (2006).

The findings of Wegman, Scott, and Said (2006) are quite lengthy and only a very brief summary is given here.

1. In general they found the writing of MBH somewhat obscure and incomplete. (This writer found the same.)
2. In general, they found the criticisms by M&M to be valid and their arguments to be compelling.
3. Use of the temperature profile in the 1902–1995 time span for centering leads to misuse of the principal components analysis. However, the narrative in MBH on the surface sounds entirely reasonable, and could easily be missed by someone who is not extensively trained in statistical methodology.
4. The cryptic nature of some of the MBH narratives requires that outsiders would have to make guesses at the precise nature of the procedures being used.
5. Much of the discussion on the *hockey stick* issue has taken place on competing web blogs. Web blogs are not an appropriate way to conduct science and thus the blogs give credence to the fact that these global warming issues have migrated from the realm of rational scientific discourse. Unfortunately, the factions involved have become highly and passionately polarized.
6. Generally speaking, the paleo-climatology community has not recognized the validity of the M&M papers and has tended to dismiss their results as being developed by biased amateurs. The paleo-climatology community seems to be tightly coupled, and has rallied around the MBH position.
7. The widely quoted assessments that the decade of the 1990s was the hottest decade in a millennium and that 1998 was the hottest year in a millennium cannot be supported by a proper rendition of the MBH analysis . . . The paucity of data in the more remote past makes the hottest-in-a-millennium claims essentially unverifiable.
8. Use of bristlecone pine proxies are inappropriate because they were probably CO_2-fertilized. It is not surprising therefore that this important proxy in MBH yields a temperature curve that is highly correlated with atmospheric CO_2. There are clearly confounding factors for using tree rings as temperature signals.
9. There are other detailed statistical problems with the MBH treatment that require specialized knowledge to understand.

2.2.3.4 Esper et al.

Section 2.1.2.2 mentions a study by Esper, Cook, and Schweingruber (2002) that said: "the MBH reconstruction has been criticized for its lack of a clear MWP." It was claimed that critics doubt that tree ring records can preserve long-term, multi-centennial temperature trends. Esper, Cook, and Schweingruber (2002) then went on to present a defense of tree ring reconstructions. However, their final result showed strong differences from that of MBH (see Figure 2.7). They concluded that MBH did not miss an MWP but rather, "it had a reduced expression of the LIA." The Esper Team appears to be part of the *paleo-climate group* (see Section 2.2.3.7) and their intent was to support MBH. However, based on Figure 2.7, their findings can be interpreted as a rejection of the MBH result.

2.2.3.5 Soon and Baliunas

The review by Soon and Baliunas (2003a, b) is a lengthy compendium and we present only a brief summary.

According to Soon and Baliunas (2003a, b), Mann, Bradley, and Hughes (1998) stated that the most fundamental assumption in their multi-proxy reconstruction effort is that all spatial patterns of climate variation over the last 1,000 years precisely follow the measured global pattern of change in near-surface air temperature of the last 80–90 years or so. Since a huge number of proxies were processed by Mann, Bradley, and Hughes (1998) into a single average result that depends only on time, presumably this implies that the spatial distribution should have remained constant over the entire time interval—which of course, it didn't.

Second, Soon and Baliunas (2003a, b) claimed that Mann, Bradley, and Hughes (1998) admitted that their results for the first eigenvectors prior to 1400 had low statistical validity (in statistical jargon: low *skill*), because no data exist for useful resolution of hemispheric-scale variability over that time period.

Third, although 12 additional proxies were added to the data base of Mann, Bradley, and Hughes (1998) by Mann, Bradley, and Hughes (1999) to reconstruct back to 1000, as opposed to 1400, the positive calibration/variance scores are carried solely by the first principal component (PC1), which consists of high-elevation tree growth proxy records from western North America. This fact led Mann, Bradley, and Hughes (1999) to report that the spatial variance explained by the distribution of their proxy networks in the calibration and verification process is only 5%, and that it is the time component—not the spatial details—that are "most meaningful" for their millennial reconstruction results. Soon and Baliunas (2003a, b) pointed out that the 1,000-year reconstructed "Northern-Hemispheric mean temperature" by Mann, Bradley, and Hughes (1999) is dominated by relative changes in the western North America time series, and that Mann, Bradley, and Hughes (1999) also specifically emphasized that their calibration/verification procedure fails if they remove the one crucial western North American composite tree ring series from the list of 12 proxies. In light of these limitations, the extension of hemispheric-scale temperature changes from 1400 to 1000 is not robust, and it must be concluded that:

> *No scientifically confident statements can be made about global temperature changes for the last 1,000 years.*
>
> *The key conclusions of Mann, Bradley, and Hughes (1998) and later papers that (a) the 20th century is "nominally the warmest" of the past millennium, valid at least over the Northern Hemisphere, (b) the decade of the 1990s was the warmest decade and 1998 the warmest year of the last millennium at "moderately high levels of confidence", (c) the notion of the LIA as a globally synchronous cold period can be dismissed,(d) the notion of the MWP applies mainly to western Europe and was not a global phenomenon, are unfounded, specious, and more political than scientific.*

Soon and Baliunas (2003a, b) claimed that tree ring reconstructions after Mann, Bradley, and Hughes (1999) have clearly shown evidence for an MWP that was at least as warm as the 20th century. This is why many authors cautioned against any definitive conclusion on the nature of true climatic change from proxy records or from EOF mathematical reconstructions.

Several other objections to the procedures used by MBH were raised by Soon and Baliunas (2003a, b). Most of these are abstruse and difficult for the non-expert to follow. One criticism that is clear, however, is that strong evidence has been accumulating that tree growth has been disturbed in many Northern Hemisphere regions in recent decades so that after about 1960–1970, the usual, strong positive correlation between the tree ring width or tree ring maximum late-wood density indices and summer temperatures have weakened. The calibration period of MBH ended at 1980, while 20 more years of climate data post-1980 (compared with the 80 years length of their calibration interval, 1902–1980) exist. If the failure of inter-calibration of instrumental and tree growth records over the last two to three decades suggests evidence for anthropogenic influences (i.e., from CO_2, nitrogen fertilization, or land-use and land-cover changes or through changes in the length of growing seasons and changes in water and nutrient utilization efficiencies, and so on), then no reliable quantitative inter-calibration can connect the past to the future. In addition, Soon and Baliunas (2003a, b) pointed out other weaknesses in the use of tree ring proxies as well.

Soon and Baliunas (2003a, b) concluded that taking all the physical criticisms and technical problems together, the answers proposed for several key questions on climate behavior of the past millennium by MBH are uncertain because of the unverifiable assumptions implicit in the mathematical extrapolation of the observed pattern of climatic changes to the full historical changes of the last 1,000 years. The MBH large-scale proxy temperature reconstruction is not capable of resolving the three specific questions posed in Soon and Baliunas (2003a, b) about the local reality of the LIA, MWP, and 20th-century warming (see Section 2.1.1).

Despite the many lengthy criticisms of MBH, Soon and Baliunas (2003a, b) do not seem to have included the points raised by M&M regarding bad statistics by MBH using an improper mean, presumably because this point was raised after Soon and Baliunas (2003a, b) was published.

In response, Mann and Jones (2003) claimed that Soon and Baliunas (2003a, b) were "flawed studies".

2.2.3.6 Zorita and von Storch

Zorita and von Storch (2005) examined methods used to construct historical temperatures. Unfortunately, it was difficult for this writer to follow all the arguments and jargon in the paper. However, it is apparent that Zorita and von Storch (2005) found significant problems with the methods used by MBH to infer long-term historical temperature records. Zorita and von Storch (2005) started with a model that the authors developed for a 1,000-year record of global temperatures called ECHO-G. The methods used by MBH were tested by following the MBH procedure, in which all data were considered to be deviations from the 1900–1980 mean value, even though this period is not representative for the temperature history of the past millennium. They followed the procedure of MBH but utilized different levels of noise as inputs. Inevitably, the methods of MBH led to a so-called *hockey stick* type of figure and grossly underestimated the variability of temperature in the past.

2.2.3.7 The paleo-climate group

As McLean (2007a) said:

> "The peer-review process was established for the benefit of editors who did not have good knowledge across all the fields that their journals addressed. It provided a 'sanity check' to avoid the risk of publishing papers which were so outlandish that the journal would be ridiculed and lose its reputation. In principle this notion seems entirely reasonable, but it neglects certain aspects of human nature, especially the tendency for reviewers to defend their own (earlier) papers, and indirectly their reputations, against challengers. Peer review also ignores the strong tendency for papers that disagree with a popular hypothesis, one the reviewer understands and perhaps supports, to receive a closer and often hostile scrutiny. Reviewers are selected from practitioners in the field, but many scientific fields are so small that the reviewers will know the authors. The reviewers may even have worked with the authors in the past or wish to work with them in future, so the objectivity of any review is likely to be tainted by this association. Some journals now request that authors suggest appropriate reviewers, but this is a sure way to identify reviewers who will be favorable to certain propositions . . . In 2002 the editor-in-chief of the journal *Science* announced that there was no longer any doubt that human activity was changing climate, so what are the realistic chances of this journal publishing a paper that suggests otherwise? The popular notion is that reviewers should be skilled in the relevant field, but a scientific field like climate change is so broad, and encompasses so many subdisciplines, that it really requires the use of expert reviewers from many different fields. That this is seldom undertaken explains why so many initially influential climate papers were later found to be fundamentally flawed. In theory, reviewers should be able to understand and replicate the processing used by the author(s). In practice, climate science has numerous examples where authors of highly influential papers have refused to reveal their complete set of data or the processing methods that they used. Even worse, the journals in question not only allowed this to happen, but have subsequently defended the lack of disclosure when other researchers attempted to replicate the work."

Wegman, Scott, and Said (2006) have suggested that the field, *temperature history of the Earth*, is dominated by a cadre (clique?) that is vitally concerned about the potential impacts of global warming, and supports the *hockey stick* result, as well as the procedure used to derive it. Wegman, Scott, and Said (2006) said:

> "If there is a tight relationship among the authors, and there are not a large number of individuals engaged in a particular topic area, then one may suspect that the peer review process does not fully vet papers before they are published. Indeed, a common practice among associate editors for scholarly journals is to look in the list of references for a submitted paper to see who else is writing in a given area and thus who might legitimately be called on to provide knowledgeable peer review. Of course, if a given discipline area is small and the authors in the area are tightly coupled, then this process is likely to turn up very sympathetic referees. These referees may have co-authored other papers with a given author. They may believe they know that author's other writings well enough that errors can continue to propagate and indeed be reinforced."

It was concluded:

> "It is immediately clear that Mann, Rutherford, Jones, Osborn, Briffa, Bradley, and Hughes form a clique, each interacting with all of the others."

Other cliques were identified as well. It seems clear that this group has control over which papers are approved for publication in journals on the topic of the history of temperature of the Earth.

It is noteworthy that M&M submitted a letter to *Nature* about a flaw in the MBH procedure. After a long (8-month) reviewing process, M&M were notified that *Nature* would not publish this letter. *Nature* concluded it could not be explained in the 500-word limit, and one of the referees said he found the material was quite technical and unlikely to be of interest to general readers. Instead, MBH were permitted to make a coy disclosure in their July Corrigendum. In an on-line Supplement (but not in the printed text itself) they revealed the non-standard method, and added the unsupportable claim that it did not affect the results. There is at least the appearance (and more likely the reality) that the *paleo-climate group* was in complete control of the situation.

Mann *et al.* (2005) was written by the MBH Team (i) to argue against von Storch *et al.* (2004), and (ii) to claim that it makes little difference whether the proxy data are standardized by utilizing only the mean of the calibration period, or the mean of the entire historical data set. What would be humorous, if it were not sad, is the fact that the *paleo-climate group* continue to relentlessly publish learned articles in defense of their methodologies, while pretending all the while that M&M do not exist.[3] Thus, for example, Mann *et al.* (2005) concluded:

> "Two widely used statistical approaches to reconstructing past climate histories from climate proxy data such as tree rings, corals, and ice cores are investigated using synthetic pseudo-proxy data derived from a simulation of forced climate changes over the past 1200 yr. These experiments suggest that both statistical

[3] Why am I reminded of Frank Morgan as the Wizard of Oz admonishing Dorothy to "pay no attention to that man behind the screen ...?"

> approaches should yield reliable reconstructions of the true climate history within estimated uncertainties, given estimates of the signal and noise attributes of actual proxy data networks.''

Mann *et al.* (2005) went on to say:

> ''We find no evidence for the suggestion (e.g., von Storch *et al.*, 2004) that real-world proxy-based temperature reconstructions are likely to suffer from any systematic underestimate of low-frequency variability. Our findings suggest that both standard methods that have been used in proxy-based reconstruction are likely to provide a faithful estimate of actual long-term hemispheric temperature histories, within estimated uncertainties.''

M&M were never mentioned.

Mann *et al.* (2007) continued the relentless defense of flawed methods:

> ''Our results reinforce previous conclusions that CFR methods, correctly implemented and applied to suitable networks of proxy data, should yield reliable reconstructions of past climate histories within estimated uncertainties.''

2.2.3.8 How reliable are proxy methods?

In order to test the robustness of methods for processing proxy data, Mann *et al.* (2005) set up a model for proxy-processing evaluation. Smerdon and Kaplan (2007) commented on this process. The description that follows is based on Smerdon and Kaplan (2007).

An artificial model is generated in which real temperature data are used for a calibration period, and a climate model is used to create *real* data prior to the calibration period. The climate model data are treated as *real* for purposes of testing. A number of *pseudo-proxies* are created by selecting some of the real data for particular locations, and adding noise to them. The point here is that a proxy is treated as an absolutely accurate temperature series at one location, but with noise superimposed. Then the challenge is to reconstruct the *real* data from the pseudo-proxies.

They considered a time period from 850 to 1980. For each year, a temperature is assigned to each spatial cell covering a $5^\circ \times 5^\circ$ range of latitude and longitude. The latitude varies from 70°N to the equator and the longitude goes from 0° to 360° in 5° steps, as shown in Table 2.3. In actuality, we cannot know the actual temperatures over such a long time period. The true temperatures are known from 1855 to 1980 as shown by the rows 1855–1980 (for columns 0° to 360°) in Table 2.3. A global climate model is used to fill in the earlier data from 850 to 1854 (rows 850 to 1854 for columns 0° to 360°). Even though this data set is not real, it is treated as *real* for purposes in testing proxy processing. Then, a set of *pseudo-proxies* is constructed by selecting some of these time series, each pseudo-proxy representing one time series for a single latitude/longitude combination as shown in the far right columns. To emulate a real case, noise is added randomly to the various pseudo-proxies.

Table 2.3. Space–Time matrix of temperature data.

Year ⇓	Longitude = 0°					5°				360°				Proxies			
Lat ⇒	0	5	10	...	70	0	5	...	70	0	5	...	70	1	2	...	N
850																	
851																	
852														Pseudo-proxy			
...	Pseudo "real" data																
1854																	
1855																	
1856					Real Data												
...																	
1980																	

Then, the question is, given a set of pseudo-proxies as a starting point: How well does the data-processing scheme reproduce the original "true" data set?

Basically, in any statistical processing of proxy data, one begins by centering the data about its mean and normalizing it (scaling the deviations from the mean) in units of the standard deviation. This is called "standardization". There exists a calibration period during which there exist both proxies and actual measurements, and there is a longer period of time over which proxies are used to infer temperatures. One can either standardize based on the mean for the shorter calibration time period, or the mean over the entire data set. Smerdon and Kaplan (2007) found that when standardization was carried out over the entire data set the results were consistent and varied only slightly with the addition of noise to a data set. However, when the mean for only the calibration period was used for standardization the results varied widely when noise was added. But Smerdon and Kaplan (2007) mentioned that, when standardization is carried out over the entire data set,

> "Such a decision may sound benign, [but] it amounts to knowing the mean and standard deviation of the target field prior to the calibration interval—a luxury that would obviate the need for a reconstruction in the first place."

Smerdon and Kaplan (2007) argued that the case where standardization is accomplished over the entire data set is artificial because one never has the full data set in reality. This would seem to suggest that the only practical way to process proxy data is based on standardization over the calibration interval, and this method is problematic because it produces variable results depending on the noise involved. As in the case of the M&M findings, the more noise that is added to the data, the more the result approaches a *hockey stick* form.

This test is good as far as it goes, but it does not allow for the possibility that systematic errors may occur in proxies, independent of noise imposed on a true temperature profile.

2.3 THE BLOGS

Quite a number of weblogs have evolved out of the controversies surrounding putative global warming. Most of these are global warming naysayers although a few represent the *paleo-climate group*. The great majority of these blogs are filled with short sound bites submitted by people who have not done the research needed in order to speak authoritatively on any subject, and indeed, the bulk of the banter is nonsense. However, three sites deserve special mention because they are technically competent and worthy of review. One, which is anti-establishment, is

http://www.climateaudit.org

run by Steve McIntyre (of M&M).

The major establishment blog is

http://realclimate.org

which presents the viewpoints of the global-warming alarmists.

A third blog is full of technical content. Although the tone is anti-establishment, it provides solid technical backup for all conclusions

http://climatesci.colorado.edu/

In addition to the above three important websites, the following sites provide sometimes meaningful content, or connections to various anti-establishment websites:

http://co2science.org
http://www.warwickhughes.com/hoyt/climate-change.htm
http://john-daly.com
http://meteo.lcd.lu/globalwarming/

2.3.1 Climate audit blog

Although the tilt of McIntyre's blog is decidedly antithetical to the global-warming alarmists, unlike other anti-warming blogs, McIntyre has penetrated into the data and details in most cases and speaks authoritatively on most subjects. For example, he showed that the IPCC Report (IPCC, 2001) cut off the data in Figure 2.32 to

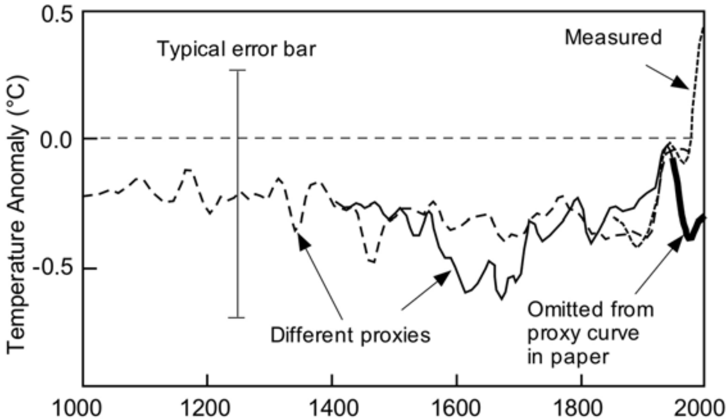

Figure 2.32. Reported *hockey stick* curves from the IPCC Report showing that the dip in a proxy curve was cleverly omitted. Adapted from McIntyre (2007).

emphasize recent warming. Such data truncation is certainly improper and may teeter on the hazy borderline of science fraud.

McIntyre's blog is very extensive on many topics and it is not possible to summarize them here. Only a few items are very briefly summarized below.

Archiving and disclosure. Any report only fulfills the scientific method if the data are made available for checking and reproduction by others. McIntyre provides specific instances where important papers in climate change have not made the data available and his attempts to acquire the data were parried by the *paleo-climate group*. McIntyre also presents examples where scientists responded fully and promptly to his inquiries for detailed data.

The Holocene Optimum. In their zeal to alert the world to the dangers of global warming, the *paleo-climate group* have promulgated the beliefs that the temperature variations in the MWP and LIA were minor, and even the Holocene Optimum was restricted to summers in the NH. As a result, unfounded claims have been made about the late 20th century being the warmest period in the past 1,000 years, and possibly for the entire Holocene.

Realclimate.org stated:

> "The [Holocene Optimum] is a somewhat outdated term used to refer to a sub-interval of the Holocene period from 5000–7000 years ago during which it was once thought that the Earth was warmer than today. We now know that conditions at this time were probably warmer than today, but only in summer and only in the extra-tropics of the Northern Hemisphere."

NOAA stated: "In summary, the mid-Holocene, roughly 6,000 years ago, was generally warmer than today, but only in summer and only in the northern hemisphere."

McIntyre rebutted these statements based in part on Stott *et al*. (2004) (see Section 1.3.5). It appears to this writer that the data are not sufficiently voluminous and reliable to be certain one way or the other, but the preponderance of data (from Section 1.3) suggests that the mid-Holocene was probably warmer than it is today.

Chicanery in proxy data manipulation by the *paleo-climate group*. McIntyre provides very lengthy detailed accounts of his difficulties in acquiring original proxy data used in published papers by members of the *paleo-climate group* (Osborn, Briffa, Jones, Crowley, Lowery, Esper, Moberg, Juckes, Mann, etc.). In general, obtaining proxy data from these authors required endless requests and cajoling, and even then was only sporadically successful. In one case, he could not get any satisfaction from the authors, and had to resort to 25 emails to the journal *Science*, and even then he was not able to recover the required data. He indicated that in several important cases, the authors utilized data from previous publications, but the data so acquired were not original, and had been processed (sometimes in ways that are suspect and difficult to trace). Seeking the original data required going back to multiple authors, leading inevitably to frustration.

Aside from the problem of acquiring the data, McIntyre found many inconsistencies and oddities in the handling of proxy data by the group members. He details these at length, although this writer found much of it difficult to absorb. One way or another, these manipulations of data all seemed to have a singular end result: amplification of the recent late–20th century warming trend, and damping of the MWP, leading to the mantra that we are currently experiencing the warmest climate in over 1,000 years. Of particularly serious concern is the charge that when McIntyre finally acquired the proxy data of Briffa *et al*. (2001) the data set included only 369 proxy sites of the supposed 387, and 18 were missing. When McIntyre examined the set of 369 by simply averaging them, he obtained Figure 2.33. McIntyre

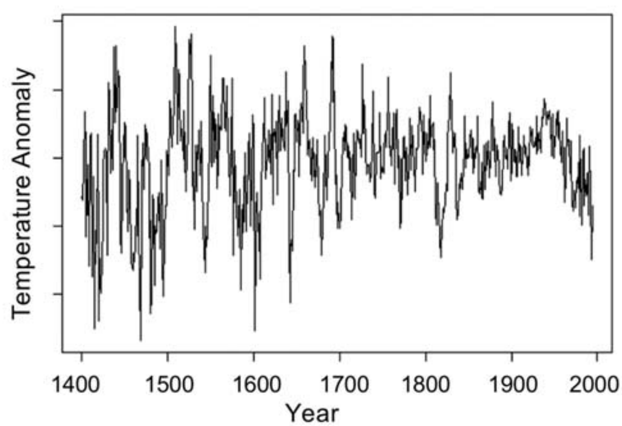

Figure 2.33. McIntyre's average of 369 proxies from Briffa *et al*. (2001). Adapted from McIntyre (2007).

then wondered how Briffa *et al.* (2001) could possibly obtain a strong up-tick in the 20th century (see Figure 2.34, color section) from such proxy data. The answer was that the statistical methods used by the *paleo-climate group* selected out those few proxies that had strong up-ticks in the 20th century and gave preponderant weight to them in the ensuing analysis. To further exacerbate this problem, these depend on results from bristlecone/foxtail pines that are highly suspect because other factors (than temperature) likely affected their 20th-century growth. McIntyre provides considerable inferences to suggest that the *paleo-climate group* have picked and chosen data, manipulated data, and processed data to maximize their desire to alert the world to their perceived dangers of global warming.

These brief remarks are merely the "tip of the iceberg" and the climateaudit.org website is very extensive and detailed.

2.3.2 Real climate blog

Like its polar opposite (climateaudit.org) the realclimate.org blog is very extensive and detailed and it is not possible to adequately describe all the material on this website. Only a few comments will be made.

Al Gore's film *An Inconvenient Truth* received a glowing review including "admirable", and "for the most part he gets the science right". Al Gore recently received the Nobel Peace Prize, presumably partly based on this film. See the Appendix for a review of this film, which subscribes to the *hockey stick*.

Realclimate.org provides a section entitled "Myth vs. Fact regarding the *Hockey Stick*."

It is claimed that

> "Numerous myths regarding the so-called *hockey stick* reconstruction of past temperatures, can be found on various non-peer reviewed websites, internet newsgroups and other non-scientific venues. The most widespread of these myths are debunked below."

Myth #0 *Evidence for modern human influence on climate rests entirely on the "hockey stick"* reconstruction of Northern Hemisphere mean temperatures indicating anomalous late 20th-century warmth.

The response to this putative myth on realclimate.org is vague and confused. A better response is this. Even if we ignore the *hockey stick* and accept that global temperatures varied significantly in the MWP and the LIA, there is a significant difference today from those periods: CO_2 and CH_4 concentrations are much higher. The major issue regarding modern human influence on climate is whether the climate models are credible that predict significant temperature growth from increases in CO_2 and CH_4 concentrations.

Myth #1 *The hockey stick reconstruction is based solely on two publications by climate scientist Michael Mann and colleagues (Mann, Bradley, and Hughes, 1998, 1999).*

The realclimate.org response is that "this is patently false." To support their position, they mention: "nearly a dozen model-based and proxy-based reconstructions ... by different groups all suggest that late 20th century warmth is anomalous in a long-term (multi-century to millennial) context." However, the other publications typically utilized PCA with the mean chosen only for the calibration period leading inevitably to some form of *hockey stick* if some of the proxies had an upward trend in the 20th century. It is not the number of papers that counts here. As Bob Foster emphasized, truth in science is not a matter of voting. The issue here is whether the reconstruction is correct, independent of whether the reconstruction was done in 2, 20, or 200 papers. This putative myth is irrelevant.

Myth #2: *Regional proxy evidence of warm or anomalous (wet or dry) conditions in past centuries contradicts the conclusion that late 20th-century hemispheric mean warmth is anomalous in a long-term (multi-century to millennial) context.*

This "myth" is presumably an allusion to the paper by Soon and Baliunas (see Section 2.2.3.5). Realclimate.org makes the point that Soon and Baliunas were rebutted by "a group of more than a dozen leading climate scientists" as though to say "our team is bigger than yours so it must be right." In addition, the "leading climate scientists" represent the *paleo-climate group*.

The rebuttal claimed that regional anomalies cannot characterize global anomalies. However, global anomalies are merely statistical averages of regional anomalies. Since temperature anomalies vary widely with location and time, a good deal of information is lost by averaging over all data because variations tend to get averaged out. As long as we understand that periods like the MWP and the LIA were not continuous and were not uniformly distributed, examination of regional anomalies one at a time can build up a much better and incisive picture of climate change than a concocted single average global temperature. And from the regional studies we learn that while there were large spatial and temporal variations during the MWP and the LIA, the preponderance of the evidence suggests predominant warmth during the MWP and predominant cold during the LIA.

Myth #3 *The hockey stick studies claim that the 20th century on the whole is the warmest period of the past 1,000 years.*

The rebuttal claimed that "this is a mischaracterization of the actual scientific conclusions." It is claimed: "it is not the average 20th century warmth, but the magnitude of warming during the 20th century, and the level of warmth observed during the past few decades, which appear to be anomalous in a long-term context." However, this response does not jibe with statements made by alarmists.

1. Mann, Bradley, and Hughes (1999) said: "... our results suggest that the latter 20th century is anomalous in the context of the last century. The 1990s was the warmest decade and 1998 the warmest year at moderately high levels of confidence."
2. The IPCC Report said: "The 1990s are likely to have been the warmest decade of the millennium in the Northern Hemisphere and 1998 is likely to have been the warmest year."
3. Singer and Avery (2007) quote a number of alarmist claims from various sources.
   - "Nineteen ninety-nine was the most violent year in the modern history of weather. So was 1998. So was 1997. And 1996 ..."
   - "A nine-hundred-year-long cooling trend has been suddenly and decisively reversed in the past fifty years ... Scientists predicted that the Earth will shortly be warmer than it has been in millions of years."
   - "A climatological nightmare is upon us. It is almost certainly the most dangerous thing that has ever happened in our history."
   - "Climate extremes would trigger meteorological chaos-raging hurricanes such as we have never seen, capable of killing millions of people; uncommonly long, record-breaking heat waves; and profound drought that could drive Africa and the entire Indian subcontinent over the edge into mass starvation."

Myth #4 *Errors in the hockey stick undermine the conclusion that late 20th-century hemispheric warmth is anomalous.*

The realclimate.org response to this was: (1) the validity of the *hockey stick* is affirmed by the number of researchers who agree with it; (2) the correction (see Mann, Bradley, and Hughes, 2004) was not an admission of the criticisms of M&M, but only admitted to very minor data issues; (3) spurious allegations made by M&M are of no value because (a) M&M are not paleo-climate specialists, (b) their articles were not published in legitimate science journals, (c) as proof of their lack of veracity, their submitted article was rejected by *Nature*.

To this, I would reply that (1) the affirmations are by members of the *paleo-climate group* who are in league with one another; (2) it is agreed that Mann, Bradley, and Hughes (2004) was not responsive to the criticisms of M&M, more to the discredit of the *paleo-climate group*; (3a) the validity of the arguments by M&M do not depend on their field of endeavor—but rather their knowledge of PCA which appears to be better than that of the *paleo-climate group*; (3b) the validity of the articles does not depend on where they were or were not published (furthermore, this is a self-serving response because the *paleo-climate group* appear to have some say over the publication of manuscripts that criticize their methods); (3c) was it *Nature* that rejected the article or was it the reviewers for *Nature* who are members of the *paleo-climate group*?

There are a great many more articles on the realclimate.org website. It is not practical to review them all here.

2.4 CONCLUSIONS ON MILLENNIUM TEMPERATURE HISTORY

Scientists abhor a vacuum. They can't seem to shrug their shoulders and admit that we just don't know the answer to a vexing problem. They demand explanations, however speculative they may be. Thus, we have theories that have gelled into beliefs on how life started on Earth, how life begins from inanimate matter, how the universe began, and how the climate of the Earth varied over past millennia.

There is evidence that the Earth has been primarily in a warming trend during much of the 20th century, although there was a definite hiatus in this rise from 1945 to 1978 and the warming has neither been continuous nor universal. The 20th century also saw a steady rise in CO_2 concentrations in the atmosphere, due presumably to the burning of fossil fuels. Many scientists (and others) have legitimately become concerned that the greenhouse effect due to this CO_2 increase may be responsible for some or most of this observed rise in temperature, and if left unchecked, could possibly lead to disastrous consequences in the future. In principle, if a sufficiently good global climate model can be produced, the effect of CO_2 concentration on Earth temperature can be calculated. Unfortunately, there are so many variables and unknowns in the Earth system that such estimates can only be made as rough approximations. As in any detective story, if direct evidence is not available, one falls back on circumstantial evidence.

One central issue in this regard is a comparison of the observed temperature rises in the 20th century with estimated variations of temperature in the past millennium or so. If past temperature fluctuations were small compared with the temperature rise in the 20th century, it would suggest that the temperature rise in the 20th century is unique, unprecedented, and likely to be due to factors unique to the 20th century (e.g., greenhouse gases). On the other hand, if past fluctuations prior to industrialization were as large as, or greater than those observed in the 20th century, it might suggest that the temperature rise observed recently might just be another fluctuation such as has occurred in the past. While this argument is not ironclad in either direction, it does provide some valuable insights. Accordingly, the quest for better space–time resolution of historical temperatures has become an important part of the effort to understand the causes of global warming.

There have been a number of studies of historical temperatures conducted in the past, either based on anecdotal records, models of solar variability and climate responses to variable solar intensity, or more likely, based on proxies for past temperature such as tree rings, ice cores, etc. Although numerous papers have pointed out the confounding factors inherent in proxies, "in the land of the blind, a one-eyed man is king."[4] Therefore, despite the problems inherent in the use of proxies, many studies of proxies have abounded in the literature. Some of these fragmentary glimpses of the past have evoked a picture of significant variations in the past climate, with a notable warm period during medieval times, and a relatively cold period called the LIA from about 1400 to about 1850, depending on the criteria for selection.

[4] In modern terms, we may say: "It is the only game in town."

The first major global, synoptic, encompassing study of historical global average temperatures from proxies was the "MBH" study reported in 1998 (Mann, Bradley, and Hughes, 1998). This was an audacious effort, encompassing over 1,000 proxies, which provided an unprecedented breadth to the study of historical temperatures. To aid in processing all these data, a sophisticated statistical data-processing methodology (PCA)[5] was utilized. This was particularly remarkable because it was primarily the product of a Ph.D. dissertation by Michael Mann at the University of Massachusetts. This initial paper was followed by several more that extended the analysis further back into the past. The end result of these studies was a historical temperature profile that had the so-called *hockey stick* shape with a relatively flat profile for a thousand years or so, followed by a sudden sharp rise in the 20th century. These papers were compact, full of jargon, and difficult to follow. Sufficient data for others to make independent checks were typically difficult to obtain. Nevertheless, they were impressive papers and gave the impression of being ironclad. As a result of this work, Michael Mann was catapulted from a newly graduated Ph.D. to a position of fame and renown and almost instantly became recognized as a world leader in paleo-climatology.

An assemblage of scientists (and others), hungry for evidence of human-induced global warming, seized on the MBH results as a landmark. The *hockey stick* figure was reproduced and disseminated widely, being offered up as strong evidence of CO_2-induced global warming in the 20th century. The *hockey stick* was adopted by the Intergovernmental Panel on Climate Change of the U.N. (IPCC), Al Gore, and in general, most of the paleo-climatology science community. The claim was made that the warming in the 20th century was unprecedented, that the 1990s was the hottest decade on record, and 1998 was the hottest year in at least the past millennium or two.

About five years later, McIntyre and McKitrick (M&M) rained on the *hockey stick* picnic. These gentlemen were experts in manipulating large noisy data sets, which is just the problem faced in reconstructing the Earth's climate. In a series of papers and informal reports, they clearly showed that

1. MBH made an innocent-looking mistake in the principal components analysis by standardizing with a mean based only on the calibration period, instead of a mean based on the entire time period covered by the data. As it turns out, this led to a chain of events that placed undue emphasis on a few highly suspect proxies that produced the *hockey stick* result.
2. Use of certain tree-ring data by MBH was unjustified because much of the observed growth in the 20th century was due to CO_2 fertilization and other factors, rather than a rise in temperature.
3. When a proper recalculation of the MBH data is performed, the result shows that although there was indeed a significant temperature increase in the 20th century, there were comparable high temperatures earlier in the millennium.

[5] Also known as "empirical orthogonal functions" (EOFs).

Thus, the bases for the claim that the 20th century exhibited an unprecedented temperature rise, and that the 1990s and 1998 were the hottest in a millennium or two, were undermined.

The responses to the findings of M&M are interesting. Instead of issuing a *mea culpa* and going on from there, Mann dug in his heels and *protected turf from truth*. He issued a response to the M&M charges that is a masterpiece of evasion and obfuscation. Most of the paleo-climatology community, which by and large adopted the *hockey stick* as its motif, cooperated by controlling which papers get published in the journals. In general, the U.N., Al Gore, and the climatological alarmists have simply ignored M&M and continued to vouchsafe the *hockey stick*, pretending that the criticism of M&M did not exist.[6] For those who are determined to raise the alarm to the world on the dangers of global warming, the *hockey stick* is too valuable as a public message to allow truth to interfere.

Further studies have shown that while in principle, one should standardize across the whole data set, in practice this may not be practical because the true data are not known except during the calibration period. If one standardizes against the calibration period, noisy data produce a *hockey stick* result if the data are rising during the calibration period. This raises questions about the reliability and utility of assembling proxy data into a global average temperature. Since the temperature was rising during the 20th century, use of 20th century data for calibration or proxies can lead to misleading results. Use of PCA can exacerbate this problem.

Anon. (N) presented a very detailed and generally objective review of surface temperature reconstructions for the past two millennia. Their conclusions are summarized below:

- "The instrumentally measured warming of about 0.6°C during the 20th century is also reflected in various proxy measurements."
- "Large-scale surface temperature reconstructions yield a generally consistent picture of temperature trends during the preceding millennium, including relatively warm conditions centered near 1000 (identified by some as the *Medieval Warm Period*) and a relatively cold period (or *Little Ice Age*) centered near 1700. The existence of a *Little Ice Age* from roughly 1500 to 1850 is supported by a wide variety of evidence including ice cores, tree rings, borehole temperatures, glacier length records, and historical documents. Evidence for regional warmth during medieval times can be found in a diverse but more limited set of records including ice cores, tree rings, marine sediments, and historical sources from Europe and Asia, but the exact timing and duration of warm periods may have varied from region to region, and the magnitude and geographic extent of the warmth are uncertain."
- "It can be said with a high level of confidence that global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries. This statement is

[6] Think of *The Emperor's New Clothes*.

justified by the consistency of the evidence from a wide variety of geographically diverse proxies."[7]

- "Less confidence can be placed in large-scale surface temperature reconstructions for the period from 900 to 1600. Presently available proxy evidence indicates that temperatures at many—but not all—individual locations were higher during the past 25 years than during any period of comparable length since 900. The uncertainties associated with reconstructing hemispheric mean or global mean temperatures from these data increase substantially backward in time through this period and are not yet fully quantified."[8]
- "Very little confidence can be assigned to statements concerning the hemispheric mean or global mean surface temperature prior to about 900 because of sparse data coverage and because the uncertainties associated with proxy data and the methods used to analyze and combine them are larger than during more recent time periods."[9]

[7] This statement reflects a generally prevailing implicit view that "the preceding four centuries" were *normal*, while the relatively higher temperatures at the end of the 20th century are comparatively *abnormal*. However, the preceding four centuries extend across the LIA, and therefore one might state the proposition differently: *Temperatures during the preceding four centuries were colder than they were at the end of the 20th century*.

[8] This author cannot find any substantial evidence that temperatures were (as claimed) generally higher in the past 25 years than they were in 900.

[9] This author has very little confidence in estimates of temperature prior to 1600.

3

Temperatures in the past century

3.1 NEAR-SURFACE MEASUREMENTS

3.1.1 Meteorological data sets

Data on near-surface air temperatures are available at a number of sites dating back about 100 years in some cases. Meteorological scientists have methodically examined these data and derived the best overall data sets that the data allow (Hansen *et al.*, 1999, 2001; Pielke *et al.*, 2007a; CCSP, 2005; and Brohan *et al.*, 2006). NASA's Goddard Institute for Space Studies (GISS), under leadership of James Hansen, has analyzed U.S. and world temperature patterns since about 1880 in great detail (Hansen *et al.*, 1999, 2001; Brohan *et al.*, 2006). Studies of temperature change over land areas are routinely made by several groups based on measurements of the meteorological station network. It is beneficial to estimate global temperature change from both the meteorological station data alone, and a combined analysis with ocean data, because the land and ocean data have their own measurement characteristics and uncertainties.

Hansen *et al.* (1999, 2001) limited their studies primarily to the period since 1880, because of the poor spatial coverage of stations prior to that time and the reduced possibility of checking records against those of nearby neighbors. Analyses for the earlier years need to be carried out on a station-by-station basis with an attempt to discern the method and reliability of measurements at each station. Global studies of the earlier times depend on incorporation of proxy measures of temperature change. Data collected and recorded by thousands of individuals with equipment and procedures subject to change over time inevitably contain many errors and inconsistencies, some of which will be impossible to identify and correct. However, Hansen *et al.* (1999, 2001) believe that the influence of errors is not dominant, because many of the errors in recording temperature are believed to be random in nature. Nevertheless, Hansen *et al.* (1999, 2001) have examined the data quality to try to minimize local errors and obtain an indication of the nature and magnitude of any artificial sources of temperature change. The various records at any location were combined into a single record for that location. Regional and global temperatures were estimated by combining local temperature records. Homogeneity adjustments were made to local time series of temperature with the aim of removing non-climatic variations in the temperature record. The non-climatic factors include changes of the environment of the station, the instrument or its location, observing practices, and the method used to calculate the mean temperature. Quantitative knowledge of these factors is not available in most cases, so it is impossible to fully correct for them. It is hoped that the random component of such errors will average out in large area averages and in calculations of temperature change over long periods. Sections 3.1.2 and 3.2.5 provide a more detailed review of the adequacy of temperature measurement networks.

The non-random inhomogeneity of most concern in surface temperature measurements is anthropogenic influence on the air sampled by near-surface thermometers. Urban heat can produce a large local bias toward warming as cities are built up and energy use increases. In studying the history of air temperature variations, it is preferable to avoid major population centers because these generate large amounts of heat locally and independently of putative global warming effects. Thus, the appropriate graph for New York City (Central Park) (Figure 3.1, see color section) shows a pronounced warming in the 20th century.

Much (or even most) of this can be attributed to heat generated locally by human activity, rather than by global changes. This is evidenced by comparing the New York City data with data for a rural area in New York State, as shown in the same figure. Prior to ~1900, the two curves are similar, but the New York City data increasingly diverge from the West Point, NY data as the 20th century progresses. Anthropogenic effects can also cause a non-climatic cooling; for example, as a result of land clearing, irrigation, and planting of vegetation in large farming areas.

Corrections for urban heating are typically made by comparing urban areas with nearby rural areas and imposing trends from rural areas on the urban areas. Figure 3.2 shows the raw measured temperature data for Tokyo, Japan in the upper panel. The middle panel shows the adjustment based on nearby rural areas. The lower panel compares the adjusted Tokyo temperature profile with that of nearby rural neighbors. Examples such as Tokyo illustrate that urban effects on temperature in specific cases can dominate over real climate trends. However, Hansen *et al.* (1999) claim that there are far more rural stations than urban stations, so it is not essential to employ the urban data in analyses of global temperature change. They included adjusted urban station data in their standard analysis primarily for the sake of the last few years of the record, especially the final year. The fraction of reporting stations that are urban jumped from about one-quarter to one-third in the mid-1990s and to about one-half in the final year of the record. It is not clear to what extent this procedure amplified global warming trends near the end of the 20th century. The problem of correcting for urban heating remains as a source of concern (see Section 5.2.5).

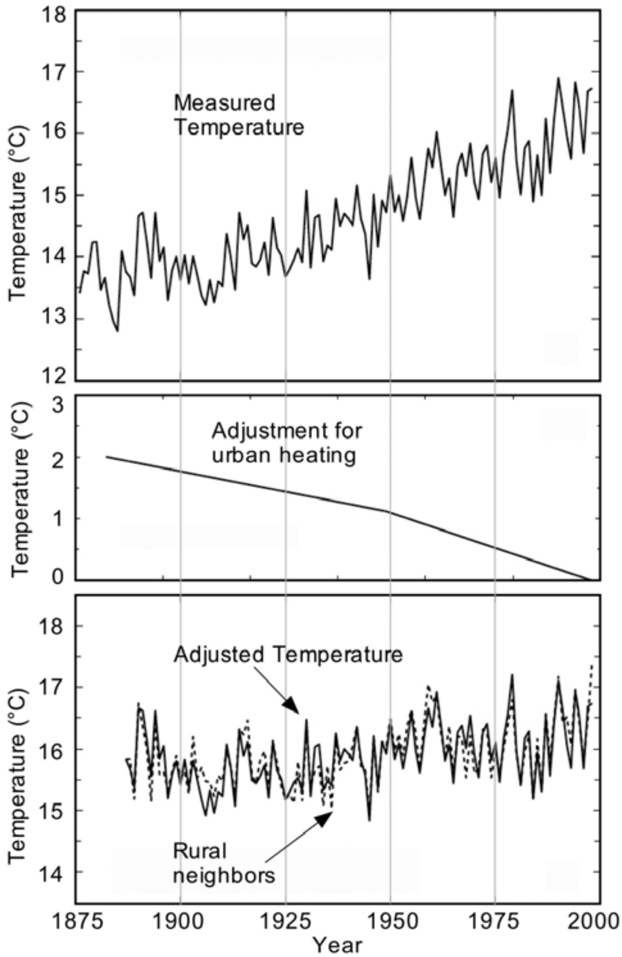

Figure 3.2. Adjustment of raw temperature data at Tokyo, Japan for urban heating. The upper panel is raw temperature data. The middle panel is adjustment for urban heating obtained by comparing Tokyo data with data for rural surroundings. The lower panel is Tokyo data after adjustment. Adapted from Hansen *et al.* (1999).

About 70% of the Earth's surface is covered by ocean. Sea temperatures play an important role in arriving at a global average temperature. In this connection, Soon and Baliunas (2003a, b) pointed out:

"The sea surface temperature (SST) record also is complicated by a change in procedure. Prior to the 1940s, SST was determined by measuring the temperature of a dunked bucket of seawater with a thermometer. After the 1940s, SST was taken by measuring the temperature of the seawater at the intake to the engine cooling system. Large adjustments had to be made to the older data to make

> it compatible with the new data. These adjustment affected average SST by 0.1–0.45°C; the upper end of this range is three quarters of the observed change in global average surface temperature for the 20th century. Problems with defining a global-scale mean climatology for SST still exist ... as late as 1961–1990."

Houghton (2004) echoed this:

> "In the case of ships, the standard method of observation used to be to insert a thermometer into a bucket of water taken from the sea. Small changes of temperature have been shown to occur during this process; the size of the changes varies between day and night and is also dependent on several other factors including the material from which the bucket is made—over the years wooden, canvas and metal buckets have been variously employed. Nowadays, a large proportion of the observations are made by measuring the temperature of the water entering the engine cooling system."

Nevertheless, Brohan *et al.* (2006) concluded that uncertainties in sea surface temperatures are lower than for land surface temperatures (see Section 3.2.5).

In addition to the near-surface data taken at Earth stations, there are also data taken by remote sensing from orbit that measure troposphere and stratosphere temperatures (see Section 3.2.6).

3.1.2 Problems with temperature data

Although the various teams who developed Earth temperature data have expressed confidence in their derived data sets (Hansen *et al.*, 2001; CCSP, 2005; Brohan *et al.*, 2006), a number of difficulties have been identified by critics (e.g., Pielke *et al.*, 2007a, c; Hoyt, 2006; Ball, 2007; Davey and Pielke, 2005). Pielke *et al.* (2007c) concluded: "The use of temperature data from poorly sited stations can lead to a false sense of confidence in the robustness of multi-decadal surface air temperature trend assessments." They suggested that there are problems in the existing temperature databases due to: (1) time-of-observation bias because, at many sites, the observing time has changed during the station's history, (2) changes in instrumentation at stations, (3) station moves or relocations, and (4) bias caused by station urbanization. In addition, three primary issues were identified relevant to

> "... land use/land clearing (LULC) and changes in LULC related to placement of climate stations. First, a station may be initially placed in what might be considered a poor LULC environment (e.g., near a highway or other man-made environment that could influence the observed temperature based on day of week, holiday, etc.). Second, a station may have been initially located at what might be considered a good LULC environment only to have that environment change over time. And third, possibly due to one of the above situations, a station may be moved from one LULC environment to another."

Pielke *et al.* (2007a) discussed unresolved issues in using surface temperature trends as a metric for assessing global and regional climate change. The issues include warm bias in night-time minimum temperatures, poor siting of the instrumentation, effect of winds, effects of surface atmospheric water vapor content on temperature trends, uncertainties in the homogenization of surface temperature data, and influence of land-use/land-clearing (LULC) change on surface temperature trends.

The observed average surface temperature at any site over land is computed by averaging observed daily maximum and minimum temperatures. While the daily maximum may be accurate, Pielke *et al.* (2007a) claim that the nightly minimum temperature (typically about 1.5 m to 2 m above the land) is subject to variation, depending on surface characteristics (heat capacity) and wind speed.

> "As the boundary layer cools at night under light winds, the greatest decrease in temperature occurs near the surface. Unlike the daytime boundary layer where convective turbulence tends to reduce vertical gradients, in the nocturnal boundary layer the cooling suppresses turbulence and enhances vertical gradients. Thus, the vertical variation in temperature in light winds can be huge with temperature changes of 6°C or more often occurring within 25 vertical meters of the surface. This is why great care must be taken to avoid contaminating the climate record with measurements from sites that have changed even a meter or two in their height of observation."

Davey and Pielke (2005) conducted a study of temperature measurement stations in Eastern Colorado.

> "It is important to know the site of stations relative to various structures and surfaces. Generally, near-surface air temperature observations should be representative of the free-air conditions over as much of the vicinity as possible, at a height approximately 1.5 m above the ground. The site should be level, without locally significant topographical variations or steep slopes or hollows, and should offer free exposure to both sunshine and wind (not too close to trees, buildings, or other obstructions). It thus becomes critical to conclusively determine how much of any potential regional change in observed air temperatures might be due to land-use changes at the site itself. These changes may include local-scale urban development around the site, changes in local vegetation characteristics, etc."

Local-scale exposure characteristics are therefore important in evaluating station data. Prior to the 1980s, a site sketch was available, illustrating the location of the weather station instrumentation and any nearby obstructions. Currently, however, only vague documentation regarding site exposure characteristics is typically available. This is particularly true for sites' terrain and surface features. Davey and Pielke (2005) visited 57 sites in Eastern Colorado, with emphasis on the 10 sites in the U.S. Historical Climate Network (USHCN). Typical findings were (1) sensors close to buildings, (2) sensors over patchworks of different land coverings, (3) vegetation around sensor locations, or urbanized sensor locations. Evidently, the temperature measurement network needs refurbishment.

The temperature measurements that we require are for the purpose of defining the global climate. If a significant portion of measurement sites are located near local "hot spots" in the form of urban heating islands (UHIs) the data can be very misleading, particularly because urbanization has increased with time, and that would produce an artificial apparent increase in global temperature. On the other hand, if urbanization becomes so widespread with the growing world population, that urban heat islands become the norm—rather than the exception—then inclusion of UHI sites may become appropriate in defining the climate. However, in that case, a significant part of global warming would be induced by urban and industrial activity. It is possible that we are approaching that point in some regions of the Earth.

In general, the effect of UHIs is to slightly decrease the daily maximum temperature (due to a variety of factors: reflection from buildings, shading, etc.) and to significantly increase the nightly minimum temperatures as stored solar energy (in concrete and structures) is released overnight. Thus, urbanization is expected to reduce the diurnal temperature range (DTR) as well as to increase the average temperature. For example, in the urban heat island of Houston, Texas between 1990 and 2000, the relative increase in air temperature had an average magnitude of 1.25°C at night but was largely absent during the day. The urban heat island had an area of about 1,000 km^2 (Streutker, 2003). Other studies report temperature increases in city centers of several degrees, with contours of decreasing temperature toward the suburbs.

Hoyt (2006) discussed the differences between urban sites and rural sites. It is claimed that those who support the IPCC viewpoint consider a town with a population of less than 10,000 people to be rural and not to require any adjustment for urbanization. But according to Hoyt (2006), quoting a 1973 paper by Oke, the temperature increase of an urban center compared with its surroundings is approximated as 0.73 log(population), so that even a town of 1,000 people has an urban temperature rise of 2.2°C.

Corrections for urbanization are especially difficult in China, where rapid growth has changed the demographics at a very rapid rate. From 1978 to 2000, China's gross domestic product grew at an average annual rate of 9.5%, compared with 2.5% for developed countries and 5% for developing countries; the number of small towns soared from 2,176 to 20,312, the number of cities increased from 190 to 663; and the proportion of urban population rose from 18% to 39%.

Using rural–urban temperature differences to estimate the impacts of urbanization on climate in China may be inappropriate for several reasons.

1. Most Chinese stations are located in or near cities, with only a few in mountainous or remote regions or on small islands.
2. Although China is comparable in size with the U.S., it has considerably fewer meteorological stations, and each city generally has only one station. For example, each of China's two biggest cities, Beijing and Shanghai, has only one station available in the Chinese network.

3. It is impossible to find a corresponding rural station for most of the urban ones, especially in eastern and southern China.
4. China's rapid urbanization in the past two decades could transfer a station from rural into urban in a very short period.
5. Chinese cities have a much higher density of population and urban buildings than do cities in most developed countries (Zhou *et al.*, 2004).

Further discussion of urban heat islands is given in Sections 3.2.5 and 5.2.5.

3.1.3 Deviations from the mean

In most cases, plots of temperature over long time periods show considerable short-term fluctuations, and it is difficult to readily perceive the underlying trends. Therefore, it is common practice to calculate the mean temperature for the period in question $\langle T \rangle$, and deal with the deviations of the temperature measurements from this mean. These deviations are usually called "anomalies" where the ith anomaly is $A_i = T_i - \langle T \rangle$, and T_i is the ith temperature measurement. The anomalies can be further refined by measuring them in units of the standard deviation

$$SD = \frac{\sqrt{\sum_i (T_i - \langle T \rangle)^2}}{(N-1)}.$$

This makes it easier to compare different sets of measurements. Figure 3.3 illustrates a partial temperature history for LaGuardia Airport. The lower panel shows seasonal

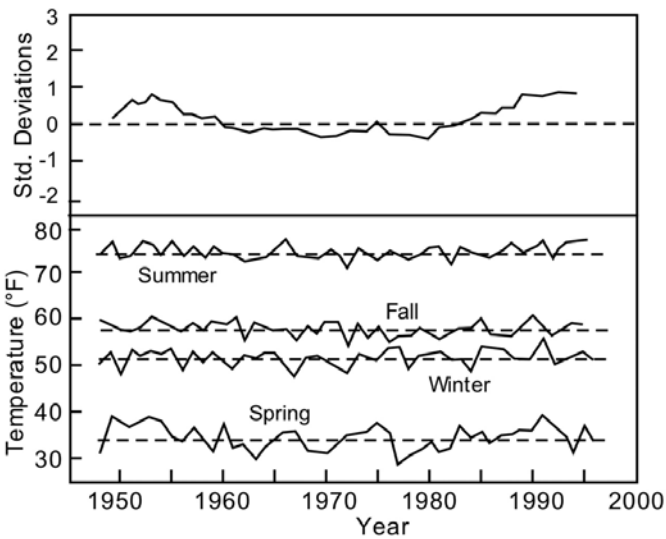

Figure 3.3. Temperatures at LaGuardia Airport (New York City). Lower panel is temperature. Upper panel is deviation from the mean in units of standard deviation. Adapted from Hansen *et al.* (1998).

temperature patterns. It is difficult to discern any trends. The upper panel shows the anomalies from the mean (for all seasons) in units of the standard deviation, from which trends are more readily determined.

In examining long-term temperature data, whether directly measured, or estimated from proxies, we are typically most interested in the trends that are buried in the data. These trends are often obscured by short-term variability. As described above, the simplest (and often most revealing) procedure is to calculate the anomalies about the mean for the data set.

3.1.4 Utility of a single global temperature

Almost all studies of global climate change deal primarily with a single global average temperature, or a single hemispheric average temperature. Global warming is expressed as a rise in such a putative temperature.

However, some have questioned whether the concept of a single average global or hemispheric temperature has much utility. At any single location, temperatures typically vary widely during a single day. Temperatures fluctuate from day to day and averages change significantly from season to season. Surface temperatures vary widely between the tropics and polar regions, and between lowlands and mountains. Additionally, the range of temperatures experienced at any location over the course of a day, a season, a year, or decades is typically very large. A lowland tropical region experiences far less difference in temperature over the course of a year than does a highland temperate region. Determining the year-to-year temperature change in one location does not indicate how temperature varies in a region with a variable geography.

From an operational point of view, the procedures by which one combines data from hundreds or thousands of meteorological sites, corrects for urban heating and other aberrations, takes into account the oceans, accommodates differing densities of stations with geography, and thereby arrives at a global or hemispheric average temperature, are complex (Hansen *et al.*, 2001; Pielke *et al.*, 2007a; CCSP, 2005; Brohan *et al.*, 2006).

One problem with attempting to deal with a single average global or hemispheric temperature is that most of the regional variations tend to cancel out, and one ends up with only small apparent net changes. One can place these changes under a magnifying glass and derive great concern from a global variation of a few tenths of a degree, but the utility of that concept seems to be limited. When the writer lived in Texas, if a cold front moved through, the temperature could drop by 25°C in one hour. Summer temperatures were over 40°C and winter temperatures dipped below freezing. There is no utility to a Texan in knowing that global temperatures changed by, say, 0.3°C. Understanding how the climate of the Earth has varied with time, and how the Earth responds to changes in the Sun as well as to man-made effluents and activities, requires a more regional approach, as discussed in Soon and Baliunas

(2003a, b). The changes in global average temperature don't even begin to describe the regional and local hardships and problems that derive from climate change.

A single global temperature does not reveal the regional variations, the seasonal variations in different regions, or the day/night variability. If the putative global temperature rises, is that due to warmer days or nights, and how does it depend on season?

As difficult as the problem is for defining a single global or hemispheric temperature based on current measurements, the problem is far more difficult in combining proxies to arrive at historical average temperatures. The problems in defining historical global average temperatures from proxies include

1. Large uncertainty in proxy signals
2. Large differences between results of different proxies
3. Large differences from model to model for the same proxies
4. Obscuration of temperature effects from interference by other variables.

It appears that proxies, by their nature, are so loaded with noise and uncertainty that the data merely produce a blurry result. Considering the noise inherent in such measurements, and the lack of spatial and temporal coverage, no historical global average temperature estimate is very precise (see Section 3.2.5).

Essex, McKitrick, and Andresen (2007) carried out a mathematical analysis of various attempts to derive a single global average temperature. It was concluded that while it is possible to construct statistical averages for any given set of local temperature data, the calculated average can vary widely depending on how the average is constructed. In some cases, averaging can actually produce opposite trends (warming vs. cooling) depending on how the averages are prepared. From a more fundamental point of view, the definition of "temperature" requires a system in thermodynamic equilibrium. Essex, McKitrick, and Andresen (2007) have emphasized that an average of measurements sampled from a non-equilibrium field is not a temperature and that the Earth does not have just one temperature. It is not in global thermodynamic equilibrium, neither within itself nor with its surroundings.

Despite the fact that a single global average of measured temperatures is not a temperature in the *thermodynamic* sense, the concept could nevertheless have utility as an indicator of trends if the elements being averaged were not so widely disparate in magnitude. It would appear that there is much more utility in describing average temperatures over regions (e.g., Western Europe) than in trying to define a single global average temperature.

Even if one could convince oneself that the concept of a single global average temperature had utility, its magnitude would be dependent on averaging a worldwide network of temperature measurements. However, the adequacy of the worldwide temperature measurement network leaves much to be desired, as discussed at length in Section 3.2.5.

3.2 MEASURED EARTH, REGIONAL, AND LOCAL TEMPERATURES

3.2.1 U.S. temperature measurements

NASA's Goddard Institute for Space Studies (GISS) has analyzed U.S. and world temperature patterns since about 1880 in great detail. Global temperatures were estimated based on rural, small-town, and homogeneity-adjusted urban stations (Hansen *et al.*, 1999). Hansen *et al.* (2001) modified the previous work from Hansen *et al.* (1999) by improving on the corrections applied to urban stations using satellite photos of Earth at night to determine areas of high power density from lighting observations, as well as a number of other corrections to the database. It is claimed that local human effects (urban warming) can be important even in suburban and small-town surface air temperature records. They said: "We believe that this evidence is suggestive of a significant urban effect within the United States, but it requires further investigation." Their final estimate for the U.S. mean temperature history (after making adjustments) is shown in Figure 3.4. The results for the U.S. show some warming early in the 20th century, followed by a cooling trend after about 1940, and a subsequent return to warming after around 1978. Based on U.S. data alone, there has been warming in the 20th century, but there is no evidence of insidious, unprecedented, irreversible warming. Within the U.S. there has been a tendency for the southeast to grow cooler and the remainder of the country to grow warmer in the 20th century. However, there was a significant dip from ∼1940 to ∼1978.

3.2.2 Global and hemispheric temperatures

GISS (2007) also estimated the global temperature change by dividing the world into broad latitude zones, estimating temperature anomaly time series for each zone, and

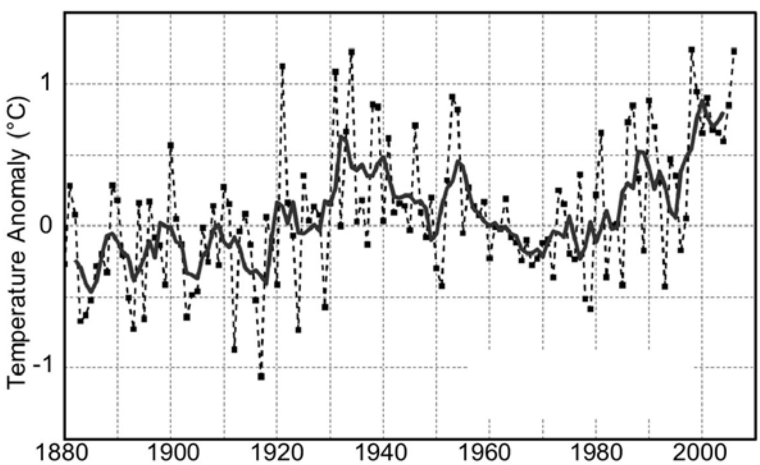

Figure 3.4. U.S. mean temperature anomalies (deviations from mean temperature). Points are yearly averages and the heavy line is a five-year moving average. Adapted from GISS (2007).

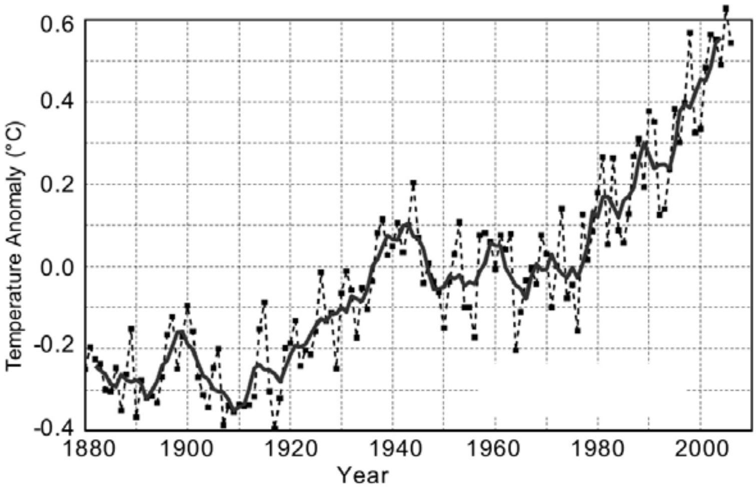

Figure 3.5. Global mean temperature anomalies (deviations from mean temperature) based on a combination of land and ocean data. Points are yearly averages and the heavy line is a five-year moving average. Adapted from GISS (2007).

then weighting these zones by their area. The zones included were: northern latitudes (90°N–23.6°N), low latitudes (23.6°N–23.6°S), and southern latitudes (23.6°S–90°S), covering 30%, 40%, and 30% of the Earth's surface, respectively.

On a global scale, the temperature history is shown in Figures 3.5 and 3.6. Here, there is greater evidence of strong global warming since 1976. However, it is not clear

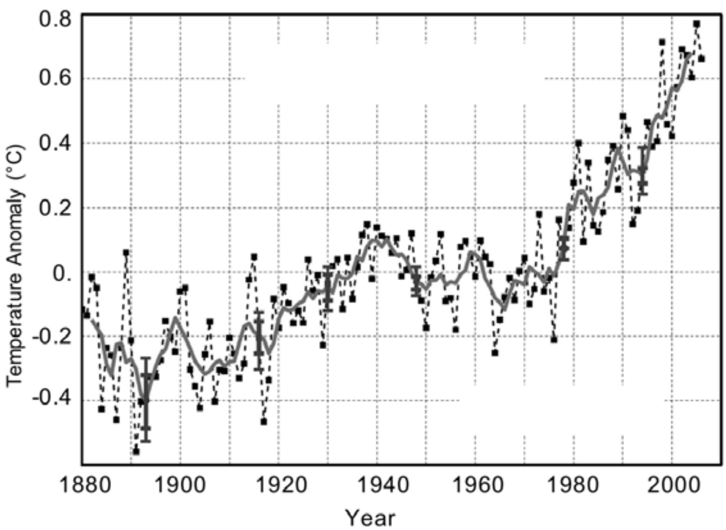

Figure 3.6. Global mean temperature anomalies (deviations from mean temperature) based only on land-based meteorological stations. Points are yearly averages and the heavy line is a five-year moving average. Adapted from GISS (2007).

how reliable the data are for the globe, and whether sufficient accounting has been taken of oceans (70% of Earth area), urban heating, and sparseness of stations. Houghton (2004) claimed that all of this has been mitigated:

> "Careful analysis of the effects of these details on observations both on land and from ships has enabled appropriate corrections to be made to the record, and good agreement has been achieved between analyses carried out at different centers."

Brohan *et al.* (2006) apparently believes that sea surface temperature records are in good shape, but sea temperatures appear to this writer to remain a source of uncertainty. The 20th-century history of temperature rises in the northern and southern hemispheres is shown in Figure 3.7 (color section). Temperature fluctuations in the north were greater than in the south. Three factors that could possibly affect these data are (1) much higher density of stations in the north, and (2) greater concentration of urban warming in the north, and (3) there is a much higher preponderance of oceans in the Southern Hemisphere.

Barnett *et al.* (2005) examined the variation of ocean temperatures over the past 40 years, on an ocean-by-ocean basis, focusing on how the temperature varies with depth. All of the major oceans have undergone heating of typically 0.2°C to 0.3°C in the upper ~75 m of depth, with little heating and some cooling at depths below 125 m. These data suggest that the upper oceans are being heated from above. The authors concluded that this temperature rise was not due to solar and volcanic forcing. They showed that GCMs would predict similar behavior and concluded that the source of ocean heating is anthropogenically produced greenhouse gases. However, this conclusion is not unique. Ocean temperatures rose during a time period when CO_2 was increasing. Increased CO_2 could be the cause of ocean warming, or it could be an effect of ocean warming.

The global temperature record for the most recent decade (1997–2006) is shown in Figure 3.8. Temperatures during this period appear to have stabilized. There is no evidence of a continuation of the sharp run-up from 1980 to 1997.

The variation in 20th-century global temperatures partitioned by latitude ranges (with roughly equal surface area) is shown in Figure 3.9. It can be seen that the greatest observed temperature rise in the 20th century has been north of 23.6°. This might be influenced by the density of stations in the north coupled to urban warming and other local human urbanization effects. In any event, a good deal of the observed recent global warming has been concentrated in the northern hemisphere.

Figure 3.10 shows global temperature anomalies as a function of latitude and time period. For the 20th century, the upper-left panel shows a moderate but consistent temperature rise. From 1900 to 1940 (upper-right panel) there was a rather drastic increase in temperature at high northern latitudes. This was followed by a decrease in temperature at high northern latitudes from 1940 to 1965 (lower-left panel). Temperatures across the globe elsewhere than north of 60°N were quite stable from 1900 to 1965. Temperatures increased globally after 1965 with the greatest increases at high northern latitudes (lower-right panel).

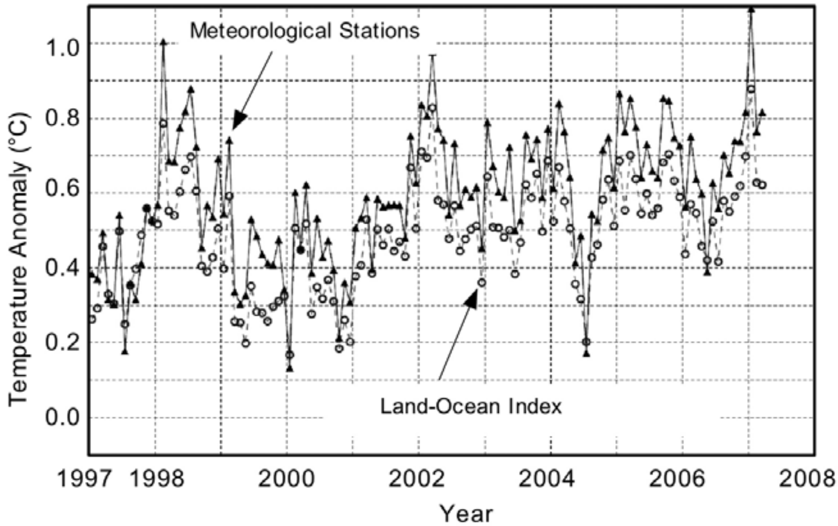

Figure 3.8. Global mean temperature anomalies (deviations from mean temperature) from 1997 to 2006 on a monthly basis. Adapted from GISS (2007).

It is not clear why there is such a significant difference between the histories of U.S. and global temperatures since 1880. Considering that the database for the U.S. appears to be more complete, presumably better corrected for urban heating, and independent of ocean temperatures (100% on land), it seems likely that the U.S. history is more reliable.

One notable feature of all the global temperature measurements of the 20th century is the fact that the temperature rise of the 20th century was divided into two steps (from 1910 to 1940 and from 1978 to 2000) with an intermediate period (roughly 1940–1978) in which temperatures actually decreased slightly. Considering that CO_2 emissions from 1910 to 1940 were far less than that needed to account for the observed temperature rise, and that the intermediate period (1940–1978) had decreasing temperatures while CO_2 emissions increased significantly, the correlation of the temperature rise of the 20th century with greenhouse gas emissions is less than satisfactory.

These facts were seized on by naysayers as evidence of the inadequacy of global climate models. However, several studies concluded that sulfate aerosols and particulates reflect incident sunlight, producing a cooling effect. The global warming alarmists then claimed that the cooling observed from 1940 to 1978 was due to an increase in aerosol production that overwhelmed the greenhouse effect, but that clean-up of power plants starting around 1980 reduced aerosol production after that. This claim was challenged, and there remains a controversy regarding yearly production rates of aerosols and the impact of aerosols on global temperatures in the mid to late 20th century. It is difficult to resolve this important issue at this time (see Section 3.2.4).

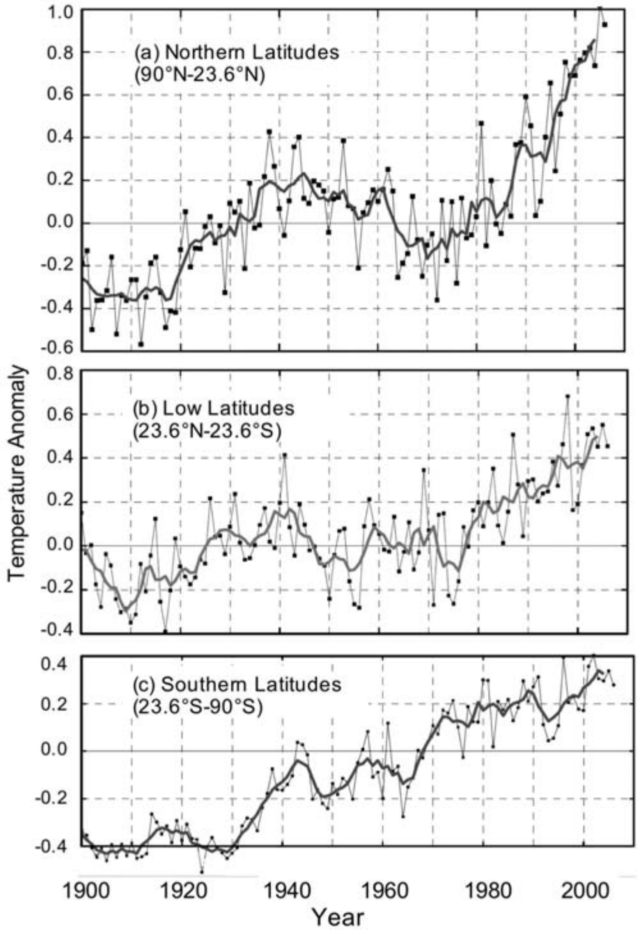

Figure 3.9. Global temperature anomalies for three latitude ranges with roughly equal surface areas. Adapted from GISS (2007).

3.2.3 Antarctic and Arctic temperatures

Taylor (2006) pointed out that high-latitude regions of the Earth (the Arctic and Antarctic) have been considered as bellwethers in the detection of global climate change. According to IPCC (2001):

> "Climate change in polar regions is expected to be among the largest and most rapid of any region on the Earth, and will cause major physical, ecological, sociological, and economic impacts, especially in the Arctic, Antarctic Peninsula, and Southern Ocean. Polar regions contain important drivers of climate change. Once triggered, they may continue for centuries, long after greenhouse gas concentrations are stabilized, and cause irreversible impacts on ice sheets, global ocean circulation, and sea-level rise."

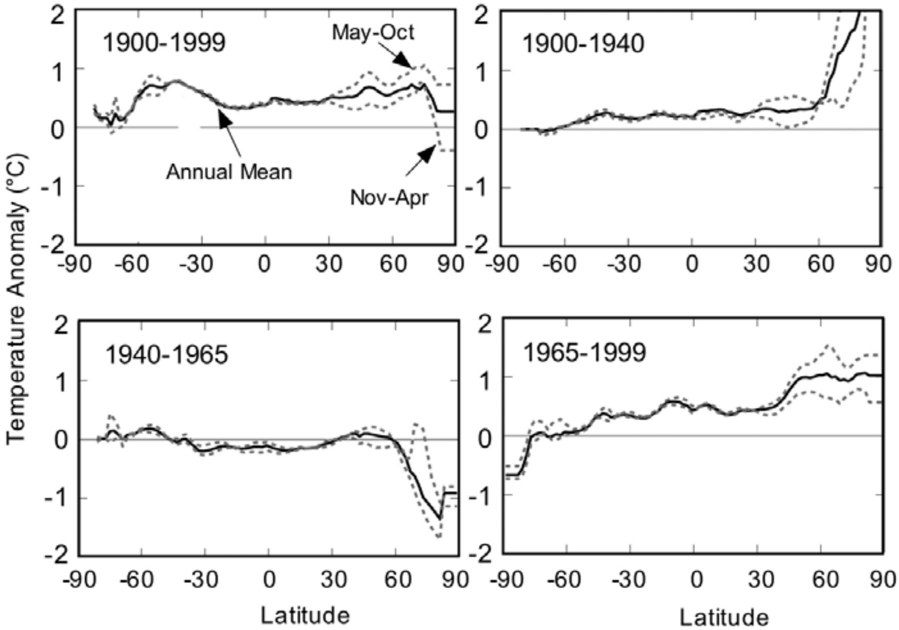

Figure 3.10. Mean temperature anomalies (deviations from mean temperature over a designated time period) as a function of latitude and time period. Adapted from Hansen *et al.* (2001).

As Taylor (2006) said:

> "Global climate models (GCMs) suggest that polar-regions should warm more quickly than temperate or tropical regions because the cold temperatures cause the air to be very dry. The low amounts of water vapor, the most important greenhouse gas, causes the relative effects of other gases, notably carbon dioxide (CO_2), to be greater. Thus climate change caused by an increase in the latter should be most evident in the polar-regions."

However, the data do not support this contention.

On the other hand, Bindschadler (2006) said:

> "Several large tidewater outlet glaciers of the Greenland and Antarctic ice sheets now appear to exhibit a nearly universal signature of recent increased discharge to the ocean. That this increase is occurring in the Northern and Southern hemispheres suggests a common cause. The culprit may be additional heat delivered by subsurface waters melting the submarine bases of these glaciers. This scenario would explain the observations and at the same time provide evidence that warmer subsurface waters are reaching the Earth's polar latitudes. Moreover, it indicates that the ocean plays a more critical role than the atmosphere in determining near-term glaciological contributions to changes in sea level."

3.2.3.1 Antarctic temperatures

Taylor (2006) presented temperature data for several Antarctic sites. One typical example is shown in Figure 3.11. There is little evidence of a temperature rise over this (40+) year period.

Taylor (2006) concluded:

> "The data clearly show that Antarctica as a whole is seeing increases in sea ice extent in recent decades, in spite of what climate models suggest should be occurring: steady warming. There are regional differences, with Weddell Sea ice extent decreasing and Ross Sea ice increasing, but overall the pattern is clear: there is more ice, not less, surrounding Antarctica."

It is interesting that George Taylor describes himself as the "Oregon State Climatologist". This set off quite a number of comments on blogs by climate alarmists that roundly attacked Mr. Taylor on claims that there is no such position. These can be found by inserting *George Taylor* into *Google Search*. It seems likely that his actual position is Climatologist at the Oregon State University, whatever that means. But what is most interesting of all is that the attacks on Mr. Taylor generally do not confront his technical findings, but rather his claimed title.

In discussing the Antarctic *continent*, it is important to distinguish between the Antarctic *peninsula*, which projects to lower latitudes, and has a low elevation, vs. the Antarctic *continent* that lies at higher latitudes and higher elevations (see Figure 3.12). Most of the climatological measurement sites are located around the continent on the coast. Only two are inland.

According to Doran *et al.* (2002), the average air temperature at the Earth's surface has increased by ~0.06°C per decade during the 20th century, and by ~0.19°C per decade from 1979 to 1998. Doran *et al.* (2002) said that models tend to indicate amplified warming in polar regions, as observed in Antarctica's *peninsula* region over the second half of the 20th century. Although previous reports suggested

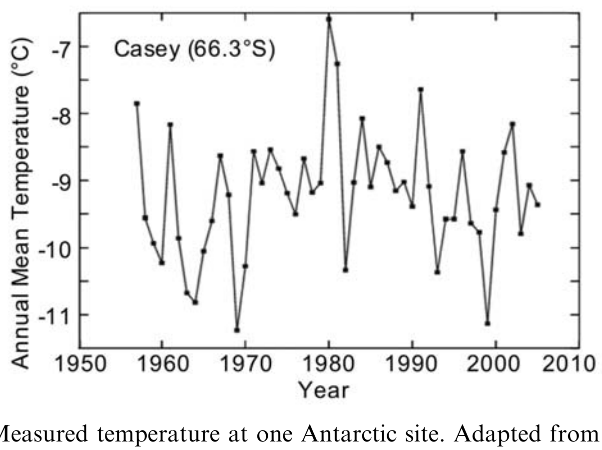

Figure 3.11. Measured temperature at one Antarctic site. Adapted from Taylor (2006).

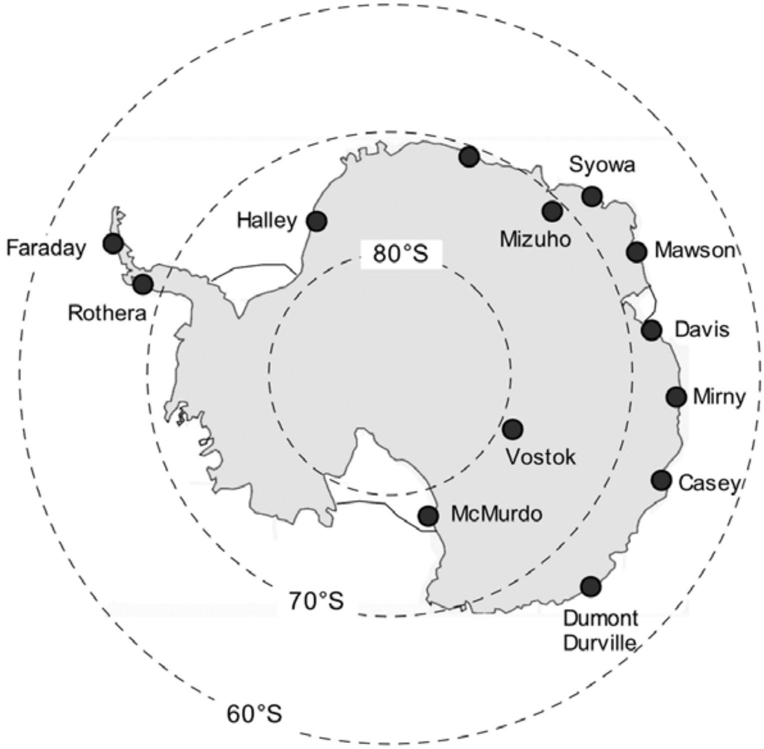

Figure 3.12. Stations in Antarctica. Adapted from Turner *et al.* (2005).

slight recent continental warming, Doran *et al.* (2002) found a net cooling on the Antarctic *continent* between 1966 and 2000, particularly during summer and autumn. They pointed out that although a previous study had found a warming trend from 1958 to 1978, this seems to have reversed itself after 1978. Doran *et al.* (2002) concluded: "Continental Antarctic cooling, especially the seasonality of cooling, poses challenges to models of climate and ecosystem change."

Turner *et al.* (2005) analyzed 19 long-term stations over the Antarctic continent. The peninsula has experienced a major warming over the last 50 years. The warming at low elevations on the western coast of the Antarctic peninsula was described as being "as large as any increase observed on Earth over the last 50 years, which at the Faraday (now Vernadsky) station amounted to about 2.5°C." However, Turner *et al.* (2005) said: "the region of marked warming is quite limited and is restricted to an arc from the southwestern part of the peninsula, through Faraday to a little beyond the tip of the peninsula." The ~14 stations around the continent were equally divided between warming and cooling, leading to an uncertain result. The data also indicated that warming trends appeared to be greater for the 1961–1990 period compared with the 1971–2000 period, suggesting that warming tailed off after 1971. It is interesting that Turner *et al.* (2005) emphasized the warming over the peninsula and described the temperatures elsewhere as "variable". The tone of this reference suggests that it supports global warming, although the authors were appropriately cautious. However, Taylor (2006) and Sherwood and Idso (2006), both written by global warming skeptics, referred to the results of Turner *et al.* (2005) as supportive of doubt regarding global warming, and it is true that the results are somewhat equivocal.

Comiso (2000) reported on surface air temperatures observed from stations in Antarctica. The results showed predominantly warming trends as high as 0.5°C/decade along the Antarctic peninsula. Surface temperatures inferred from infrared satellite data from 1979 to 1998 were analyzed in combination with data from 21 stations that have relatively long record lengths. The surface temperatures derived from infrared data were claimed to agree well with Antarctic station data. The 45-year record of station data showed a net warming of 0.012°/year (±67%) while the 20-year record of station data showed a net cooling of 0.008°C (±300%). The 20-year record of satellite measurements indicated a cooling of 0.042°C/year (±150%). The 20-year record length was claimed to be about the minimum length required for a meaningful trend analysis study. It was concluded:

> "The slight cooling of the entire ice sheet observed in both in situ and satellite records during the last 20 years is intriguing since during the same time period a general warming is being observed globally."

Thompson and Solomon (2002) indicated that recent trends in SH tropospheric circulation contributed to warming over the Antarctic peninsula and cooling over the Antarctic plateau.

3.2.3.2 Arctic temperatures

According to Hanna and Cappelen (2003):

> "The Polar Regions are among the most interesting regarding the ongoing debate on global climate change because, due to several key climatic feedbacks, they are potentially extremely climatically sensitive. The best known is the ice–albedo feedback by which an initial perturbation (slight warming) melts some ice; this new more extensive darker melt-water area absorbs more incoming sunlight, which accelerates the warming and melting of surrounding ice. Therefore it is crucial to improve our understanding of current conditions and past history of the major ice sheets and sea ice, and to model how they are likely to behave in future (e.g. in response to man-made global warming). This requires not only glaciological observations but also meteorological ones. Unfortunately polar areas are noted for their dearth of observations. Greenland, the world's largest island,[1] hosts the world's second largest ice sheet (after Antarctica) and is important in both meteorological and glaciological terms. It is a vast heat sink, due to its predominantly ice-covered surface that reflects some 60–90% of incoming solar

[1] Other than Australia.

radiation. The Greenland Ice Sheet is a huge ice dome, 3 km thick in the middle, which locally rises to more than 3 km above sea level. Cold, dense air streams off the surface and fierce katabatic winds roar down ice fjords near the outer edges. If the ice sheet were to melt in its entirety, which would take some thousands of years at projected rates of global warming, it could contribute around 6–7 m to global sea level. Recent studies, especially airborne laser measurements of surface elevation of the ice, suggest that most of the interior of the ice sheet is relatively stable or growing slightly, whereas the margins have thinned substantially over the past few years. Most melting of the ice, and resulting loss by runoff of surface melt water, occurs within a relatively thin zone (about 100–200 km) around the edges, and depends strongly on summer temperatures, so the mass balance of the ice sheet is highly sensitive to climatic change. Likely future warming could also affect the way the ice flows outwards near the edges, and the rate of iceberg calving (formation), the latter another important mass loss process. Meanwhile, changes in precipitation and snowfall are paramount for snow accumulating on the ice sheet ... Climatic change in Greenland has been important historically. The period 800–1100 was relatively warm and favored Viking expansion to Greenland. A climatic deterioration then set in from c. 1250 through 1350. The fourteenth century is considered the coldest in the last 1000 years in Greenland. The subsequent chill of the little ice age over Europe may have been muted over western Greenland ... although there is evidence for a LIA cooling over central Greenland. A glacial advance that began in Greenland about 400 years ago continued until the eighteenth, nineteenth or even early twentieth centuries ... followed by a recession back towards the LIA level ... In contrast to general global warming, Greenland (also Iceland and the Faeroes) cooled significantly during the latter half of the twentieth century.''

Hanna and Cappelen (2003) said:

''Analysis of new data for eight stations in coastal southern Greenland, 1958–2001, shows a significant cooling (trend-line change -1.29°C for the 44 years), as do sea-surface temperatures in the adjacent part of the Labrador Sea, in contrast to global warming ($+0.53^\circ$C over the same period). The land and sea temperature series follow similar patterns and are strongly correlated but with no obvious lead/lag either way.''

Hanna and Cappelen (2003) said:

''Different temperature and precipitation records, covering the period 1958–99, from six stations in Southern Greenland have been studied ... Despite global warming over the past few decades, the SW marginal areas of southern Greenland seem to have actually cooled, especially daytime temperatures in winter ... It will be intriguing to see if this trend continues, as it could substantially influence the mass balance (through changes in snow accumulation, surface melt runoff and iceberg calving) of the southern parts at least of the ice sheet. The overall cooling

> may also have caused a sharp increase in snowfall days at some of the coastal stations, where snow as a fraction of precipitation is critically dependent on temperature. These results demonstrate the regional vagaries of the global weather machine; climatic change is not a simple uniform process. Yet as one of these regions, Greenland greatly influences the surface heat budget, atmospheric circulation and (through the waxing and waning of its ice sheet) global sea level.''

Przybylak (2002) provided a detailed analysis of intra-seasonal and inter-annual temperature variability for the whole Arctic for the period 1951–1990. Four temperature variables were used: average (T_{MEAN}), maximum (T_{MAX}) and minimum (T_{MIN}) temperatures, and the diurnal temperature range (DTR). Ten stations were utilized, representing almost all climatic regions in the Arctic. Regional trends in intra-seasonal and inter-annual temperature variability were mixed and the majority of them were insignificant. Trends in intra-seasonal temperature variability were upward in the Norwegian Arctic and eastern Greenland and downward in the Canadian and Russian Arctic. The final conclusion was:

> ''The absence of significant changes in intra-seasonal and inter-annual variability of T_{MEAN}, T_{MAX}, T_{MIN} and DTR is additional evidence (besides the average temperature) that in the Arctic in the period 1951–1990 no tangible manifestations of the greenhouse effect can be identified.''

According to Chylek, Box, and Lesins (2004):

> ''A considerable and rapid warming over all of coastal Greenland occurred in the 1920s when the average annual surface air temperature rose between 2 and 4°C in less than ten years (at some stations the increase in winter temperature was as high as 6°C). This rapid warming, at a time when the change in anthropogenic production of greenhouse gases was well below the current level, suggests a high natural variability in the regional climate . . . Since 1940, however, the Greenland coastal stations data have [undergone] predominantly a cooling trend. At the summit of the Greenland ice sheet the summer average temperature has decreased at the rate of 2.2°C per decade since the beginning of the measurements in 1987. This suggests that the Greenland ice sheet and coastal regions are not following the current global warming trend.''

Chylek, Dubey, and Lesins (2006) found that ''current Greenland warming is not unprecedented in recent Greenland history.'' Warming experienced from 1995 to 2005 also occurred from 1920 to 1930, except that the rate of warming from 1920 to 1930 was about 50% higher than that in 1995–2005.

Zwally *et al.* (2005) extended the analysis of radar altimeter data from two European remote-sensing satellites to 90.0% of the Greenland ice sheet, 77.1% of the Antarctic ice sheet, and 81.8% of the Antarctic ice shelves. The estimated changes in ice mass from elevation changes derived from 10.5 years (Greenland) and 9 years

(Antarctica) of satellite radar altimetry data indicated that the Greenland ice sheet is thinning at the margins (−42 Gt/yr below the equilibrium-line altitude (ELA)) and growing inland (+53 Gt/yr above the ELA) with a small overall mass gain (+11 Gt/yr). The ice sheet in West Antarctica (WA) is losing mass (−47 Gt/yr) and the ice sheet in East Antarctica (EA) shows a small mass gain (+16 Gt/yr) for a combined net change of −31 Gt/yr. The contribution of the three ice sheets to sea level is $+0.05 \pm 0.03$ mm/yr. The Antarctic ice shelves show corresponding mass changes of −95 Gt/yr in WA and +142 Gt/yr in EA. Expected responses of the ice sheets to climate warming are growth in thickness of the inland ice areas, due to increasing precipitation, accompanied by thinning near the margins, due to increasing surface melting.

Soon and Baliunas (2003a, b) pointed out:

> "In considering the possible link of early 20th century warming to the rise in atmospheric CO_2 concentration, it should be noted that the Arctic-wide temperatures of Overpeck *et al.* (1997) began rising in the mid-19th century and peaked around 1940–1960, when the increase in the air's CO_2 content was less than 20–30% of the cumulative CO_2 increase to date."

Polyakov *et al.* (2003b) examined long-term Arctic surface air temperature and pressure data for the period 1875–2000 poleward of 62°N. The Arctic air temperature and pressure displayed substantial variability on timescales of 50–80 years. They suggested that the origin of this variability might lie in the complex interactions between the Arctic and North Atlantic. The two periods of highest temperatures in the Arctic were: in the 1930s–1940s, and in recent decades. They speculated that global warming alone cannot explain the retreat of Arctic ice observed in the 1980s/1990s. They concluded:

> "The complicated nature of Arctic temperature and pressure variations makes understanding of possible causes of the variability, and evaluation of the anthropogenic warming effect most difficult."

Similarly, Polyakov *et al.* (2003a) found a high level of Atlantic temperature variability in and sea surface salinity fluctuations on the Siberian Shelf and the Amundsen Basin. They suggested that there are "strong limitations on our ability to define amplitudes of anomalies by comparing recent synoptic measurements with [climate models], especially for [such] regions characterized by strong variability." This echoed the conclusion from an earlier paper (Polyakov and Johnson, 2000) that said:

> "Our results suggest that the decadal Arctic oscillation and multi-decadal low-frequency oscillation drive large amplitude natural variability in the Arctic, making detection of possible long-term trends induced by greenhouse gas warming most difficult."

Howat, Joughin, and Scambos (2007) found large year-to-year variations in ice loss from ice sheets. Shepherd and Wingham (2007) reviewed the results of more than a dozen satellite-based studies of ice loss from the Greenland and Antarctic Ice Sheets. They estimated that the East Antarctica Ice Sheet (EAIS) is gaining some 25 Gt/year, the West Antarctica Ice Sheet (WAIS) is losing about 50 Gt/year, and the Greenland Ice Sheet (GIS) is losing about 100 Gt/year. These trends provide a modest contribution to sea level rise of about 0.35 mm/year. However, these short-term results should not be extrapolated because of the oscillatory behavior of ice sheet loss.

3.2.4 The NH temperature dip, 1940–1978: effect of aerosols

A number of figures in Section 3.2.2 (e.g., Figure 3.7) show that in the NH, temperatures rose from about 1920 to 1940, dipped from 1940 to 1978, and then rose again from 1978 to the present. Since the period from 1940 to 1978 experienced increasing CO_2 emissions, these data would appear to conflict with the belief that the 20th-century temperature rise was due to the greenhouse effect. This fact was seized on by naysayers as an indication that warming in the 20th century was not directly tied to CO_2 concentration. However, the alarmists responded by indicating that there was a build-up in sulfate aerosols as power plants expanded in the mid–20th century, and these aerosols acted as a cooling force to counteract the build-up of greenhouse gases. The claim is that as the 20th century wore on, greenhouse gases continued to build up while the developed nations began to control sulfur emissions, and late in the century, the temperature began to rise again. For example, Overpeck *et al.* (1997) suggested: "the observed slowdown in warming from 1950 to 1970 may have been influenced by the increase in Arctic tropospheric aerosols that occurred after 1950."

These opposing viewpoints can be found on a number of websites and blogs.

The effect of aerosols on climate is not known precisely. Hansen (2004) said:

> "Some 'white aerosols', such as sulfates arising from sulfur in fossil fuels, are highly reflective and thus reduce solar heating of the earth; however, black carbon (soot) ... absorbs sunlight and thus heats the atmosphere. This aerosol direct climate forcing is uncertain by at least 50 percent, in part because aerosol amounts are not well measured and in part because of their complexity."

Anderson *et al.* (2003) discussed two methods for incorporating aerosol forcing in climate models. In the "forward" approach, pertinent aerosol physics and chemistry are used to estimate the aerosol-induced forcing *a priori* and the climate model is based on this. In the "inverse" approach, the climate model is exercised using the aerosol forcing as an adjustable parameter, and the parameter is adjusted to maximize agreement with experimental temperatures, assuming that the other forcings are known better. However, as we discuss in Section 6.2, the forcings due to water vapor and clouds remain quite uncertain. Forward calculations suggest a higher forcing than is inferred from inverse models. Current climate studies typically use only the lower aerosol forcing values consistent with the inverse approach. If the larger range of aerosol forcings from the forward calculations were used, the total forcing from pre-industrial times to the present might be small or even negative. If this were correct, it would imply that climate sensitivity and/or natural variability (i.e., variability not forced by anthropogenic emissions) is much larger than climate models currently indicate. However, greenhouse gases accumulate in the atmosphere, whereas aerosols do not. Thus, as greenhouse gas emissions continue to increase in the 21st century, the forcing will turn positive provided aerosol emissions are controlled. Anderson *et al.* (2003) concluded: "... the possibility that most of the warming to date is due to natural variability ... must be kept open."

The translation of estimated sulfur emissions into aerosol concentration, and the subsequent conversion of this concentration to an effective forcing (W/m^2) has not been clearly elucidated in the literature. Mitchell and Johns (1997) estimated future temperatures in the 21st century based on assumed forcings from CO_2 and aerosols. They stated:

> "The scenarios are plausible, though there are large uncertainties in future greenhouse gas concentrations, and even greater uncertainties in those of sulfates and the associated direct radiative forcing. The effects of sulfate aerosols on clouds, and possible changes in other forcing including that due to industrial soot, tropospheric ozone, and biogenic aerosols, are ignored."

However, the actual figures used by Mitchell and Johns (1997) seem rather strange and incredible. The CO_2 concentration in 2000 was assumed to be 522 ppm (and we know it was actually about 370 ppm), and the CO_2 concentration was assumed to rise to 1,414 ppm in 2100, which is 2.5 to 3 times what it is most likely to be (see Section 6.2). The aerosol forcing was assumed to rise from zero in the pre-industrial era to about $-0.7\,W/m^2$ in 2000 to about $-1.5\,W/m^2$ in 2100 but it is not clear how this was derived.

Lefohn, Husar, and Husar (1999) was the most authoritative source on aerosol production, but Stern (2005a, b) written about six years later, appear to encompass the earlier paper as well as adding more recent data. The estimate of world sulfur emissions by Stern (2005a) was compared with estimates made by others, particularly the data of Lefohn, Husar, and Husar (1999). The result is shown as Figure 3.13. Stern (2005a) suggested that some rebound in aerosol production would seem likely in the current business cycle (after 2000), especially as the downtrend in the 1990s was strongly affected by the collapse of the Soviet Bloc economies. Some recent data are available for the U.S. and China that suggest that increases in China will outweigh decreases in the U.S. Stern (2005a) concluded: "global emissions likely declined through 2002 but in 2003 and following years emissions could be rebounding moderately."

While the focus of Stern (2005a, b) was on the decade 1991–2000, estimates were also made for the historical period 1850 to 2000. Data were not available for all locations over all time spans and some extrapolation was required. Figure 3.14 (color section) shows the estimate of sulfur emissions prepared by Stern (2005b). World emissions peaked around 1975–1985 and declined afterward. After 1989 a precipitous

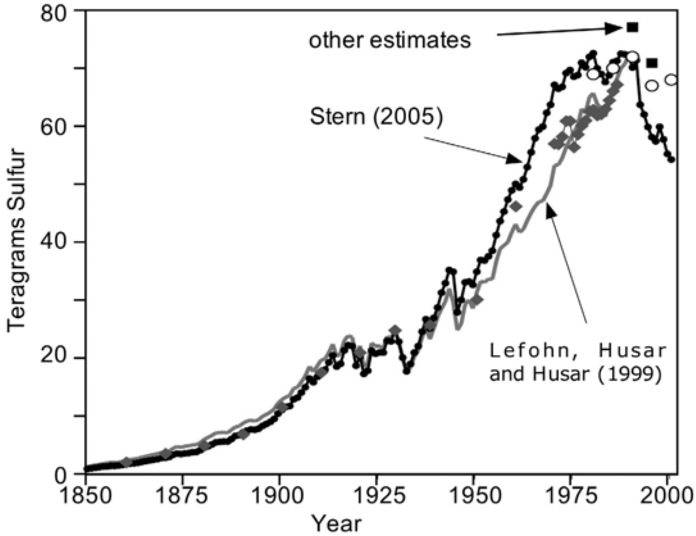

Figure 3.13. Estimate of sulfur emissions 1850–2000. Vertical scale is teragrams (10^{12} grams) of sulfur. Adapted from Stern (2005a), and Lefohn, Husar, and Husar (1999).

decline set in, only punctuated by the Kuwait oil fires, which contributed around 4.7 Tg of sulfur,[2] as the Soviet Union and Eastern European economies collapsed. Chinese emissions overtook U.S. emissions in 1987 to make China the largest single emitter. Chinese emissions were claimed to have peaked in 1996. However, it is known that in 2007, China is adding one coal-fired power plant per week, and since China seems to have little interest in pollution control of any form, this seems hardly believable.

Stern (2005a) estimated that the net radiative forcing in 1990 due to aerosols was about $-2.0\,W/m^2$, and that the change in forcing from 1985 to 2000 was $\sim+0.35\,W/m^2$. This would seem to imply that the peak aerosol forcing around 1987 was about $-2.1\,W/m^2$ and dropped to about $-1.7\,W/m^2$ by 2000. However, it is not clear how this was derived.

Two related papers (Nagashima *et al.*, 2006; Nozawa *et al.*, 2005) carried out global climate models that included the impact of aerosols on 20th-century climate change. However, these papers appear to raise more questions than they answer. Nozawa *et al.* (2005) did not actually isolate the effect of aerosols but rather, carried out four calculations: (1) full (with all forcings), (2) natural (with only solar and volcanic forcing), (3) anthropogenic (with GHG and aerosols forcing), and (4) GHG (with only greenhouse gas forcing). However, by subtracting (4) from (3), the effect of the aerosols can be discerned. Nozawa *et al.* (2005) found that the natural model underestimated late 20th-century warming by a significant amount. The anthropogenic model underestimated mid and late-century warming. The GHG model

[2] 1 teragram (Tg) = 10^{15} grams.

overestimated late-century warming. And the full model fit best. However, this does not make any sense to this writer because the full model includes natural plus anthropogenic forcing, and since both of these are low in the late 20th century, how can the full model fit late 20th-century temperature data? Nevertheless, despite this apparent inconsistency, it can be noted that the difference between the anthropogenic and GHG curves in Nozawa *et al.* (2005) was 0.28°C in 1950, 0.38°C in 1975, and 0.60°C in 2000. These can be attributed as the temperature decrease due to aerosols alone. Nozawa *et al.* (2005) does not quite succeed in reproducing the observed temperature dip from 1940 to 1978 but the natural curve goes downward after 1940 including a sharp dip from 1960 to 1970, and this, rather than aerosol production fall-off, leads to a lull in temperature rise in that decade. However the credibility of their natural curve is doubtful.

In a related activity, Nagashima *et al.* (2006) used a climate model to infer the effect of aerosols on climate. They examined the effect of sulfate aerosols and carbon aerosols separately. They found that without aerosols being included, the climate model predicted too much warming in the 20th century. When both carbon and sulfate aerosols were included the fit to experimental temperature data was better. However it is not clear from this study what produced the temperature decline from 1940 to 1978, or how the model was contrived to fit the data.

The observed dip in global temperature from 1940 to 1978 does not seem to correlate well with Figures 3.13 and 3.14 (color section). The aerosol peak occurred well after temperatures began rising again after 1978. The temperature dip from 1940 to 1978 remains only partly attributable to aerosols, and in the absence of credible explanations remains as an unexplained issue.

Ghan and Schwartz (2007) provided a comprehensive review of the status of modeling aerosols in various generations of global climate models, past, present and future. Early approaches for incorporating the effects of aerosols simply adjusted the albedo as a crude approximation, while subsequent models used much more sophisticated representations of aerosols, but even these did not adequately account for interactions of aerosols with other climate elements.

> "It is now recognized that accurate representation of aerosol influences must take into account phenomena such as correlations of aerosol loading with meteorological variables and the influence of aerosol on clouds and precipitation, and hence that aerosol loading and those properties must be represented actively and interactively in climate models. It is this recognition that is driving much of the current effort to actively represent aerosol processes, properties, and effects in climate models" (Ghan and Schwartz, 2007).

The treatment of aerosols in future generations of climate models will rest on an improved understanding of the processes that control aerosol properties and the ways that they affect climate. Ghan and Schwartz (2007) provide a plan for systematically improving our understanding of aerosols in the future.

3.2.5 Adequacy of the global temperature network

According to McLean (2007a):

> "In the early days thermometers could only show the temperature at the moment of reading and so the data recorded from that time was for just one reading each day. Later the thermometers were able to record the minimum and maximum temperatures, and so the daily readings were those extremes in the 24 hour period. Only in the last 20 or 30 years have instruments been available that record the temperature at regular intervals throughout the 24 hours, thus allowing a true time-based daily average to be calculated. The so-called 'average' temperatures both published and frequently plotted through time are initially based on only a single daily value, then later on the mathematical average of the minimum and maximum temperatures. Although time-based averages are now available for some regions they are not generally used because the better instrumentation is not uniformly installed throughout the world and the historical data is at best a mathematical average of two values. The problem is that these averages are easily distorted by brief periods of high or low temperatures relative to the rest of the day, such as a brief period with less cloud cover or a short period of cold wind or rain."

A number of papers have estimated global temperatures during the past century (e.g., Smith and Reynolds, 2005; Peterson *et al.*, 2000; Rayner *et al.*, 2003; Smith *et al.*, 2005). In a 1999 report entitled *Adequacy of Climate Observing Systems*, the National Research Council said:

> "Climate researchers have used existing, operational networks because they have been the best, and sometimes only, source of data available. They have succeeded in establishing basic trends of several aspects of climate on regional and global scales. Deficiencies in the accuracy, quality, and continuity of the records, however, still place serious limitations on the confidence that can be placed in the research results."

Figure 3.15a is a plot of the mean temperature stations around the world. The upper plot shows all stations and the lower plot shows stations with 100 years (or more) of data.

The U.S. and Western Europe play a dominant role. In most of the world, we don't have adequate station coverage for temperature and even less for precipitation. Seventy percent of the world is ocean, for which the database is uncertain. The Arctic and the Antarctic have very skimpy data. African and South American stations are sparse. Figure 3.15b shows the same information for stations that measure maximum and minimum temperature. Figure 3.16 shows the longevity of existing stations, the rise in the number of stations in the 20th century, and the decrease in the number of stations after 1970.

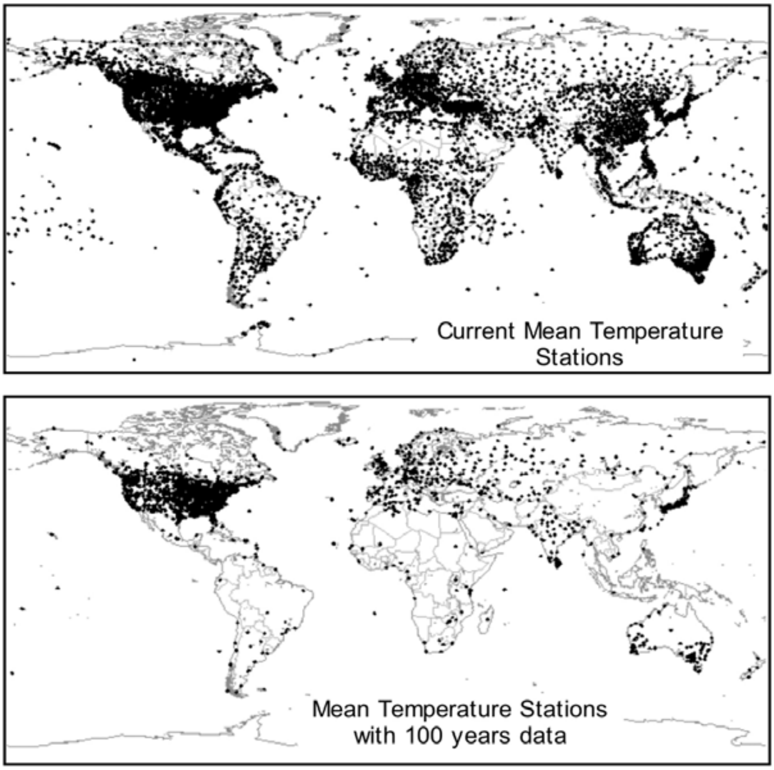

Figure 3.15a. Maps of GHCN mean temperature station locations: (upper) all GHCN mean temperature stations and (lower) mean temperature stations with data in 1900. From Peterson and Vose (1997).

In a quotation available in various places on the Internet, Kevin Trenberth, a leading climatologist, said:

> "It's very clear we do not have a climate observing system ... This may come as a shock to many people who assume that we do know adequately what's going on with the climate but we don't."

Global warming alarmists have emphasized the temperature rise of the 20th century. For example, the IPCC said:

> "The global average surface temperature has increased by $0.6 \pm 0.2^{\circ}$C since the late 19th century."

Ball (2007) then went on to point out that another way of putting this is: an increase somewhere between 0.4°C and 0.8°C. Such wide error bars do not convey confidence

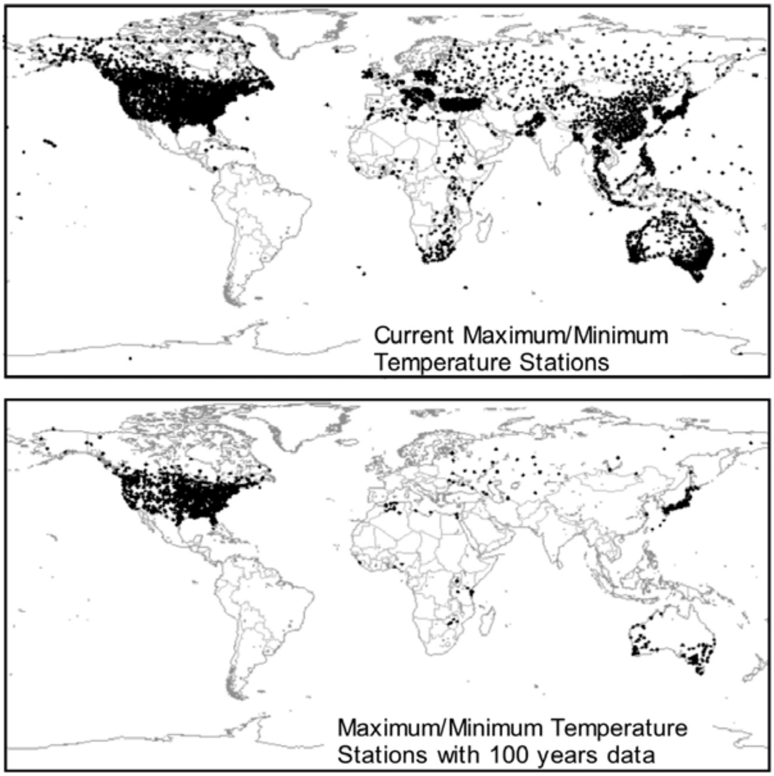

Figure 3.15b. Maps of GHCN maximum/minimum temperature station locations: (upper) all GHCN mean temperature stations and (lower) mean temperature stations with data in 1900. From Peterson and Vose (1997).

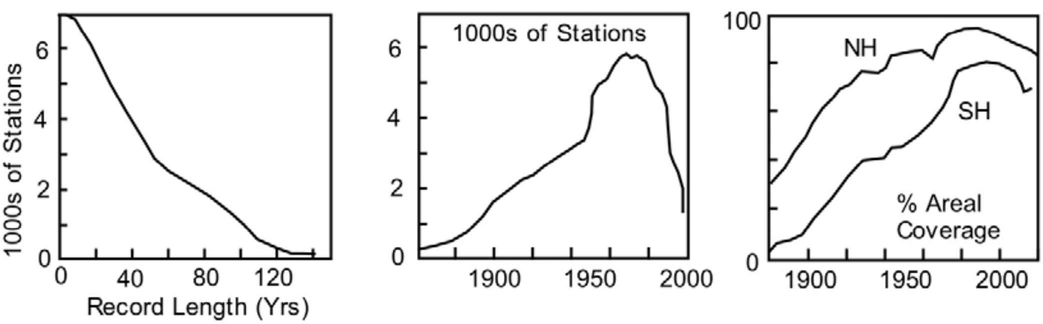

Figure 3.16. World temperature measurement stations. Left panel shows number of stations vs. record length. Middle panel shows number of stations vs. year. Right panel shows areal coverage. Adapted from Ball (2007).

in the estimate. Ball (2007) also raised the question of how these error bars were set and concluded they were "rubbish". Ball (2007) claims that Phil Jones (a leading climatologist, a believer in the *hockey stick*, and a global warming alarmist) was asked to disclose how he came up with this estimate of uncertainty in the temperature rise. Ball (2007) claims that Jones replied in an email:

> "We have 25 or so years invested in the work. Why should I make the data available to you, when your aim is to try and find something wrong with it?"

When a world-leading climatologist is more concerned with protecting his turf than finding truth, things have taken a very bad turn.

But the point that was made by Ball (2007) (brushing aside issues regarding whether it makes sense to even talk about a single global temperature or how one deals with the oceans), is how can we know what the global temperature rise was "since the late 19th century" when (i) there hardly were any stations in the late 19th century, (ii) station sparsity was meager until about 1950 and still inadequate after that date, (iii) the number of stations with record lengths of 100 years is minimal, (iv) areal coverage was low until about 1950? The short answer is: we can't know.

The decrease in the number of stations in the late 20th century is alarming. If this is due to "weeding out" poorly equipped and situated stations, that might improve the quality of the residual database but it exacerbates the sparseness. Furthermore, it raises questions regarding the quality of the thousands of stations that were phased out late in the 20th century.

A more upbeat view of the network for temperature measurement on Earth was given by Brohan *et al.* (2006). A new upgrade to the temperature measurement network (TMN) was described. The database is derived from a collection of homogenized, quality-controlled, monthly-average temperatures for ~4,350 stations. "Station normals" (monthly averages over the normal period 1961–1990) were generated from station data for this period where possible. However, "normals" were derived from station data "wherever possible" and various approximations were used in many cases. Using these "normals", anomalies were calculated as deviations from the means of the "normals". The discrete set of station anomaly data were then converted to a temperature distribution across a global grid by interpolation, typically at $5^\circ \times 5^\circ$ resolution.

> However, this paper did not present a plot like Figure 3.16 that shows how the number of stations diminishes with time in the past.

Marine data used by Brohan *et al.* (2006) consist of a gridded data set made from *in situ* ship and buoy observations from the new International Comprehensive Ocean–Atmosphere data set. For each grid box, mean temperature anomalies, measurement and sampling error estimates, and bias error estimates are available.

Blending a sea surface temperature (SST) data set with land air temperature data makes an implicit assumption that SST anomalies are a good surrogate for marine air temperature anomalies. It is claimed that this is the case, and that marine SST measurements provide more useful data and smaller sampling errors than marine air temperature measurements would. So it is claimed that "blending SST anomalies with land air temperature anomalies is a sensible choice." Over the period from 1850 to 1940, the predominant SST measurement process changed from taking samples in wooden buckets, to taking samples in canvas buckets, to using engine room cooling water inlet temperatures. A bias correction was applied to remove the effect of these changes on the SSTs, but this adds some uncertainty. Brohan *et al.* (2006) said:

> "As with the land data, the uncertainty estimates cannot be definitive: where there are known sources of uncertainty, estimates of the size of those uncertainties have been made. There may be additional sources of uncertainty as yet unquantified."

Brohan *et al.* (2006) said:

> "If the gridded data had complete coverage of the globe or the region to be averaged, then making a time series would be a simple process of averaging the gridded data and making allowances for the relative sizes of the grid boxes and the known uncertainties in the data. However, global coverage is not complete even in the years with the most observations, and it is very incomplete early in the record. In general, global and regional area-averages will have an additional source of uncertainty caused by missing data. To estimate the uncertainty of a large-scale average owing to missing data the effect of sub-sampling on a known, complete dataset is used."

The monthly averages are dominated by short-term fluctuations in the anomalies; combining the data into annual averages produces a clearer picture, and smoothing the annual averages with a 21-term binomial filter highlights the low-frequency components and shows the importance of the bias uncertainties. The bias uncertainties are zero over the normal period by definition. The dominant bias uncertainties are those due to bucket correction and thermometer exposure changes, both of which are larger before the 1940s. The station, sampling and measurement, and coverage errors depend on the number and distribution of the observations, and these components of the error decrease steadily with time as the number of observations increases. These components also decrease with averaging to larger space and timescales, so they are smaller in the annual than the monthly series, and smaller again in the smoothed annual series. The bias uncertainties, however, do not reduce with spatial or temporal averaging, and they are largest in the early 20th century; so the smoothed annual series, where the uncertainty is dominated by the bias uncertainties, also has its largest uncertainty in this period (Brohan *et al.*, 2006).

Brohan *et al.* (2006) discussed three types of errors in the database: (i) station error (the uncertainty of individual station anomalies due to measurement errors, changes in location, changes in time of measurement, or changes in instrumentation), (ii) sampling error (the uncertainty in a grid box mean caused by estimating the mean from a small number of point values), and (iii) bias error (the uncertainty in large-scale temperatures caused by systematic effects such as urban heat islands, and exposure changes). Effects of heat generation by urbanization are also discussed in Section 5.2.5. It is difficult to summarize the net result of all the contributing errors. Data presented in Brohan *et al.* (2006) (their figs. 5, 6, and 9) seem to suggest that potential errors in anomalies of 1°C to 2°C are commonplace, which exceeds the putative temperature rise of the 20th century. However, in their final summing up of hemispheric and global temperatures, Brohan *et al.* (2006) indicated much smaller temperature uncertainties. But the really surprising aspect of this is that according to Brohan *et al.* (2006), the uncertainty in sea surface temperatures is fairly flat at ±0.1°C from 1850 to 2000. By contrast, the uncertainty in land temperatures is claimed to range from about ±0.4°C around 1850 to about ±0.15°C in 2000. Since the oceans occupy about 70% of the globe's surface area, the overall uncertainty would be expected to depend more on the ocean data. According to Brohan *et al.* (2006):

> "A notable feature of the global time series is that the uncertainties are not always larger for earlier periods than later periods. The uncertainties are smaller in the 1850s than in the 1920s, at least for the smoothed series, despite the much larger number of observations in the 1920s."

Figure 3.17 shows the resultant smoothed monthly temperatures for the two hemispheres and the globe as derived by Brohan *et al.* (2006). The widths of the

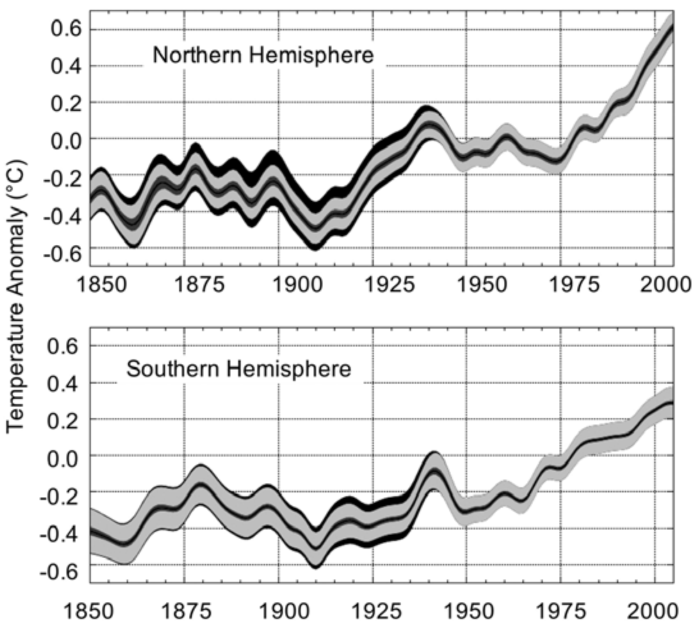

Figure 3.17. Smoothed monthly temperatures for the two hemispheres. Adapted from Brohan *et al.* (2006).

swaths are measures of the uncertainties associated with each set of measurements. A comparison of the smoothed mean temperature anomalies for the Northern Hemisphere and Southern Hemisphere shows the difference in uncertainties between the two hemispheres. According to Brohan *et al.* (2006), the difference in the uncertainty ranges for the two series stems from the very different land/sea ratio of the two hemispheres. The Northern Hemisphere has more land, and so a larger station, sampling, and measurement error, but it has more observations and so a smaller coverage uncertainty. The bias uncertainties are also larger in the Northern Hemisphere both because it has more land, and because the SST bias uncertainties are largest in the Northern Hemisphere western boundary current regions.

Brohan *et al.* (2006) calculated the global temperature as the mean of the NH and SH series (to stop the better-sampled Northern Hemisphere from dominating the average). Figure 3.18 shows the resultant smoothed monthly temperatures based on land measurements, sea measurements, and overall.

There are a number aspects of Brohan *et al.* (2006) that are confusing. First, consider the point that it is claimed that sea temperature measurements are more precise than land temperature measurements. On the one hand, this would seem to be intuitively correct because the sea measurements are not afflicted with site aberrations due to urbanization, shade or sun, exposure to winds, changes in land use, etc. However, as we pointed out in Section 3.1.2, doubts have been raised about the accuracy of sea temperature measurements due to the changes in measurement procedures over the years. Next, consider that despite the huge preponderance of sites in the NH compared with the SH, and the fact that the number of SH sites probably falls off much more rapidly as one goes back in time, Brohan *et al.* (2006) claims that the measurements of temperature in the SH are more precise. This, of course, is based on the putative accuracy of sea temperatures and the preponderance of ocean in the SH. Nevertheless, this seems counter-intuitive and worthy of further examination. But the strangest thing about Figures 3.17 and 3.18 is that they do not seem to link to one another very well. For example, the upper panel in Figure 3.18 is the global temperature anomaly, and it should be an arithmetic mean of the SH and NH curves in Figure 3.17. However, it is not. For example, at the far right of these graphs, the values are global = 0.62, NH = 0.62, and SH = 0.28. By averaging the NH and SH, one should get 0.45 for the global, not 0.62. Something is amiss here. Another problem is that if we take 30% of the land curve and 70% of the sea curve in Figure 3.18, we do not end up with the global curve (upper panel in Figure 3.18). Once again, at the far right of the graphs, we find $0.7 \times 0.35 + 0.3 \times 0.67 = 0.45$ whereas the global curve indicates 0.62. It is also difficult to reconcile the width of the uncertainty in the upper panel.

The ultimate results on temperature profiles derived by Brohan *et al.* (2006) date back to 1850 as shown in Figures 3.17 and 3.18. Spatial coverage varied widely with some areas (U.S. and Western Europe) having a higher density of stations, and the remainder of the world being quite sparse (see Figure 3.15). In converting station data to a gridded data set, all gridded cells are treated equally. Since the majority of the gridded cells pertain to regions with sparse station coverage, the high densities of stations in the U.S. and Western Europe are greatly diluted by the low density of

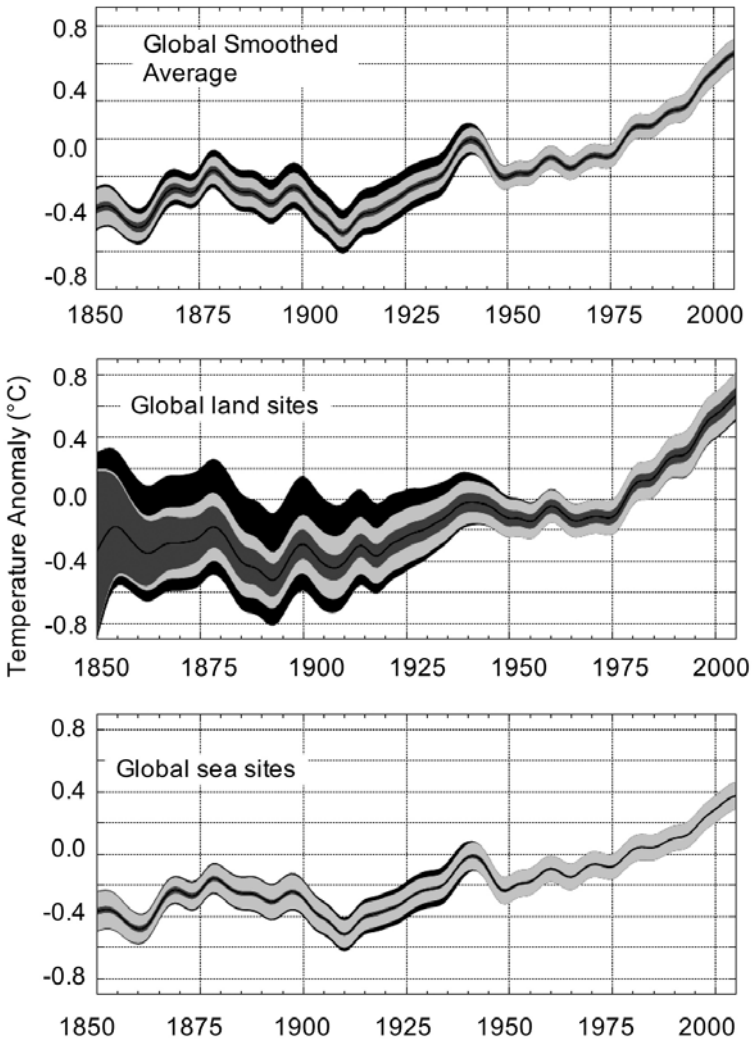

Figure 3.18. Global smoothed monthly sea surface temperatures. Upper panel: all sites. Middle panel: land sites. Lower panel: sea sites. Adapted from Brohan *et al.* (2006).

stations elsewhere. Thus, the total number of stations (~4,350) becomes an irrelevant figure when the dataset is converted to a grid. In actual fact, it is not the total number of stations that matter, but rather the distribution function for the number of stations per grid cell. This function will have strong peaks for cells in the U.S. and Western Europe, but will be very low for most of the world, leading to the inevitable conclusion that spatial coverage across the globe is very poor.

Furthermore, very few of the ~4,350 stations dated back to 1850, or even 1900, as shown in Figure 3.16. In addition, it seems likely that the majority of stations that do date back to 1900 or 1850, are located in the U.S. and Western Europe. Hence, not only is spatial coverage poor throughout most of the world for all years, but spatial coverage prior to perhaps 1940 is even worse than it was after that.

> Since Brohan *et al.* (2006) did not provide data on the distribution of the number of sites per gridded cell for all years, it is difficult to be certain just how flimsy the historical global temperature record is, but clearly, the weaknesses of the temperature measurement network have been glossed over.

3.2.6 Troposphere temperatures

Tropospheric temperature measurement, like every other aspect of global climate analysis, leads to uncertainties, disagreements, and confusion.

Marsh (2002) pointed out:

> "The layer of the Earth's atmosphere from the ground up to an altitude of a few miles is called the troposphere, and the boundary between it and the rest of the atmosphere above is called the tropopause. The tropopause is about 11 miles high at the equator and only about five miles high at the poles. The troposphere is the part of the atmosphere that is responsible for the greenhouse effect, since it contains essentially all of the greenhouse gases. Because the Earth's troposphere, surface and boundary layer are closely coupled by air movement, they are considered to be a single thermodynamic system. For this reason, changes in radiative flux at the tropopause are used to express changes to the climate system."

According to Gregory *et al.* (2004):

> "Heat is rapidly exchanged within the troposphere and at the surface; the troposphere, surface and upper ocean thus constitute a tightly coupled 'climate system.' The stratosphere tends to equilibrate separately and on a timescale of only a few months."

Most "recent global climate models hindcasts and forecasts are consistent in depicting a tropical lower troposphere that warms at a rate about 1.3 times that of the surface." Thus, the models would predict that the trend for warming of the troposphere would be at a higher rate than the surface.

NOAA has flown about ten MSU satellites since 1979. Each satellite has a life cycle of a few years but their timing is arranged so there is overlap between successive satellites.

The MSU instruments have four channels spanning a moderate frequency range. Thermal emission from atmospheric oxygen constitutes the major component of the measured brightness temperature, with the vertical weighting profile varying from near the surface in Channel 1 to the stratosphere in Channel 4. About 80% of the signal for Channel 2 at 53.74 GHz comes from the troposphere, with the weighting function peaking from 4 km to 7 km above the surface, depending on the Earth incidence angle. The remainder of the signal comes from the surface and stratosphere, with the exact contribution of each dependent on the surface type and the atmospheric profile at the point of measurement (Mears, Schabel, and Wentz, 2003).

Initial processing of the data for the past two decades indicated that while the trend of surface temperature anomalies has been about +0.17°C per decade, the trend of tropospheric temperature anomalies was slightly negative at −0.03°C/decade (Christy, 1995). This initial contradiction between experiment and the GCMs was seized on with glee by the naysayers who used it as ammunition against global-warming alarmists.

Some work in the late 1990s revealed the presence of a spurious cooling trend introduced by neglect of the differential effects of satellite orbit decay on near-limb and near-nadir observations. Accounting for this led to an increase in the global trend of approximately 0.12°C/decade, bringing the lower troposphere observations in the direction toward GCM predictions and surface measurements. However, Christy, Spencer, and Braswell (2000) discovered additional diurnal and target temperature contributions that they claimed largely offset the orbit decay effect, leading to a tropospheric trend of +0.04°C/decade, thus continuing the surface/troposphere disconnect.

Further processing of data from Channel 2 uncovered a number of important sources of error, including inter-satellite offsets, diurnal warming with slow evolution in the satellite local equator crossing times, and the presence of a significant correlation between observed inter-satellite brightness temperature differences and satellite hot calibration load temperature. Impacts of these various contributions were gradually identified and corrected in successive versions of their merged data set, with resulting long-term trends indicating cooling relative to the surface, particularly in the tropics and subtropics. These results, combined with the even more rapid cooling in the modified data set MSU 2LT, sparked a lively debate regarding errors in the tropospheric temperature data, how to correct for them, and the relationship to inconsistency with general circulation model predictions (Mears, Schabel, and Wentz, 2003; Anon. (B)).

Mears, Schabel, and Wentz (2003) carried out a complete reanalysis of systematic errors in the MSU data set because of its importance in climate change research. The details of this process are complex and intricate and are beyond the scope of the present discussion. The results of Mears, Schabel, and Wentz (2003) shown in Figure 3.19 indicate a global warming trend in the troposphere over the past two decades of +0.097°C/decade.

The most recent paper on the subject of tropospheric temperatures is Christy *et al.* (2007). As always, the arguments are complex and intricate, and the results do not necessarily inspire high confidence. As Christy *et al.* (2007) said:

> "Deep layer observations from satellites have excellent spatial coverage but suffer from intersatellite biases, calibration deficiencies, and drifting orbits. Uncertainty

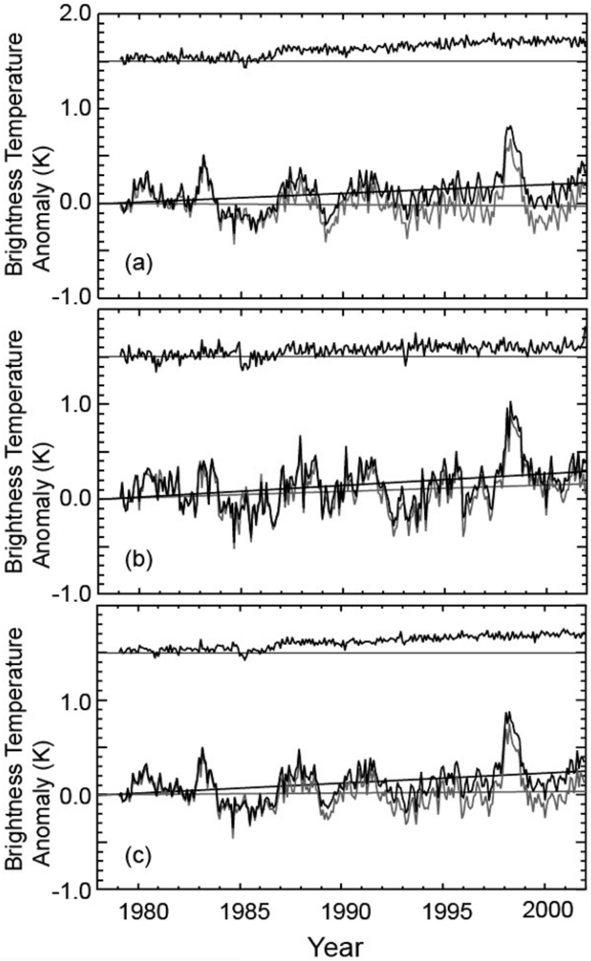

Figure 3.19. Trends in global MSU Channel 2 brightness temperatures. Black traces are from Mears, Schabel, and Wentz (2003) while gray traces are adapted from Christy, Spencer, and Braswell (2000). Differences are also shown. (a) Ocean-only. (b) Land only. (c) Ocean and land.

in their corrections can be of the same magnitude as the long-term trends being sought. Thus observational uncertainty makes checking the variability of modeled vertical temperature more difficult.''

''These data are observed by complicated instruments that measure the intensity of the emissions of microwaves from atmospheric oxygen, requiring physical relationships to be applied to the raw satellite data to produce a temperature value. Further, the program under which these satellites were designed and operated was intended to improve weather forecasts, not to generate precise, long-term climate records. Since 1992, the UAH LT data set has been revised seven times or about once every 2 to 3 years. There is no expectation that

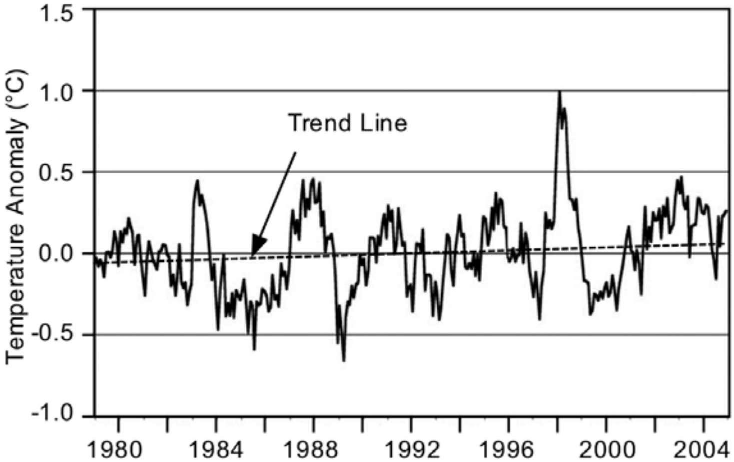

Figure 3.20. Tropospheric temperature over two decades. Adapted from Christy *et al.* (2007).

> the current version will not continue to be revised similarly as better ways to account for known biases are developed and/or new biases are discovered and corrected. Thus the production of climate time series from satellites will continue to be a work-in-progress. Usually, developers of data sets underestimate the measurement error ranges of their products. To this point ... the degree of veracity of the comparison data sets has not been established.''

The result of analysis by Christy *et al.* (2007) led to Figure 3.20 illustrating their conclusion that a comparison of satellite and radiosonde measurements at tropical sites led to a trend in the range 0.07°C to 0.13°C and the satellite measurements for all the tropics led to a trend of 0.05°C to 0.07°C. These remain low compared with the reported surface trend of ~0.13°C. However, these trends were established over a short period of about two decades, and the variations about the trend line are so large compared with the slope of the trend that addition or subtraction of one major ''bump'' in the curve can significantly change the trend, possibly even reversing its sign.

The U.S. Climate Change Science Program maintains a website (Anon. (L)) with a number of reports and news releases. Their review of troposphere temperatures (Wigley *et al.*, 2006), written two years prior to Christy *et al.* (2007), presents a much more reassuring viewpoint. It was claimed that whereas ''early versions of satellite and radiosonde data showed little or no warming'' in the troposphere, and this had ''been used to challenge the reliability of climate models and the reality of human-induced global warming'', this problem ''no longer exists because errors in the satellite and radiosonde data have been identified and corrected''.

However, they admit that some data sets indicate greater warming at the surface (than in the troposphere), while others indicate just the opposite.

> "Thus, due to the considerable disagreements between tropospheric data sets, it is not clear whether the troposphere has warmed more than or less than the surface ... Although the majority of observational data sets show more warming at the surface than in the troposphere, some observational data sets show the opposite behavior."

In addition, there is considerable variance in the predictions of GCMs:

> "The most recent climate model simulations give a range of results for changes in global-average temperature ... Over the period since 1979, for global-average temperatures, the range of recent model simulations is almost evenly divided among those that show a greater global-average warming trend at the surface and others that show a greater warming trend aloft."

Thus, this website appears to be intent on brushing over discrepancies:

> "There is no fundamental inconsistency among these model results and observations at the global scale."

This attempt to "put on a happy face" seems quite artificial:

> "Given the range of model results and the overlap between them and the available observations, there is no conflict between observed changes and the results from climate models."

In other words, there is no disagreement between models and data because neither the models nor the data are self-consistent enough to allow a comparison to be made!

Wigley *et al.* (2006) also endorse the alarmist viewpoint:

> "Studies to detect climate change and attribute its causes using patterns of observed temperature change in space and time show clear evidence of human influences on the climate system (due to changes in greenhouse gases, aerosols, and stratospheric ozone)."
>
> "The observed patterns of change over the past 50 years cannot be explained alone by natural processes, nor by the effects of short-lived atmospheric constituents (such as aerosols and tropospheric ozone)."

The first of the above quotes seems to be quite an extrapolation from variable measurements of tropospheric temperatures, and the second quote would be satisfactory if *"cannot be explained"* were replaced by *"have not been explained"*.

3.2.7 Diurnal temperature range

Vose, Easterling, and Gleason (2005) reported data on maximum temperatures, minimum temperatures, and diurnal temperature range over the equivalent of

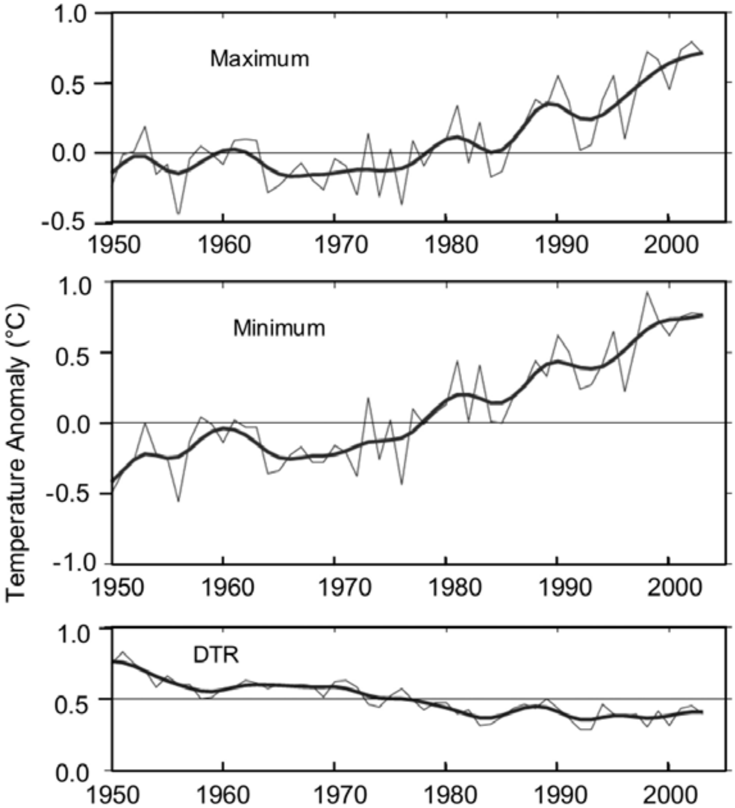

Figure 3.21. Trends in maximum temperatures, minimum temperatures, and diurnal temperature range over the equivalent of 71% of the total global land area. Adapted from Vose, Easterling, and Gleason (2005).

71% of the total global land area. Their results for global land areas are shown in Figure 3.21. The minimum temperature increased more rapidly than the maximum temperature (+0.20°C/decade vs. +0.14°C/decade) from 1950 to 2004, resulting in a significant DTR decrease (−0.066°C/decade).

Over the most recent period from 1979 to 2004, the trends in maximum and minimum temperatures were nearly equal at +0.29°C/decade resulting in almost no change in the DTR.

The changes in temperature and DTR were considerably greater in the NH than in the SH.

Leathers *et al.* (1998) analyzed variations in the DTR across the U.S. They found that the annual cycle of the DTR across the U.S. varies both spatially and temporally and is associated in one manner or another with moisture content of the atmosphere. In many areas the DTR undergoes large abrupt changes in magnitude at specific times within the annual cycle.

The DTR was characterized in three regions of the U.S. as follows:

Region	*DTR in summer*	*DTR in winter*
Entire northern tier of the country from Maine, westward to Washington, and then south along the Pacific coast	Maximum	Minimum
Southern tier of the United States from the southeast coast to Texas	Minimum	Maximum
The remainder of the U.S.	Maxima during spring and fall; minima in summer and winter	

Urbanization produces reductions in DTR because heat is emitted during the night by urban structures and roads, as discussed in Section 5.2.5. Degaetano and Allen (2002) found significant effects of urbanization, particularly in regard to unusually warm nights.

3.2.8 Ruminations of Bob Foster

R. J. Foster of Australia has written a series of articles that present a different viewpoint on global warming (Foster, 2001).

Foster began by stating three principles of relevance here:

- It is unwise to deny tangible data just because we do not yet know why things are so.
- A dominant paradigm is not withdrawn by its custodians, but overthrown from outside.
- The advancement of science is not a matter of voting.

There is no need to elaborate on these tenets, because they are self-evident.

Two central points made by Foster are

1. An examination of Figure 3.9 suggests that starting around 1976–1977, a sudden and decisive change occurred in the Earth's climate, sending near-surface temperatures spiraling upward since then. Foster also discerned an earlier period of moderate temperature rise from 1910 to 1945. The gap between 1945 and 1976 is slightly downward.
2. By contrast, temperatures in the troposphere, as measured by satellite, were quite flat. Foster said this data "reveals modest warming in the Northern Hemisphere, but slight cooling in the Southern Hemisphere." He also pointed out: "if the influence of the prominent El Niño warm event in 1998 were to be ignored, the globally-averaged temperature of the atmosphere would display a cooling trend." This led him to conclude that the absence of a warming trend in the

lower atmosphere (except for a single step rise in 1976–1977) indicates the absence of a significant greenhouse effect.

Foster proposed an "oceanic impedance" hypothesis of global climate change. Basically, he claimed that a change occurred in ocean upwelling in 1976–1977 that persisted thereafter, causing the oceans to warm, which in turn caused the observed increase in near-surface temperature on Earth that followed this event. Further details on this phenomenon are given in Section 5.2.11. The amount of heat brought to the surface by El Niños is tremendous.

His model seems to be perhaps as credible as the greenhouse model. However, like most people concerned with global warming, he seems to be absolutely sure that he is right and harbors no doubt at all about his hypotheses.

3.2.9 European temperatures: 1751–1995

Balling, Vose, and Weber (1998) pointed out:

> "For most of the planet, temperature records are sparse, particularly before the turn of the 20th century. Large ocean basins, desert regions, and mountainous areas are especially limited in their long-term historical temperature records. When interest is focused on temperature records that extend back in time by more than a century, few areas qualify for any meaningful analysis."

Fortunately, records are available at around 50 sites across Europe that date back as far as 1751. Balling, Vose, and Weber performed a detailed analysis of these temperature records. Their results are shown in Figure 3.22. There were rather wide swings in temperature from year to year. The coldest time in the 11-year running average curve during this period was around 1890. There was a significant

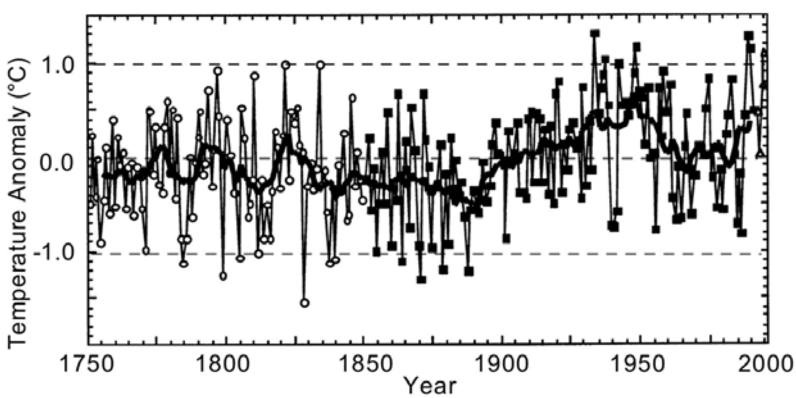

Figure 3.22. Temperature anomalies averaged over about 50 European sites from 1751 to 1995, referenced to a norm taken as the average for European temperatures for 1890 to 1950. The heavy line is an 11-year running average.

temperature rise between 1890 and 1950, and a dip between 1950 and 1970, and a fairly sharp rise from 1980 to 2000.

Balling, Vose, and Weber suggested that urbanization may have contributed significantly to the rise from 1890 to 1950. This was based on the observation that oceanic temperatures rose far less rapidly than land temperatures. It was also noted that the greatest warming occurred in the winter months, which is predicted by climate models for greenhouse gases. However, the effects of urban heat islands are also likely to be greater in the winter months as well. As Balling, Vose, and Weber pointed out, even though Europe only represents 2% of the Earth's surface (7% of the land surface), it provides the only credible data base for temperatures that date back this far in time.

4

Variability of the Sun

The Sun is the powerhouse that drives the Earth's climate. No understanding of climate change is possible without an understanding of the behavior of the Sun.

4.1 SOLAR IRRADIANCE

4.1.1 Introduction

We know from geological evidence that over the past million years (and more), the Earth has gone though many thermal cycles of glaciation ("ice ages") and intervening warm periods. It is widely believed that variations in the Earth's orbit are associated with these climate changes, although the correlation of models with geological data appears to be far from perfect. Other factors, including variation of solar irradiance, may also be involved. The last great ice age peaked some 20,000 years ago and we have been in a post-glacial warming period for the past ~11,000 years.

We also have evidence that over the past millennium or so, there have been smaller fluctuations in the Earth's climate. The MWP and the LIA represent fluctuations during this time period. Since these events occurred prior to the recent major industrialization, they were due to land clearing and naturally occurring phenomena, possibly variations in *total solar irradiance* (TSI), changes in ocean currents, and for short periods, volcanic eruptions.

Today, we are in a period of global warming, and it is not immediately clear whether long-term variability of the TSI might have contributed significantly to this effect. The Earth is clearly warmer in 2000 than it was in any period over the past 500 years or so. How much of this could be due to an increase in TSI?

It has been assumed in the past that the TSI is quite constant, and indeed, many papers and books refer to the "solar constant". However, there is no experimental basis for this assumption. Since 1978, measurements of TSI have commenced in

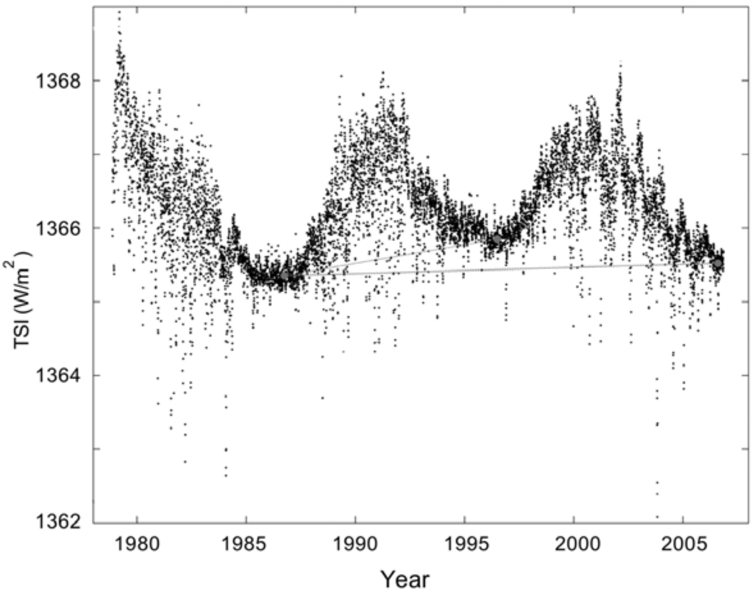

Figure 4.2. Composite of TSI measurements as developed by Willson. Adapted from Willson (2006).

space. While relative variations in TSI are measured with high precision, absolute calibration has been more difficult (see Figure 4.1, color section). Nevertheless, we have good measurements of TSI over a period of about 25 years (see Figure 4.2). These measurements indicate that the TSI varies slightly (about 0.1%) over the ~11-year solar cycle. If we simplistically extrapolate these data backward in time, such variations appear to be too small to explain the temperature variations in the MWP or the LIA.

There are two major reasons to estimate the variability of TSI over the past millennium. One reason is to estimate whether such variability is sufficient to explain the putative climate variations of the MWP and the LIA. A second reason is to provide a comparison of the solar forcing of today's Earth's climate with solar forcing during previous periods in the past millennium. This would help in the critically important problem of distinguishing between natural (solar) variations as a cause of global warming vs. anthropogenic contributions (via greenhouse gas effects).

Fragmentary bits and pieces of evidence exist regarding past variations in solar activity in general, and TSI in particular. These include recorded variations in sunspot numbers and length of the solar cycle (see Sections 4.2 and 4.4). A number of attempts have been made to reconstruct variations in TSI over the past millennium using these data. In addition, there is evidence from cosmogenic nuclides, and comparison of our Sun with behavior of Sun-like stars (see Section 4.4.4). Depending on the assumptions made, a wide range of results is possible. These range from solar variations acting as the major warming factor in the 20th century to solar variations being a minor contributor to recent global warming. At this juncture, it does not seem possible to unequivocally resolve the past variations in TSI. The various methods and assumptions are discussed in considerable detail in Section 4.4.

For any given level of solar forcing of the Earth's climate, the impact of variations in TSI on global temperatures is an important consequence. This is discussed in Section 4.6.

There are many reconstructions of past TSI. However, even the best of these are quite speculative.

4.1.2 Measurements of TSI in space since 1978

Monitoring total solar irradiance (TSI) from the ground is plagued by problems due to atmospheric absorption and scattering, weather, and other environmental factors. Variations in the extraterrestrial TSI were first measured by a new generation of electrically self-calibrating cavity sensors on extended spaceflight experiments that began in the late 1970s. The instruments typically utilize a pair of closely matched hollow cavities. One faces the Sun and is warmed by absorption of solar irradiance. The other faces away from the Sun and is electrically heated to bring it to the exact same temperature as the one facing the Sun. This provides an electrical power equivalent to the solar irradiance.

These instruments were capable of reducing the uncertainties of total solar irradiance TSI monitoring by several orders of magnitude. The modern record began with observations by the Earth Radiation Budget (ERB) experiment on the NOAA Nimbus 7 satellite (1978–1993). This was followed by the first experiment designed specifically for precision TSI monitoring, the Active Cavity Radiometer Irradiance Monitor (ACRIM1) on NASA's Solar Maximum Mission (SMM) (1980–1989).

The ACRIM1 experiment invoked a new mode of in-flight calibration that provided the first unambiguous detection of intrinsic solar variability on timescales from minutes to the sunspot cycle. The ACRIM1 experiment was followed by the Earth Radiation Budget Satellite Earth Radiation Budget Experiment (ERBS/ERBE) in 1984 and the Upper Atmosphere Research Satellite (UARS) ACRIM2 experiment in 1991. Three satellite TSI monitoring experiments were operational in early 2007: the Solar Heliospheric Observer (SOHO) Variability of solar Irradiance and Gravity Oscillations (VIRGO) launched in 1995, the ACRIMSAT/ACRIM3 launched in 1999, and the Solar Radiation and Climate Experiment (SORCE) Total Irradiance Monitor (TIM) launched in 2003. The ACRIMSAT/ACRIM3 and SORCE/TIM experiments are operating at full capabilities but the SOHO satellite and VIRGO instrument have had some performance degradation occurrences and after more than 10 years in operation the SOHO/VIRGO experiment's remaining useful lifetime is uncertain. A summary of the current TSI monitoring database is shown as Figure 4.1 (color section). These data are corrected for the slightly elliptical orbit of the Earth and adjusted to 1 AU distance from the Sun.

The absolute accuracy of these instruments is far less precise than their relative accuracy. Thus, if all of these measurements are scaled to the same standard and joined to form a continuous record, one obtains Figure 4.2.

Figure 4.2 shows that over the 11-year solar cycle, the mean TSI varies by about 0.14% in going from solar minimum (SMIN) to solar maximum (SMAX). There are wider swings in TSI on a daily basis, as much as $\pm 0.2\%$ (Willson, 2006).

4.1.3 Short-term TSI models

The short-term variations in TSI described in Section 4.1.2 have been analyzed in terms of sunspots and faculae on the surface of the Sun, and it appears that such solar surface features account for most of the observed short-term variations in TSI. It is possible to extrapolate TSI to time periods prior to the 1970s for periods in which sunspots and faculae have been carefully measured, based on correlations between TSI and sunspot and faculae characteristics observed post-1978. However, this would not account for any slowly varying long-term secular components to the TSI that are not discernible from two or three cycles of data. We will have more to say about this in Section 4.4.

Solanki, Krivova, and Wenzler (2005) describe models for predicting daily variations of TSI in terms of sunspots and faculae. The model includes a regression formula for the variation of TSI in terms of sunspot umbrae, penumbrae, and faculae measurements. An illustration of their results is shown in Figure 4.3.

As a consequence of the Sun's rotation we cannot exclude the possibility that energy transport to the surface and its emission into space is anisotropic. Anisotropy is therefore an additional potential source of variability. Some anisotropy is caused by the 27-day solar rotation (Beer, Mende, and Stellmacher, 2000).

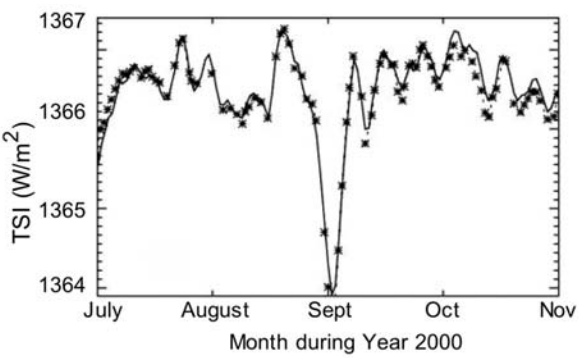

Figure 4.3. Comparison of calculated TSI (line) based on short-term correlations of TSI with sunspots and faculae with measured values (points). Adapted from Solanki, Krivova, and Wenzler (2005).

4.1.4 Long-term TSI models

According to Beer, Mende, and Stellmacher (2000), the long-term energy flow from the Sun (irradiance) is determined by the rate of fusion of hydrogen to helium in the solar core on a billion-year timescale and follows a hyperbolic trend. However, the short-term deviations from this trend are extremely small. From physical models of the Sun's evolution it was computed that the early solar radiation output 4 billion years ago, was only about 75% of today's output. Since then, the energy output of the Sun steadily increased and will continue to do so for another 4 billion years.

The energy transport through the radiative zone (0.3 to 0.7 solar radii) is probably very stable on a million-year timescale and does not generate any measurable variability. However, the heat transport through the convective zone (0.7 to 1.0 solar radii) is related to convective and magnetic structures. It is probably the main source of variability of solar radiation on timescales of years to 100 kyr.

Irradiance variability is essentially due to the response of the outer solar layers to thermally or magnetically driven excitation near the bottom of the convection zone. This excitation also generates the conspicuous photospheric features such as sunspots and faculae. So, short-term irradiance and solar surface features have a common cause that explains their high correlation.

The rate of change of the fusion process is extremely small (10^{-4} W/m^2) per 1,000 years. Therefore, the variability potential of the fusion process is completely negligible in regard to current climate change. However, it is interesting to ask how the Earth has managed to remain a habitable planet with globally distributed liquid water during the past 4 billion years and why it did not turn either into an icy or a hot planet? This question is known as the "the early faint Sun paradox". It might well be that higher levels of greenhouse gases from active volcanism kept the Earth warm despite the much lower solar irradiance.

4.2 ASPECTS OF SOLAR VARIABILITY

4.2.1 The solar cycle

As Beckman and Mahoney (1998) pointed out:

> "We are all familiar with the 11-year sunspot cycle. One familiar factor is the effect of solar activity on short-wave radio communications. During sunspot maximum high-energy protons and alpha particles from the Sun affect the ionosphere, reducing its effectiveness as a mirror from which short radio waves are reflected round the world, disrupting transmissions for days at a time. The association with the presence of large numbers of dark spots on the solar disc is widely known, and well understood, and it is also clear that such maxima repeat every 10 or 11 years, with minima between them ... The key impulse here was the work of Eddy in the late 1970s, focused especially on the historical period between 1645 and 1715, for which there is evidence that sunspot activity was strongly suppressed or virtually absent. If this is accepted as true, it has strong implications

for our ideas of how magnetic fields in stars are produced. Of more impact, it might go some of the way, even all of the way, to explaining the observed pattern of global warming of the Earth in the last decades of the 20th century.''

4.2.2 Sunspots

Sunspots (Figure 4.4, color section) are dark, planet-sized regions that appear on the ''surface'' of the Sun. Sunspots are ''dark'' because they are colder than the areas around them. A large sunspot might have a temperature of about 4,000 K. This is much lower than the 5,800 K temperature of the bright photosphere that surrounds the sunspots (Anon. (M)).

Sunspots are only dark in contrast to the bright face of the Sun. If you could cut an average sunspot out of the Sun and place it in the night sky, it would be about as bright as a full moon. Sunspots have a lighter outer section called the penumbra, and a darker middle region named the umbra.

Sunspots are caused by the Sun's magnetic field welling up to the photosphere, the Sun's visible ''surface''. The powerful magnetic fields around sunspots produce active regions on the Sun, which often lead to solar flares and Coronal Mass Ejections (CMEs).

Sunspots form over periods lasting from days to weeks, and can last for weeks or even months. The average number of spots that can be seen on the face of the Sun is not always the same, but goes up and down in a cycle. Historical records of sunspot counts show that this sunspot cycle has an average period of roughly 11 years although it has varied widely over the past century.

Our Sun isn't the only star with spots. Just recently, astronomers have been able to detect ''starspots'' (''sunspots'' on other stars).

Some sunspots expand with time and evolve into ''groups'' (Figure 4.5, color section).

4.2.3 Faculae

Faculae are hot structures in active regions of the Sun (Figure 4.6, color section).

Faculae = plural of facula, Latin for ''small torch''. They were originally discovered near the limb in full-disk images of the Sun. Faculae are the small, bright, patterns around dark sunspots and in the ''photospheric network''.

> ''Modeling of sunspots ... confirms that their darkness can be understood as thermal 'plugs' in which intense vertical magnetic fields divert heat flow from deeper layers. Magnetic brightenings act in the opposite sense, as local thermal leaks. They are bright because the effect of their smaller-scale magnetic field is to form small depressions in the photospheric surface, enabling radiation from lower and hotter atmospheric layers to escape more easily ... Calculations with a thermal impedance model of solar luminosity variation show that the heat flux diverted by a spot is not merely shunted aside to reappear nearby. Instead, the

blocked heat flux effectively remains stored in the Sun for hundreds of millennia instead of appearing elsewhere on the surface ..." (Foukal *et al.*, 2006).

The Sun's remarkable ability to store energy, rather than quickly reradiate fluctuations in heat flow to the photosphere is due to the fact that diffusion of heat within the Sun is rapid compared with the rate at which it radiates. The radiative equilibrium timescale is about 100,000 years.

4.2.4 Sunspot indices

Two major reconstructions of solar activity have been made on the basis of direct observations of the Sun. The International Sunspot Numbers (Wolf or Zürich sunspot numbers) have long served as the primary time series defining solar activity since the year 1700. This time series was derived by Rudolf Wolf in the 19th century and has been maintained by his successors. Wolf defined the sunspot number, R_Z, as

$$R_Z = k(10g + f)$$

where g is the number of sunspot groups, f is the number of individual sunspots, and k is a correction factor for each observer. For years prior to 1817, the number of missing days was so great that Wolf only tabulated monthly means. There are no observations for many months from 1749 to 1818, as well as for a few months after 1818. Wolf filled in these months by interpolation and using magnetic needle observations. Thus, the numbers R_Z are a mixture of direct sunspot observations and estimated values (Vaquero, 2007).

Hoyt and Schatten (1998) made a new reconstruction of solar activity from sunspot observations. This time series is known as the Group Sunspot Number, R_G, because it uses the observed number of sunspot groups. Hoyt and Schatten (1998) defined the Group Sunspot Number as a sum of the number of sunspot groups observed, times a normalization factor, chosen to make the mean of R_G identical with the mean of R_Z for 1874 through 1976. Daily, monthly, and yearly means were derived from 1610 to the present. Hoyt and Schatten (1998) calculated daily values of solar activity on 111,358 days for 1610–1995, compared with 66,168 days for the International Sunspot Numbers, as well as tabulated estimates of their random and systematic errors. This series has complete or nearly complete coverage from about 1800 to 1995 and from 1645 to 1727 (Figures 4.7–4.9).

The Group Sunspot Numbers are strongly recommended for analysis of sunspot activity before 1880. The Wolf and Group numbers are not fundamentally different alternative proxies of solar activity because the Group numbers are an upgrade of the Wolf numbers. Hathaway, Wilson, and Reichmann (2002) concluded that the R_G numbers are most useful for extending the sunspot cycle data further back in time and thereby adding more cycles and improving the statistics. However, the R_Z numbers are slightly more useful for characterizing the ongoing levels of solar activity.

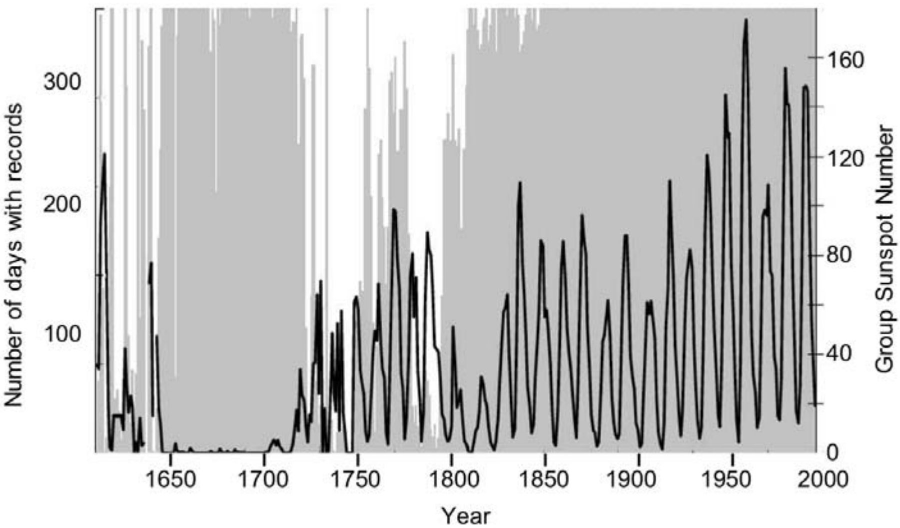

Figure 4.7. Estimated group sunspot numbers (right scale) since ~1600. Gray bars are days with records. Adapted from Vaquero (2007).

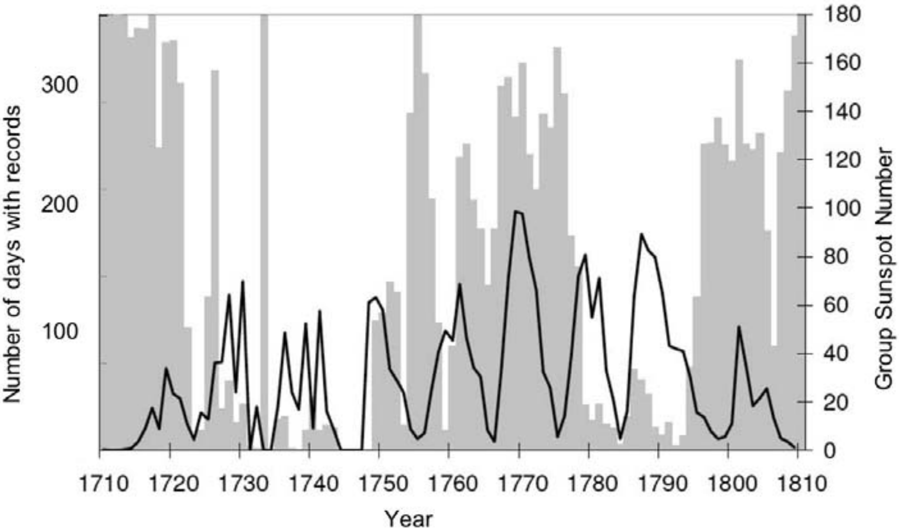

Figure 4.8. Estimated group sunspot numbers (right scale) from 1728 to 1799. There are many years with only sparse observations. For 1744–1745, and 1747, there exist no reports of sunspot observations. Adapted from Vaquero (2007).

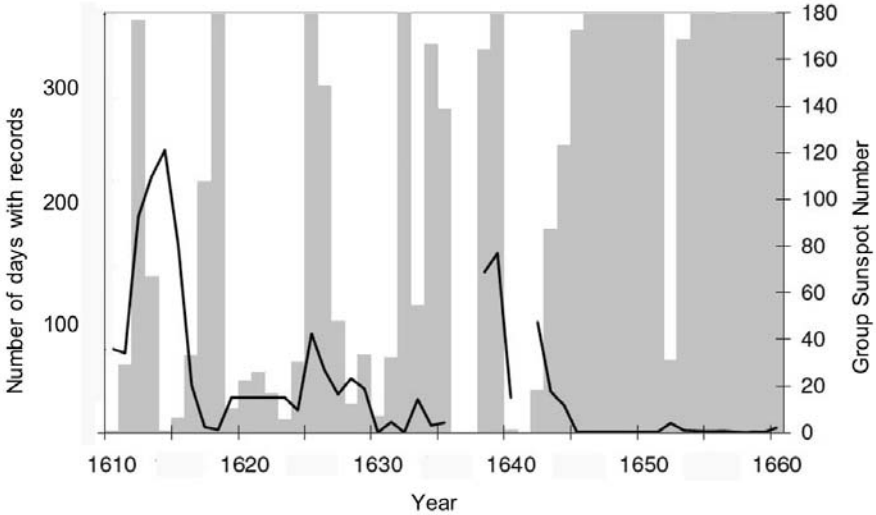

Figure 4.9. Estimated group sunspot numbers (right scale). From 1610 to 1644 there are many years with only sparse observations. For 1636–1637 and 1641, there exist no reports of sunspot observations. Lines indicate sunspot numbers observed. Adapted from Vaquero (2007).

The characteristics of the R_Z and R_G series are very similar for the 19th and 20th centuries (see Figure 4.10). Twenty-five year moving averages of the two indices are presented in Figure 4.11, showing the long-term differences between them.

The various solar cycles are numbered, with the cycle that reached solar maximum just after year 2000 designated as Cycle 23, and Cycle 1 being the cycle that reached solar maximum around 1760.

4.2.5 Estimation of sunspot activity from proxies

Usoskin *et al.* (2003) carried out an analysis leading to estimates of sunspot number as far back as 850 based on the measured ^{10}Be concentrations in ice cores drilled at the Dye-3 site in Greenland (annual data for 1424–1985) and at the South Pole (roughly 8-year sampled data for 850–1900). The methodology is quite complex and depends on the several sequential steps. The isotope ^{10}Be is formed in the Earth's atmosphere by the impact of cosmic rays on oxygen or nitrogen. The flux of cosmic rays that impinges on the Earth's atmosphere is reduced during SMAX and increases during SMIN due to the effect of the higher magnetic fields between the Sun and Earth during SMAX. These magnetic fields provide a partial shield against energetic particles. The actual model is a three-step process for any year: (a) the ^{10}Be concentration is used to estimate the cosmic ray flux, (b) the cosmic ray flux is used to estimate the solar open magnetic flux, (c) the sunspot number is estimated from the solar magnetic flux. The resultant reconstruction is shown in Figure 4.12 (color section). In this figure, data from Antarctica are shown in red and those from

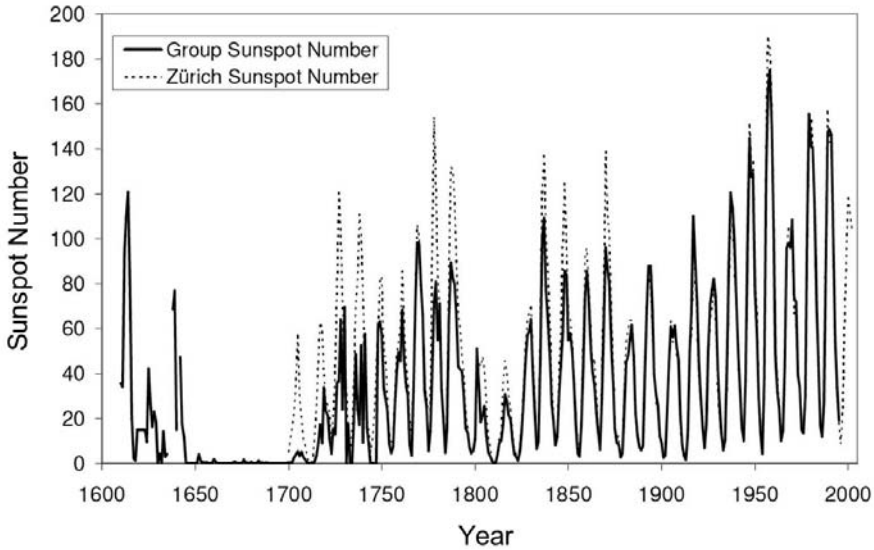

Figure 4.10. Comparison of R_G and R_Z series. Cycle 22 is the leftmost cycle in this plot. Adapted from Vaquero (2007).

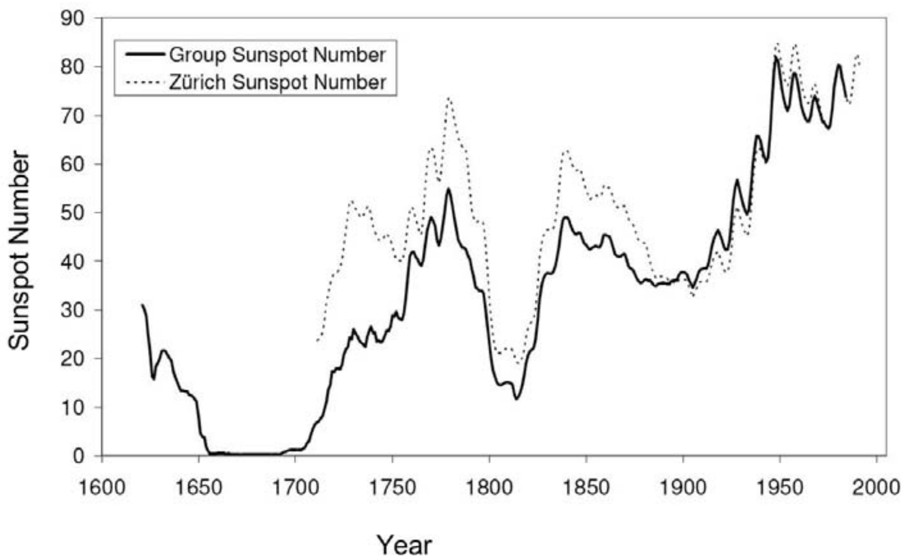

Figure 4.11. Comparison of 25-year moving averages of R_G and R_Z series. Adapted from Vaquero (2007).

Greenland are blue. The orange curve shows the observed group sunspot number since 1610 and the dashed black curve shows the (scaled) ^{14}C concentration in tree rings, corrected for variation of the geomagnetic field. The gray areas indicate the times of minima and maxima. The temporal lag of ^{14}C with respect to the sunspot number is due to the long attenuation time for ^{14}C. If these data are correct, it would imply that the sunspot numbers at SMAX are higher today than they have been for 1,000 years.

4.2.6 Diameter of the Sun

According to Foukal *et al.* (2006), measurements of the solar diameter originally attracted attention because solar diameter variations seemed to offer a unique diagnostic of otherwise unobservable internal temperature variations. However, data from the Michelson Doppler Imager (MDI) instrument on the SOHO spacecraft show no evidence of secular trends in diameter, or variations attributable to the 11-year cycle at the level of a few milli-arcseconds (a few kilometers on the Sun). This is consistent with, but ten times better than, upper limits from the best ground-based measurements of the Sun's diameter. However, conflicting detections nearly two orders of magnitude larger continue to be cited. Foukal *et al.* (2006) concluded that it is unlikely that diameter measurements can reveal deeper lying sources of solar irradiance variation, as was originally hoped. In fact, such measurements put strict limits on the presence of such sources. Their small amplitude also implies that changes in the size of the solar disk contribute negligibly to the TSI.

4.2.7 Indices of solar activity

A number of geomagnetic indices have been devised for characterizing the activity of the Sun. These include

1. Planetary magnetic activity indices (K_p, a_p, and A_p)
2. Planetary daily character figure (C_p, $C9$, C_i)
3. Geomagnetic *aa* Index (*aa*, *Kpa*)
4. Geomagnetic *am* Index (*am*, *an*, *as*, *Km*, *Kn*, *Ks*, *Am*, *An*, and *As*)
5. Disturbance Storm-Time Index (D_{st})
6. Bartels solar rotation number
7. International Sunspot number (R_z, R_i)
8. Ottawa 10.7 cm solar radio flux adjusted to 1 AU ($F_{10.7}$)
9. Auroral Electrojet Index (AE)
10. Polar Cap Index (PC)
11. Comprehensive Flare Index (CFI)

These are beyond the scope of the present discussion, but they are described at the following website:

http://www.spenvis.oma.be/spenvis/help/background/indices.html

The coronal source surface occurs where the solar magnetic field becomes approximately radial and lies at a heliocentric distance of about 2.5 solar radii. The total magnetic flux leaving the Sun, and thereby entering the heliosphere by threading through this surface, is the coronal source flux, F_s. Lockwood and Stamper (1999) and Lockwood (2002) have developed techniques for estimating F_s (see Section 4.4.7).

4.2.8 Effect of the Sun–Earth distance

The orbit of the Earth about the Sun is slightly elliptical. The Sun is located at one focus of the ellipse. The length of the semi-major axis of the ellipse is called the astronomical unit (AU), and is equal to 1.496×10^8 km. The eccentricity of the ellipse is 0.017, so the Earth–Sun distance varies from 0.983 AU around January 1 to 1.017 around July 1. Thus, the amplitude of the annual variation in the Earth–Sun distance is about 3.4%. Since the extraterrestrial TSI at the top of the Earth's atmosphere is proportional to the square of the distance to the Sun, the variation in TSI from January 1 to July 1 is about 6.8%. For a nominal TSI of $\sim$1,366 W/m^2, the annual variation (from high to low) due to the elliptical orbit is $0.068 \times 1{,}366 \sim 93$ W/m^2. However, when spread over the spherical surface of the Earth, this amounts to $93/4 \sim 23$ W/m^2. That is a huge variation. As Section 4.4 shows, the expected maximum long-term variation in TSI over the past millennium is somewhere in the range 2 W/m^2 to 10 W/m^2. Section 4.1 showed that the current variation from SMIN to SMAX is around 1.3 W/m^2. As Section 4.6 shows, a consistent long-term change in TSI of 93 W/m^2 would produce a large change in Earth temperature, leading to worldwide massive climate change. However, the time lag in establishing a new equilibrium when the TSI is changed reduces the impact of these annual fluctuations. Therefore, the Earth acts as a rectifier to damp out the annual variations (and even the 11-year variations) and ideally, the Earth reacts to the average of TSI changes that occur annually. However, the 23 W/m^2 annual variation is so large, considering the chaotic nature of Earth feedback systems and climate response, that it could conceivably trigger global climate changes that could mask the effects of smaller long-term changes.

As Section 4.4 shows, a number of investigators have attempted to infer how the average value of TSI has varied in the past, before measurements were begun in 1978. The motivation for this was to try to explain inferred historical temperature variations prior to the industrial age. But the problem is made more difficult because one is trying to identify the effect of slowly varying (decades to centuries) changes of perhaps a few W/m^2 in TSI, while the solar cycle is producing changes of $\sim$1 W/m^2 every $\sim$11 years and the Earth's orbit is producing changes of 93 W/m^2 on an annual basis.

4.3 THE MAUNDER MINIMUM; JOHN EDDY'S STUDY

4.3.1 Historical telescope observations of sunspots

Eddy (1976) wrote an authoritative paper on the Maunder Minimum (MM) in 1976 that has greatly influenced thinking about global climate variations ever since. In this paper, Eddy traced out the history of accumulation of data on sunspot observations and suggested that the reliability of the data may be graded into four epochs.

1. Reliable from 1848 to the present
2. Good from 1818 through 1847
3. Questionable from 1749 through 1817
4. Poor from 1700 through 1748.

In addition, he traced out reports from various sources that indicated that the number of sunspots was minimal (or almost zero) for a 70-year period from 1645 to about 1715, and a more speculative indication that sunspot numbers may have been low for many years prior to 1645, which in turn might suggest that the era of higher sunspot numbers we have witnessed since 1715 may be an aberration from "normalcy". These sources were initially accumulated by E. W. Maunder around the turn of the 20th century, which is why the period of low sunspot numbers in the late 17th century is referred to as the "Maunder Minimum" (MM).

Eddy's paper is lengthy and detailed, and should be required reading for anyone interested in global climate change. Only a very brief summary is given here. Eddy provides the following arguments.

Observation of sunspots was well within the capability of observers with simple optical telescopes in the 17th century, and probably the latter half of the 16th century. Many reports of sighting an occasional sunspot *as a rarity* during the MM indicate their prevalent absence during that period even though specific counts may not have been available.

4.3.2 Historical records of aurorae

Eddy (1976) said:

> "Records of occurrence of auroras offer an independent check on past solar activity since there is a well-established correlation between sunspot number and the number of nights when aurorae are seen. Auroral displays are produced when charged particles from the Sun interact with the Earth's magnetic field, resulting in particle accelerations and collisions with air molecules in our upper atmosphere. Aurorae register, therefore, those particle-producing events on the Sun (such as flares and prominence eruptions) that happen to direct their streams toward the Earth. Since these events arise in active regions on the Sun, where there are also sunspots, we find a strong positive correlation between reported numbers of the two phenomena. Aurorae are especially valuable as historical indicators of

solar activity since they are spectacular and easily seen, require no telescopic apparatus, and are visible for hours over wide geographic areas ... An increase in the number of reported aurorae inevitably follows a major increase in solar activity, and a drop in their number can generally be associated with the persistence of low numbers of sunspots, with certain reservations. As with sunspots, aurorae will not be seen unless the sky is reasonably clear, and an absence of either on any date in historical records could be due simply to foul weather ... The period between 1645 and 1715 was characterized by a marked absence of aurorae. Far fewer were recorded than in either the 70 years preceding or following."

Eddy (1976) went on to present quantitative data on aurora observations to back up these conclusions.

4.3.3 Historical visual observations of sunspots

Eddy also provided information on historical observations of sunspots by eye prior to the advent of the telescope, including Asian reports dating back to 300 AD. The data are fragmentary and sporadic, but to the extent that they are credible (which is difficult to judge) they suggest that sunspot activity may have been relatively low for 2,000 years prior to the MM.

4.3.4 ^{14}Carbon in tree rings

Eddy also discussed evidence provided by the abundance of terrestrial ^{14}C in tree rings. This isotope of carbon is continuously formed through the action of galactic cosmic rays acting on ordinary ^{12}C in the CO_2 in the atmosphere. This process is modulated by solar activity. When the Sun is active, magnetic fields between the Sun and the Earth reduce the number of incoming galactic cosmic rays that reach the Earth. At these times, corresponding to maxima in the sunspot cycle, the amount of ^{14}C produced in the atmosphere is lower, and therefore less ^{14}C is found in tree rings formed at such times. When the Sun is quiet, terrestrial bombardment by galactic cosmic rays increases and the ^{14}C proportion in the atmosphere rises. Since tree rings are automatically dated as 1 year per ring, a yearly history of ^{14}C deposition into trees can be derived. However, there is a time lag of 10 to 50 years because of the finite time required for distribution of ^{14}C in the atmosphere and absorption by trees. Therefore, the ^{14}C abundance in any tree ring is not an instantaneous record of the solar activity in that year, but is somehow a representation of the previous few decades. During periods of several decades where solar activity is relatively constant, the tree rings should provide an indicator of relative solar activity. Eddy reported that the first major anomaly found in studies of ^{14}C history was a marked and prolonged increase that reached its maximum between about 1650 and 1700, in remarkable agreement in sense and date with the Maunder Minimum. The phenomenon, known in carbon dating as the "DeVries Fluctuation", peaked at about 1690. However, Eddy cautioned that one must take care in assigning any of the ^{14}C variations to a solar cause for there are other important mechanisms that can affect the flux of incoming galactic cosmic rays. The trajectories of such charged particles are affected by the Earth's magnetic field, which has varied considerably over time. Unfortunately, the ^{14}C index is not useful in modern times because of fossil fuel combustion, which introduces CO_2 with different carbon isotopic abundance ratios, the so-called "Suess Effect".

4.3.5 The solar corona

According to Eddy (1976), historical accounts of the solar corona at total eclipse offer another possible check on anomalies in past solar behavior. He pointed out that the shape of the corona seen at eclipse varies with solar activity: when the Sun has many spots, the corona is made up of numerous long, tapered streamers that extend outward like the petals of a flower. As activity wanes, the corona dims and fewer and fewer streamers are seen. At a normal minimum in the solar cycle the corona seen by the naked eye is highly compressed and blank. Coronal streamers are rooted in concentrated magnetic fields on the surface of the Sun, which are associated with solar activity and sunspots. As sunspots fade, so do concentrated surface fields and associated coronal structures. Eddy compared two cases. (1) In a total absence of solar activity, he expected to observe a dim, uniform glow around the Moon at eclipse: the zodiacal light, or false corona, would remain, since it is simply sunlight scattered from dust and other matter in the space between the Earth and the Sun. (2) At times of normal solar activity the corona seen at eclipse is a mixture of the true *K*-corona and the weaker glow of zodiacal light.

Eddy said that first-hand descriptions of total solar eclipses during the Maunder Minimum seem entirely consistent with an absence of the modern structured corona, but proof seems blurred by the customs of observing eclipses in the past and by the fact that scientists seldom describe what is missing or what is not thought to be important. Despite uncertainties in the historical record, Eddy concluded:

> "It thus seems to me more probable that, through much of the long period of the Maunder Minimum and the Spörer Minimum, extending between perhaps 1400 and 1700, the Sun was at such a minimum of activity that the *K*-corona was severely thinned or absent altogether ... In any case the corona as we know it may well be a modern feature of the Sun. It is an interesting question, and another important challenge for historians."

4.3.6 Beckman and Mahoney on Eddy's work

Beckman and Mahoney (1998) commented extensively on Eddy's work. The absence of sunspots for some 70 years in the 17th century was first pointed out by Spörer in 1887. A few years later it was noted that this dearth of sunspots apparently coincided with an absence of terrestrial aurorae. Much later, Maunder (1922) found a note by Flamsteed, the first Astronomer Royal, describing a sunspot seen at Greenwich in 1684, in which Flamsteed said that it is the first he had seen since 1674. In spite of Spörer's, and especially Maunder's advocacy, most specialists were fairly skeptical about the reliability of a prolonged sunspot absence. It was suspected that the main reason for few reports of sunspots from 1650 to 1715 was that people were not observing the Sun, or at any rate not systematically. Eddy showed that this was not the case.

Eddy (1976) succeeded in convincing many researchers that there was real evidence for the sunspot absence in the Maunder Minimum period. He also showed that the solar corona at eclipse during the period was strongly suppressed compared with its present exhibition of major streamers. In addition, he also looked at the tree ring ^{14}C record, and confirmed a high incidence of ^{14}C during that period. While Eddy's arguments for a lull in solar magnetic activity during the Maunder Minimum seems to be widely accepted, some controversy has arisen out of his claim that the Maunder Minimum coincided in time with an era of colder weather, and that by implication the absence of magnetic activity was accompanied by a net fall in TSI. An implicit corollary is that TSI in later years has been increasing, with a consequent warming of the Earth. Even this also seems to be widely accepted but controversy still surrounds the question of whether solar variability is sufficient to explain the full extent of Earth warming in the late 20th century.

4.3.7 Eddy's conclusions

In addition to the $\sim$70-year period of solar quiet during the Maunder Minimum (1645–1715) Eddy discerned a period of prolonged solar quiet between about 1460 and 1550 (which he called the Spörer Minimum) and a prolonged sunspot maximum between about 1100 and 1250 that is sometimes referred to as the Medieval Warm Period (although some other studies have placed the MWP a century or two earlier). He speculated that if the prolonged maximum of the 12th and 13th centuries and the prolonged minima of the 16th and 17th centuries are extrema of a repetitive cycle of solar change, the cycle has a full period of roughly 800–1,000 years. If this change is periodic, he further speculated that the Sun might now be progressing toward a grand maximum that might be reached in the 21st to 23rd centuries. He pointed out that the overall envelope of solar activity has been steadily increasing since the end of the Maunder Minimum, giving some credence to this view. The coincidence of the Maunder Minimum with the coldest excursion of the LIA suggests possible relations between the Sun and the terrestrial climate. These coincidences suggest a possible relationship between the overall envelope of the curve of solar activity and terrestrial climate in which the 11-year solar cycle may be effectively filtered out or simply unrelated to the problem. The mechanism of this solar effect on climate may be the simple one of ponderous long-term changes in the total radiative output of the Sun, or "solar constant". These long-term drifts in solar radiation may modulate the envelope of the solar cycle through the solar dynamo to produce the observed long-term trends in solar activity. The continuity, or phase, of the 11-year cycle would be independent of this slow, radiative change, but the amplitude might be controlled by it. According to this interpretation, the cyclic coming and going of sunspots would have little effect on the output of solar radiation, or presumably on weather, but the long-term envelope of sunspot activity carries the indelible signature of slow changes in solar radiation which surely affect our climate.

Eddy made a strong case that during the Maunder Minimum, solar magnetic activity was at a minimum and may have ceased altogether for periods of years. This appears to have caused a reduction in TSI during that period, but it is difficult to evaluate the magnitude of this decrease. (We shall have more to say about estimates of TSI during the MM in Section 4.4.) It seems likely that this caused colder weather, particularly at higher latitudes, but it is difficult to describe the climate in the late 17th century based on what we know today.

4.4 RECONSTRUCTING TOTAL SOLAR IRRADIANCE (TSI) IN THE PAST

4.4.1 Reconstructions based on sunspots, solar cycles, and solar activity

4.4.1.1 Introduction

The observed TSI record was shown in Figure 4.2. The variation in TSI between solar maximum (SMAX) and solar minimum (SMIN) is roughly 0.14%. Over the time interval covered by Figure 4.2, the sunspot numbers ranged from well over 100 at sunspot maximum to less than 10 at sunspot minimum. Any model that relates TSI merely to sunspot number based on these data will inevitably conclude that the lowest value that the TSI can ever reach (or has ever reached in the past) is when the sunspot number goes to zero, in which case the TSI would be close to what it presently is at SMIN, or about 0.14% less than it presently is at SMAX. That being the case, it would be concluded that at no time in history has the TSI ever been less than it presently is at SMIN, about 1,365.3 W/m^2. These models are referred to by Hoyt and Schatten (1993) as "constant quiet Sun models" (CQSMs) because the TSI for a quiet Sun is taken as constant for all time (see Section 4.4.2). Several models have been developed on this basis. Some have been used to predict the daily variations shown in Figure 4.2 over a couple of decades. With enough empirical parameters, such predictions have been quite good. For example, Wenzler, Solanki, and Krivova (2005) modeled TSI for 2,055 days between November 1992 and September 2003 based on solar observations. Daily variations of TSI were well reproduced. The model used in these estimates was based on the measured position and flux density of magnetic features on the solar disk extracted from full-disk magnetograms. These magnetic features are classified as either sunspot umbrae, sunspot penumbrae, or faculae, based on their brightness in full-disk continuum images. The details on how this was done do not seem to have been revealed. Such models are interesting, but they do not seem to lead to estimates of TSI in the distant past prior to measurements of solar magnetograms. Other references reporting short-term modeling include Fligge *et al.* (2000) and Solanki and Krivova (2004).

As we have seen above, models based on current observations of TSI correlated with surface features (sunspot number, faculae, etc.) can reproduce the daily fluctuations in TSI observed by instruments such as ACRIM3. Unfortunately, as Reid

(1997) amply demonstrates, such small variations in TSI are too small to account for historical variations in surface temperature. Any constant quiet Sun model that is based solely on the current solar cycle with an ultimate minimum TSI of 1,365.3 W/m^2 cannot possibly explain past climate variations. A case in point is discussed in Section 4.4.2.

In addition, there is a very large variation in TSI that occurs yearly due to the Earth's elliptical orbit. This is usually neglected, based on the assumption that the Earth's thermal response is very slow compared with a yearly variation in TSI. However, the variation of 6.8% between January 1 and July 1 is a major perturbation and may not be entirely negligible.

4.4.1.2 Hoyt and Schatten

This section was excerpted from Hoyt and Schatten (1993).

TSI measurements in orbit only exist since around 1978. No data are available prior to that date. Since the TSI measurements were made in Earth orbit, a number of investigators have developed relationships that allow one to use observations of sunspots and faculae to predict TSI.

Over the past two centuries, a number of scientists have hypothesized that the solar irradiance at the top of the Earth's atmosphere varies with time. Recent satellite measurements confirm that small variations exist at least on the timescale of the 11-year solar cycle. Most of the modeling of these secular variations in the solar "constant" was phenomenological, providing parameters that enable short-term TSI variations to be fit. Although the models do not answer questions concerning the basic cause of secular solar variations, they do allow us to examine the photospheric manifestations of these variations. To date, most of the solar constant secular variations observed (over a couple of decades) have been associated with *photospheric blemishes* (dark sunspots, bright faculae, and a bright network). At present, there seem to be only a few attempts to understand potential long-term secular trends. One view of active region physics suggests a positive correlation of the variations in the solar "constant" with solar activity if the active region process effectively transfers heat outward. In this view, the active regions are distinguished from the background photosphere by the influence of the magnetic field that produces down-flows at sunspots and up-flows at faculae. These effects were thought to be the origin of the positive correlation of solar activity with solar irradiance variations.

Even if we can understand the solar cycle correlation with activity, these features may be merely *photospheric blemishes* and may not have a great influence on the longer timescale "river of solar luminosity" flowing outward from the Sun's interior, but rather primarily serve only to divert the flow and/or temporarily store and release minor amounts of this vast energy flow. The perturbations from active surface regions may not necessarily extend to the deep interior to influence very long timescale solar luminosity and solar "constant" variations. To understand the long-term secular variations, the Sun might need to be viewed on a larger, more synoptic basis, with global observations (e.g., solar rotation, solar diameter, etc.).

On the timescale of decades to centuries, four classes of models were described by

Hoyt and Schatten (1993) that postulate different variations of the Sun's output. These models can be called

(1) The *constant quiet Sun model*. The constant quiet Sun model (CQSM) postulates that the solar irradiance has only an 11-year cycle and all radiation changes can be explained by the presence or absence of active features. Since all solar minima are essentially the same in these models, it is called the constant quiet Sun model. In this model, the historical TSI when solar activity was at a minimum (as, for example, in the Maunder Minimum) would be set equal to the contemporary TSI at solar minimum. Examples of such models include Tapping *et al.* (2006), Foukal and Lean (1990), and Vaquero *et al.* (2006).
(2) The *solar diameter model*. The solar diameter model uses the solar diameter or its time rate of change as a proxy for solar irradiance variations. However, some controversy still exists about the history of solar diameter variations (Foukal *et al.*, 2006). See Section 4.2.6.
(3) The *activity envelope model*. The activity envelope model postulates that long-term solar irradiance variations follow the envelope of solar activity such as the so-called Gleissberg cycle (an ~88-year overall modulation of the 11-year solar cycle), so that solar minima irradiances vary over time.
(4) The *umbra/penumbra (U/P) variations model*. The U/P models are so-called because early models of this class used sunspot structure expressed as the ratio of umbral areas to penumbral areas as a proxy measure of solar irradiance. Subsequent studies have used solar equatorial rotation rate and sunspot cycle duration to derive similar models. The U/P variations model and the activity envelope model are similar except they are out of phase with each other with variations occurring ~20 years earlier in the U/P variations model. Hoyt and Schatten (1993) argued that the solar indices used in the U/P variations model are proxy indicators of long-term secular changes in convective energy transport. Additional proxies for the U/P variations model have been introduced; namely, the sunspot decay rate, the fraction of penumbral sunspots, the decay rate of the solar cycle, and the mean level of solar activity.

In addition to these models mentioned by Hoyt and Schatten in 1993, several models were developed in ensuing years. These include the following (named by this writer):

(5) The *MM temperature model*. The MM temperature model is based on (i) an estimate of the temperature lowering during the MM compared with today's temperatures, (ii) an estimate of the reduction in TSI needed during the MM to produce that lowering of temperature, and (iii) a linear scaling of the change in temperature from the MM to current times, with the change in sunspot number at SMAX from the MM (zero) to today (over 100) (see Section 4.4.3).
(6) The *stellar Ca HK index model*. The stellar Ca HK index model is based on (i) an estimate of the enhanced level of TSI vs. the solar Ca HK index model from recent measurements, (ii) observation of the Ca HK index for non-cycling Sun-like stars, (iii) the assumption that non-cycling Sun-like stars are representative of

the Sun during the MM, (iv) linear extrapolation of the dependence of TSI from current solar measurements to the expected Ca HK index for non-cycling Sun-like stars in order to estimate TSI during the MM (see Section 4.4.4).

(7) The *solar cycle duration model*. The solar cycle duration model utilizes the duration of the solar cycle from peak to peak rather than sunspot numbers as a measure of TSI.

(8) The *coronal source flux model* is based on correlations of coronal source flux with TSI. The coronal source flux, F_s, is the total magnetic flux leaving the Sun, and thereby entering the heliosphere.

4.4.2 Constant quiet Sun models

4.4.2.1 CQSM based on sunspot number

The period between 1700 and the present is important because there is a continuous record of sunspot number, which is a directly measured index of solar activity, of known pedigree with established relationships with other activity indices, and which antedates the rapid increase in anthropogenic greenhouse gases that began with the industrial revolution. A vital aspect of climatology studies is the issue of how the TSI varied over the past several centuries, particularly back to the Maunder Minimum (1645–1715). This will require some form of "bootstrap" model that associates recent measurements of TSI with parameters that have histories that go back in time. From past records of these parameters, the TSI in the past can be inferred.

Group Sunspot Numbers of variable quality are available since 1610. Sunspot areas and white light facular areas are available since 1874. Ca II plage areas are available since 1915. Various models use one or more of these proxies in order to reconstruct historical irradiance. Observations of sunspots and faculae go back to about 1954, and Lean and Foukal (1988) utilized these data to estimate TSI for the period 1954 to 1985. However, this procedure cannot estimate TSI over several centuries. There are a variety of proxies from which TSI might be inferred over long time periods (tree rings, ice cores, etc.) and these will be discussed in later sections. One parameter that has been used by a number of investigators to estimate TSI as far back as the 17th century is the Group Sunspot Number (Figures 4.7–4.11). It is rather unfortunate that many of these papers have provided the end result: plots of TSI vs. year for hundreds of years, but they have not usually provided the detailed algorithms from which these data were derived. Since some of these are essentially one-parameter models, there must exist a functionality:

$$\text{TSI} = \text{function of } (N)$$

where N = Group Sunspot Number. This functionality does not seem to appear in most of the relevant papers. In some cases, the models use long-term sunspot data and other proxies, in which case the functionality would take the form:

$$\text{TSI} = \text{function of } (N, a, b, \ldots)$$

where $a, b, \ldots$ are parameters associated with proxies, but once again these functionalities are not typically stated very clearly.

> "The history of solar irradiance variation is a critical component in understanding the solar–terrestrial climate connection and the relative role of the Sun in current climate change. However, direct measurements of solar irradiance currently cover only about three decades. Beyond that interval irradiance has to be estimated using available observations and activity indices. This entails three major difficulties: (a) the physical connection between the observed activity phenomena, such as sunspot number with irradiance is complex and difficult to quantify. Often the result is the need to use connections that are often largely empirical, (b) proxies might have to be used. In a sense this has some commonality with (a), except that here the physical connection is even less well understood, but a historical high correlation between the proxy and the desired quantity justifies its use, (c) having constructed a model which necessarily incorporates elements of (a) and (b), it has to be extrapolated substantially outside the parameter space that was used to set up that model" (Tapping *et al.*, 2006).

Tapping *et al.* (2006) developed a model for long-term TSI based on group sunspot number.

> "Modeling irradiance is difficult. Firstly we do not fully understand the processes driving irradiance variations; the underlying physics is complex and multifaceted, and includes phenomena below and at the photosphere. Most of the relationships we have to work with are empirical, although the correlation coefficients between total irradiance and indices such as the 10.7 cm solar radio flux are high. For example, since total irradiance is highly correlated with sunspot number, it seems logical to plot irradiance against sunspot number and extrapolate back to zero sunspot number, and then conclude that the corresponding value of irradiance is the value that would be reached if solar activity remained low for an extended period. *This is almost certainly not the case*. Sunspots do not cause increases in irradiance; it is the accompanying active region structures, such as faculae and elements of the active network that do this. Although there might not be any sunspots, there are signs of activity during every observed minimum of the solar activity cycle ... Sunspots might be a good indicator of magnetic activity when present, but they are not useful when activity is low. When examining solar activity during a sustained change in the solar activity cycle, or even a temporary cessation, one needs to examine two issues: firstly, does the nature of the process by which magnetic flux is processed change, and secondly, what is the solar activity machine below the photosphere doing? ... In the case of this investigation, the input to the model has to be sunspot number, which is the only direct index of solar activity available. In this paper we develop a model for the processing of solar magnetic flux and use it to model the historical record of total irradiance" (Tapping *et al.*, 2006).

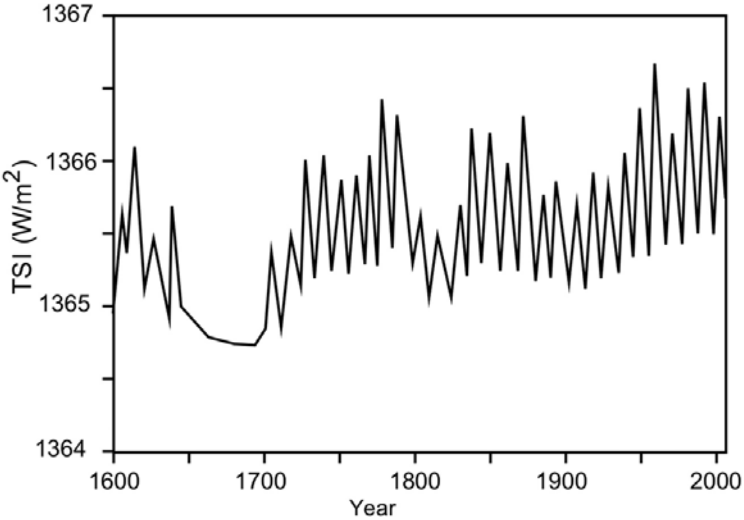

Figure 4.13. Modeled TSI through the MM up to the present. Adapted from Tapping *et al.* (2006).

Tapping *et al.* (2006) started out with a set of group sunspot numbers very nearly the same as that given in Figure 4.7. Then they carried through an involved procedure that is difficult to follow in detail, in which they estimated the TSI indirectly from the historical record of sunspot numbers. But in the end, since their procedure involved only the single parameter of sunspot number as given in a chart similar to Figure 4.7, they must have implicitly developed a relationship of the form

$$\text{TSI} = \text{function of } (N),$$

although this functionality was not explicitly stated in their paper. However, we can surmise what that relationship must have been by comparing their estimate for TSI (as shown in Figure 4.13) with the sunspot record (as given in Figure 4.7). At each peak in the TSI plot we note the peak TSI and the corresponding peak sunspot number. We then plot peak TSI vs. peak sunspot number as shown in Figure 4.14. We can also prepare a similar plot based on the sunspot minima as shown in Figure 4.15. Although Tapping *et al.* (2006) never actually revealed these functional relationships between TSI and sunspot number they must have implicitly used relationships similar to those implied in Figures 4.14 and 4.15.

According to Figure 4.13, the best estimate for the TSI during the Maunder Minimum was about 1,364.7 W/m^2, compared with a current average of about 1,366 W/m^2, for a decrease of about 1.3 W/m^2 (about 0.1%) during the Maunder Minimum.

The interesting thing about this model is that although Tapping *et al.* (2006) went to great pains to emphasize

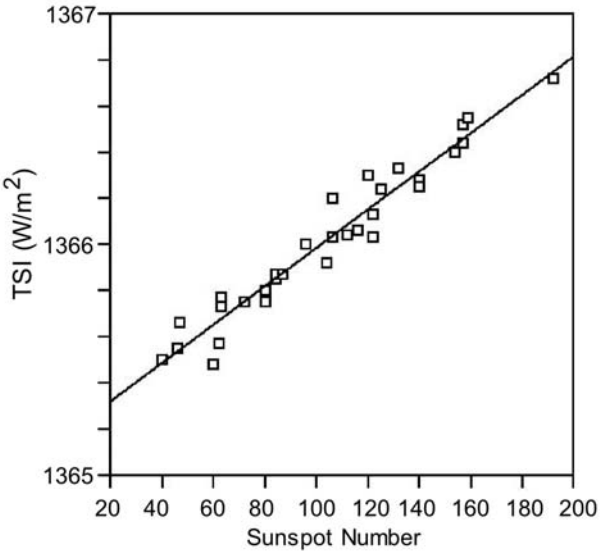

Figure 4.14. Relationship between TSI and sunspot number at the periodic peaks in the historical record of sunspots ($S = 1{,}365.16 + 0.008SSN$).

"... since total irradiance is highly correlated with sunspot number, it seems logical to plot irradiance against sunspot number and extrapolate back to zero sunspot number, and then conclude that the corresponding value of irradiance is the value that would be reached if solar activity remained low for an extended period. *This is almost certainly not the case*."

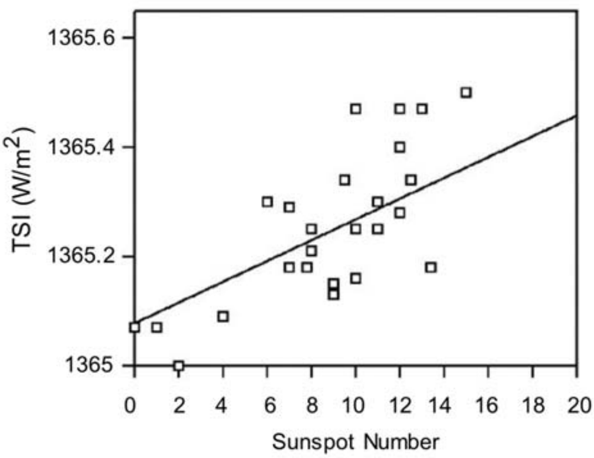

Figure 4.15. Relationship between TSI and sunspot number at the periodic minima in the historical record of sunspots ($S = 1{,}365.08 + 0.019SSN$).

Nevertheless they went ahead and carried out a CQSM model anyway, leading inevitably to the result that TSI during the MM was a mere ~0.1% lower than it is today—*which is almost certainly not the case*.

Foukal and Lean (1990) developed models for predicting TSI from data on sunspots and faculae. In the short term where good data on sunspots and faculae are available, the model works very well. However, to estimate TSI at earlier dates, they had to rely on sunspot numbers alone. It was noted that while sunspots reduce the TSI, sunspot occurrence is always accompanied by the presence of faculae, and the net result is that TSI increases with increasing sunspot number.[1] For the few cycles examined by the ACRIM instrument, they were able to develop a relationship between TSI and sunspot number. However, this model relied on the assumption that the lowest TSI that is possible is the lowest TSI recorded by ACRIM for a quiet Sun at SMIN (i.e., a CQSM). With an active Sun, the TSI could increase above this value in proportion to the sunspot number. At the time they wrote their paper, it was estimated that TSI for a quiet Sun was about 1,366.8 W/m^2, so they assumed that TSI never drops below this value. Foukal and Lean (1990) realized the futility of this approach.

> "... solar irradiance variations of the magnitude below 0.1% expected from photospheric activity are unlikely to have had significant influence on climate over the past century ... Much larger variations in solar luminosity could be caused by global solar changes not associated with photospheric sunspots and faculae. A secular variation approaching even 1% over the past century cannot strictly be ruled out, given the low precision of pyrheliometry, until modern data became available from satellites beginning in 1978. The theory of the solar radiative interior and convection zone is also insufficiently accurate to rule out luminosity variations of such amplitude" (Foukal and Lean, 1990).

4.4.2.2 CQSM based on sunspot area and cycle duration

Vaquero *et al*. (2006) developed a correlation of TSI with yearly average sunspot area based on measurements of sunspot area made since 1832. However, the units of sunspot area were not specified. Vaquero *et al*. (2006) based their paper on previous work by Solanki and Fligge (1998, 1999).

The fundamental assumption made in Vaquero *et al*. (2006) and Solanki and Fligge (1998, 1999) is that the variations that we currently observe in TSI during the solar cycle are due to changes in sunspots and faculae in active regions of the Sun. Their combined effect on TSI is embodied in a term $\Delta(AS)$ representing the change in TSI due to such solar activity. Based on observations of the Sun since 1978, this term is typically quite small. The network (and possible changes in solar convection) provide the main contribution to TSI variations on timescales longer than the solar cycle, and secular changes in the network are denoted as variations in the quiet Sun

[1] However, it is believed that for very high sunspot numbers (~150), the TSI tops out and eventually decreases with increasing sunspot number.

($\Delta(QS)$). However, these long-term variations are presumably much larger than those due to solar activity, and therefore use of the term "quiet Sun" is misleading.

Thus, according to this concept, TSI at any epoch is the sum of three terms:

$$\mathrm{TSI} = \mathrm{TSI}(0) + \Delta(QS) + \Delta(AS)$$

where $\mathrm{TSI}(0)$ = a constant to produce the correct absolute TSI
$\Delta(QS)$ = additive term to account for long-term secular variations of the so-called "quiet Sun"
$\Delta(AS)$ = additive term to account for solar activity via the solar cycle.

Since $\Delta(QS)$ varies slowly with time, measurements of TSI made in space since ~1980 over two decades can be presumed to include a current value of $\Delta(QS)$ corresponding to 1980–2000. The active Sun term $\Delta(AS)$ can be correlated with a parameter such as sunspot number or sunspot area by comparing the two decades of TSI measurements with variations in such parameters. Solanki and Fligge (1999) made such a comparison with the daily sunspot number. Although the data were very noisy, they were able to arrive at a correlation by binning the data. The result was:

$$\mathrm{TSI}(0) = 1{,}365.4\ \mathrm{W/m^2}$$

$$\Delta(AS) = 0.0161(SN) - 0.000055(SN)^2$$

where SN = Zurich sunspot number.

This function increases with SN until about $SN \sim 150$, and decreases for higher SN. For low SN, as SN increases, the facular area increases faster than the sunspot area. However, for high SN, the reverse occurs.

Vaquero *et al.* (2006) performed a similar correlation based on sunspot area. They obtained:

$$\mathrm{TSI}(0) = 1{,}365.4\ \mathrm{W/m^2}$$

$$\Delta(AS) = 6.8 \times 10^{-4}(SA) - 1.0 \times 10^{-7}(SA)^2$$

where SA = sunspot area (units not given).

In either case, whether based on sunspot number or area, $\Delta(AS)$ contributes a relatively small oscillatory term to TSI that varies with the solar cycle.

The key to evaluating TSI is estimation of the term $\Delta(QS)$. However, as Solanki and Fligge (1999) said:

> "We stress, however, that determining the quantitative long-term variations of the quiet Sun is highly speculative and subject to large uncertainties."

Solanki and Fligge (1998) generated two estimates for $\Delta(QS)$. Unfortunately, the descriptions of the procedures for doing this are rather murky to this writer. One procedure was based on an assumed linear relationship between chromospheric emission in the core of the Ca H and K lines and photospheric brightness, as will be discussed later in connection with Figure 4.22 (Lean *et al.*, 1998). The other is a linear correlation between the length of cycles and observed brightness of solar-type

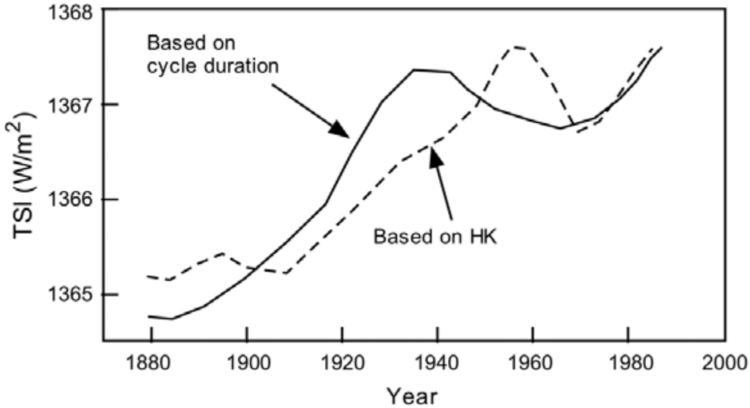

Figure 4.16. Reconstructed TSI since 1880. Adapted from Solanki and Fligge (1998).

stars. Each of these correlations was apparently used independently to estimate past values of $\Delta(QS)$ from observations of either the Sun's cycle duration or HK measurements. Since such measurements are limited to post-1880, Solanki and Fligge (1998) only reconstructed TSI back to 1880. The results are shown in Figure 4.16.

Solanki and Fligge (1999) followed their 1998 paper with the intent to reconstruct TSI as far back in time as 1700. As before, Solanki and Fligge (1999) are equally obscure on the details of reconstructing $\Delta(QS)$. They mention Sun-like stars but it is not clear how stars relate to the procedure, which seems to involve either sunspot numbers or solar cycle duration. The procedure remains murky to this writer. The result is shown in Figure 4.17. The huge peak around 1770 and the dip around 1800 appear to be anomalous.

Vaquero *et al.* (2006) prepared a new estimate for $\Delta(AS)$ based on sunspot area, and combined this with the two estimates for $\Delta(QS)$ from Solanki and Fligge (1999). Vaquero *et al.* (2006) provided the $\Delta(QS)$ data for Figure 4.18a, but these data were obtained from Solanki and Fligge (1999). The reconstructed TSI in Vaquero *et al.* (2006) is shown in Figure 4.18b.

It is difficult to appraise the results presented in Figures 4.16–4.18 because the descriptions of how $\Delta(QS)$ was derived are so obscure. One obvious fact is that the correlations based on cycle duration lead to wider swings in TSI than correlations based on sunspot numbers.

4.4.3 The MM temperature model

Reid (1997) began by asserting

> "Any attempt to reconstruct the historical variation in TSI and to relate it to terrestrial climate variations is bound to be a highly speculative activity. Nevertheless, striking correlations between global-scale variations in temperature and solar-activity parameters suggest that such a relationship does exist."

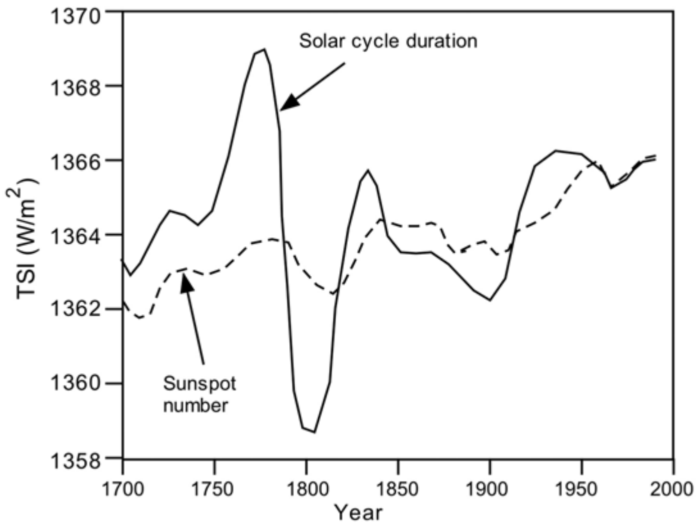

Figure 4.17. Reconstructed TSI based on sunspot number or cycle duration. Adapted from Solanki and Fligge (1999).

Reid delineated two extreme scenarios that have been put forward in the past to reconstruct TSI variations. He referred to Foukal and Lean (1990) as an example of a CQSM model that assumed that the variation in irradiance is strictly linked to the surface activity, so that the 0.1% variation seen so far (during the current solar cycle) is close to the maximum that ever occurs, being representative of the change from sunspot maximum, when surface activity is high, to sunspot minimum, when it is virtually absent. The record of surface magnetic activity can then be used to reconstruct a history of irradiance variability that consists solely of 11-year cycles, with amplitude somewhat less than that observed during the recent period, since solar cycles have been generally growing in amplitude over recent decades. However, Reid

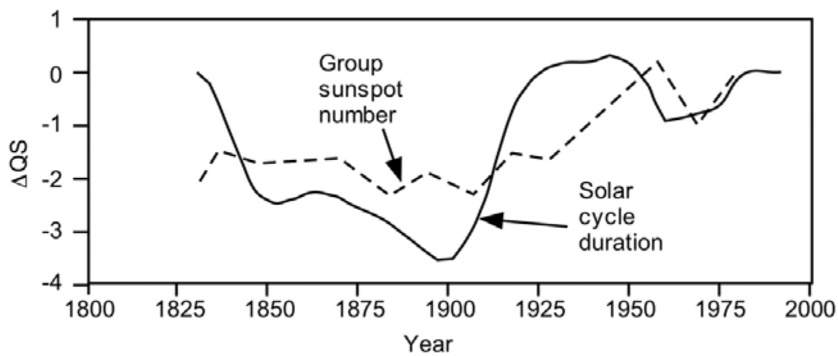

Figure 4.18a. Estimates of $\Delta(QS)$ (W/m^2) based on sunspot number or cycle duration. Adapted from Vaquero *et al.* (2006).

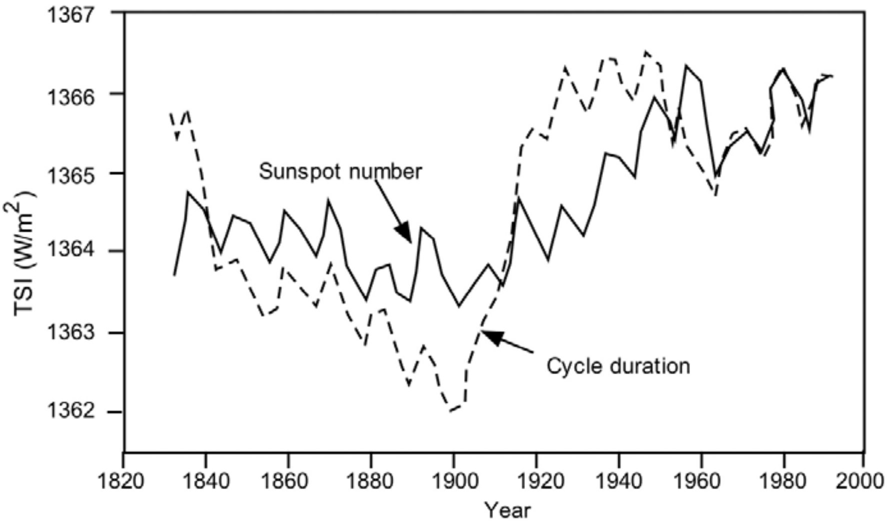

Figure 4.18b. Reconstruction of TSI using two models for the "quiet-Sun contribution". Adapted from Vaquero *et al.* (2006).

argued that the inferred irradiance variations from such a CQSM model (see Section 4.4.2) are too small to be climatically significant. At the other extreme, Reid quoted an earlier 1991 paper of his own, in which the 11-year cycles were smoothed out completely, and only the longer period variations in solar activity were retained. Reid's 1991 paper suggested that irradiance variations of several tenths of a percent may have occurred over the past several hundred years, and he estimated that the TSI during the Maunder Minimum period in the late 17th and early 18th centuries was about 0.65% below the present level. This is a considerably larger variance than other independent estimates of the MM TSI.

The approach taken by Reid (1997) was based on the assumption (inferred from historical records) that the prevailing temperature during the MM was about 1°C lower than it is currently. (It should be noted that climatologists favoring the *hockey stick* model would argue that this is an overestimate, see Section 2.2.) Reid (1997) used climate models to infer how much lower the TSI must have been during the MM to account for this putative 1°C drop. Then, given the known current levels of TSI and sunspot number during the MM, he was able to derive a relationship between long-term TSI and group sunspot number, assuming a linear relation. It is of the highest importance to distinguish between two very different models that might appear at first glance as if they were the same. One can analyze the current TSI data (as, for example, in Figure 4.2) in terms of a CQSM formula

$$\mathrm{TSI} = A + B(GSN)$$

where A and B are constants and GSN is the group sunspot number. This can be made to work for the period 1978–2007. The constant A is close to the minima in Figure 4.2 and the constant B is adjusted to make TSI approach the maxima in

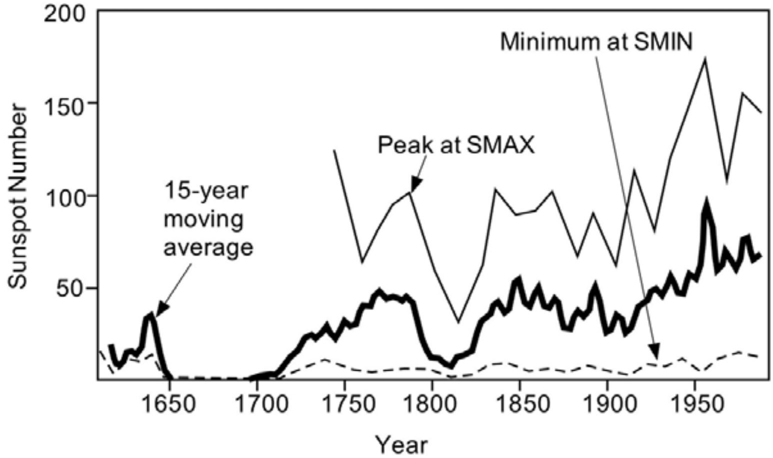

Figure 4.19. Reid's 15-year moving average of group sunspot variations (heavy line). Adapted from Reid (1997).

Figure 4.19 at SMAX. This CQSM formula can never produce a variation in TSI greater than about 0.1%.

Reid (1997) discarded the solar cycle altogether and dealt with the average TSI vs. year over long time periods. He did this by filtering the sunspot data to acquire a 15-year moving average (see Figure 4.19). His climate model indicated that in order to achieve a 1°C temperature drop during the MM compared with recent times, the TSI must have been about 0.65% lower in the MM than it was in 1980. He used an excessively high value of the 1980 TSI (~1,372.6 W/m^2) based on early Nimbus-7 measurements, and based on the 0.65% reduction concluded that TSI during the MM was about 1,363.7 W/m^2. Then he set

$$\text{TSI} = 1{,}363.7 + 0.114(FSSN)$$

where *FSSN* is the 15-year filtered group sunspot number. This formula may appear similar to the one above (in terms of *A* and *B*) but it is fundamentally different.

We must adjust his model because the Nimbus-7 measurements are too high as evidenced by Figure 4.4 (color section). Hence we use a modified version of Reid's formula based on a current average TSI of 1,366.5 W/m^2:

$$\text{TSI} = 1{,}357.6 + 0.114(FSSN).$$

This formula yields 1,366.5 W/m^2 when $FSSN = 78$ (for 1980). A plot of this formula is shown in Figure 4.20.

A modified version of Reid's TSI vs. year is shown in Figure 4.21, based on the lower estimates for TSI from Figure 4.2.

In his model, Reid included greenhouse warming for 1980, but not for the MM. This would imply that solar forcing accounted for only a part of the 1°C temperature

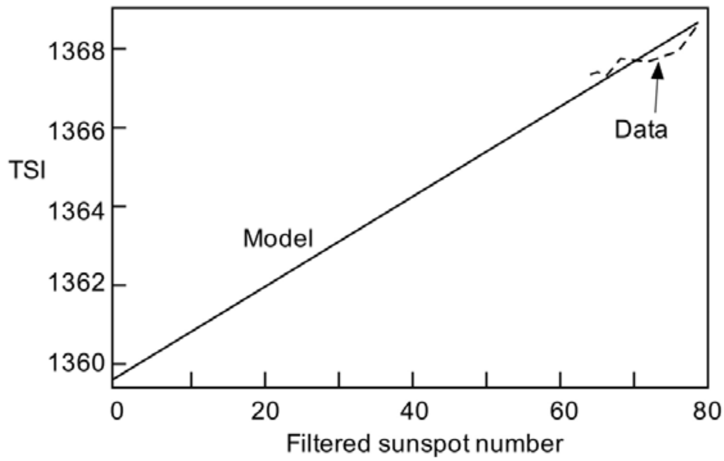

Figure 4.20. Dependence of long-term TSI on 15-year filtered sunspot number. Adapted from Reid (1997).

rise from the MM to 1980. Reid estimated that greenhouse forcing in 1980 was about 1.5 W/m^2 due to CO_2, and another 1.2 W/m^2 due to other greenhouse gases for a total of 2.7 W/m^2. According to Figure 4.21, the increase in TSI since the MM was about 8 W/m^2, which would imply that solar forcing was $8/4 = 2\ W/m^2$ so that he estimated that with solar forcing alone, the rise in temperature from the MM to 1980 would be ~0.45°C.

Reid compared his results with the study by the 1995 IPCC Report. Reid pointed out that the 1995 IPCC Report assumed much smaller differences in TSI between the MM and 1980, and these small differences are much too small to explain the putative

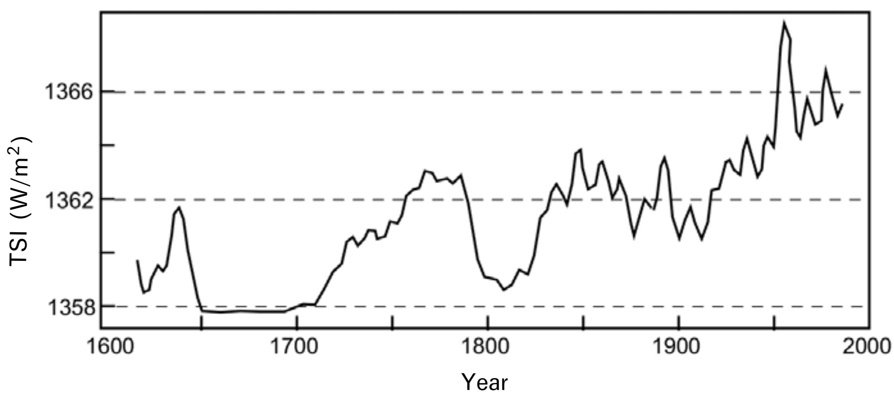

Figure 4.21. Modification of Reid's estimate of variation of TSI over four centuries using updated TSI. From Reid (1997).

cold temperatures of the Maunder Minimum period. Reid said:

> "This ... essentially leaves the cold temperatures of the Maunder Minimum period to be explained by some unknown global forcing factor other than solar variability. While such a possibility cannot be ruled out, no alternative mechanism has yet been suggested."

However, the *hockey stick* advocates would simply deny that the MM was that cold. Reid concluded:

> "The irradiance reconstruction presented here suggests that solar forcing may have been a more important factor in recent climate change than the IPCC estimate would imply."

4.4.4 Stellar Ca HK index models

Beckman and Mahoney (1998) reviewed the magnetic variability of nearby stars that are similar to our Sun. The hope is that we might be able to observe variations that could provide clues as to whether the solar cycles of other stars may vary with time. A good indicator of magnetic activity in the Sun is the emission fluxes of the H and K resonance lines of ionized calcium that maximizes at SMAX for our Sun. Over the 11-year solar cycle, these vary with peak-to-peak amplitude of about 30%. Starting in the 1960s, a long-term observation program for the H and K resonance lines emitted by Sun-like stars has been underway at Mt. Wilson. There are now records of H + K intensity for over a hundred stars covering 30 years. However, the interpretation of the data must take into account the fact that stars that rotate faster will have a stronger magnetic field, and also stronger H + K emission. Usually, the older a star, the slower it rotates. Thus, H + K emission has been used as an indicator of age.

> "If a star shows H + K variability, with amplitude similar to that of the Sun, say, a single measurement which catches the star at a maximum or minimum will give a misleading age estimate; what is required is a mean over a stellar cycle, or over a long enough period to cover short-term variations. In a cluster these effects can be cancelled even at a single epoch by averaging over its population, but for a single star this is not possible. The situation is worsened if stars have Maunder minima, because a measurement of H + K during a Maunder Minimum would give the false impression of very low activity, and very great age. Stars with low activity have indeed been found. A significant fraction, maybe 20% of the isolated solar-type stars of the Mt. Wilson survey have low, constant H + K levels. These might just be very old stars, but a similar situation is found in the stars of the open cluster M67, which is just a little younger than the Sun. This strongly suggests that solar-type stars do go through phases of low magnetic activity, and that these Maunder minima last some 20% of the time. Many doubts remain; only one star has possibly been 'caught' in transition from low to 'normal' activity, from a sample

> for which more than 5 such transitions could be expected during their period of observation. Possibly, the stars with low activity are always like this and are simply slow rotators ... The whole question is open and is a subject of active investigation" (Beckman and Mahoney, 1998).

Starting in the 1960s at Mt. Wilson, a long-term study of magnetic cycles in cool stars was begun using the variable emission flux of the H and K resonance lines of ionized calcium, the appearance of which in emission is characteristic of activity in stellar chromospheres (Beckman and Mahoney, 1998). There is an excess of H and K emission in the faculae that surround sunspots, and epochs of sunspot maximum coincide with epochs of maximum H and K emission. If the Sun were a distant star, we could observe its 11-year cycle as a variation in integrated $H + K$ flux with this period and with a peak-to-peak amplitude some 30% of the mean. Thus, while the Sun's TSI varies by perhaps 0.1% across the 11-year solar cycle, the $H + K$ flux varies by perhaps 30% and is therefore far more easily detectable. As Beckman and Mahoney (1998) discussed, this project set out to determine whether stars of similar spectral type and luminosity class (i.e., similar surface temperature and mass) show comparable variations in cycling. This entailed a major project involving the monitoring of the fluxes of a group of stars for decades. The result is that there are now well-sampled records of $H + K$ intensity for over a hundred stars covering 30 years, plus samples of many hundreds more. One of the implications of these results is the possible detection of absence of solar cycling in some stars that might be analogous to Maunder Minima in Sun-like stars.

Beer, Mende, and Stellmacher (2000) reported on an investigation of 30 solar-type stars over the past 30 years that showed that cyclic variability is typical for solar-type stars. The observed periodicities ranged from 7 to 20 years in analogy to the Sun's 11-year cycle. Most of these stars exhibit much larger brightness changes with cyclic peak-to-peak amplitudes of up to 1%, compared with the $\sim$0.1% irradiance amplitude observed for the Sun. This leads to the suggestion that the variability potential of the Sun might have been much greater during time periods other than the satellite-based observational period of the past few solar cycles. It is remarkable that the brightness of most monitored stars show significant inter-cyclic variations; the minimum levels change from cycle to cycle by several percent. This raises the question whether the Sun could develop similar variations over time in contrast to CQSM models.

In very broad terms, for two similar stars, the one that rotates faster will have a stronger magnetic field, and also stronger $H + K$ emission. Again, in general terms, the older a star, the slower it rotates. Thus, $H + K$ emission is an indicator of age, and has been calibrated against open stellar clusters, whose ages can be determined via collective photometry of their complete populations. One obvious problem here is that if a star shows $H + K$ variability, with amplitude similar to that of the Sun, a single measurement that catches the star at a maximum or minimum will give a misleading age estimate; what is required is a mean over a stellar cycle, or over a long enough period to cover short-term variations. In a cluster, these effects can be canceled even at a single epoch by averaging over its population, but for a single star this is not possible. The situation is worsened if stars have Maunder Minima, because a measurement of H + K during a temporary Maunder Minimum would give the false impression of very low activity, and very great age. Stars with low activity have indeed been found. A significant fraction (perhaps 20%) of the isolated solar-type stars in the Mt. Wilson survey have low, constant H + K levels. These might just be very old stars, but a similar situation is found in the stars of the open cluster M67, that is just a little younger than the Sun. This suggests that solar-type stars may go through phases of low magnetic activity, and that these Maunder Minima last some 20% of the time. Many doubts remain; only one star has possibly been "caught" in transition from low to "normal" activity, from a sample for which more than five such transitions could be expected during their period of observation. Possibly, the stars with low activity are always like that and are simply slow rotators. Up to now, no observable correlation of activity with rotational period has been possible (the periods must be of order weeks or months, which requires extreme spectral resolution to measure). According to Beckman and Mahoney (1998), the whole question is open and is a subject of active investigation. In particular, direct measurements of indices of total stellar luminosity are being taken together with the H + K indices, to see whether, and to what degree stellar (and thus solar) total power is correlated with magnetic field strength. The solar work provided the first clue, and the stellar work provides a framework to quantify, to predict, and eventually model the behavior of the Sun.

Lockwood, Skiff, and Radick (1997) and Lockwood *et al.* (1997) monitored the Ca II HK variations of 41 program stars and their 73 comparison stars (nearby, similar in color and brightness) from 1984 through 1995. The predominantly main sequence program stars spanned ranges of temperature and mean chromospheric activity centered on solar values. About 40% of all the stars showed measurable variability, typically at levels below $\sim$1%, on both night-to-night and year-to-year timescales.

Knaack *et al.* (2001) concluded that compared with Sun-like stars, the TSI variations of the Sun over the solar cycle appear to be relatively small for its average activity level (variation of TSI of the Sun across a cycle is a factor of 2 to 3 smaller than variation of TSI for Sun-like stars). It has been suggested that part of the reason for this might be due to the special position of Earth-based observers in the ecliptic plane, who see the Sun almost equator-on, and earlier papers concluded that this could be the case. However, Knaack *et al.* (2001) found that while measured TSI variations across a cycle for stars depend on inclination angle, the observed variation of TSI across a solar cycle will change by only $\sim$40% as the viewing angle changes from 0° to 90° (highest at 90°). This can only account for part of the observed difference between the Sun and Sun-like stars. On the other hand, they found that the Ca II flux variation of Sun-like stars between activity minimum and maximum does depend significantly on the inclination of the rotation axis relative to an observer (change of about a factor of 2 in going from 0° to 90°).

Lockwood, Skiff, and Radick (1997) and Lockwood *et al.* (1997) reported on the results of ongoing observations of Sun-like stars. It was pointed out that stellar photometric precision at the level of 0.05%–0.10% is needed to detect year-to-year variations as small as that of the Sun. This is a tough challenge, and it is admitted that the photometry

> "... approaches but does not quite reach this precision, but provides useful comparisons with the solar example on a timescale comparable with the current solar TSI record."

However, the data appear quite noisy to this writer. In general, it is found that older stars tend either to vary in a smooth, cyclic fashion or have steady levels of HK emission, whereas young, active stars vary strongly but irregularly. Sun-like stars are characterized by their "chromospheric activity", which is the ratio of the Ca HK emission level to the innate luminosity of the star. Among Sun-like stars that have been studied, the Sun has somewhat lower than average chromospheric activity. However, chromospheric variability (i.e., periodic changes in HK emission) is slightly above average for its level of chromospheric activity. In general, the cyclic variability of TSI of stars increases with chromospheric activity. The Sun, as recorded by TSI measurements since 1978, has unusually low variability of TSI compared with Sun-like stars. Observations have not been conducted over enough time or with enough precision to determine how rapidly stars change in activity and variability.

Anon. (M) studied the behavior of stars in the M67 cluster that are believed to contain Sun-like stars with similar age and metallicity as the Sun. This reference presented the results of a spectroscopic survey of the Ca II HK core strengths in a sample of 60 solar-type stars from the open cluster M67. They used the HK index, defined as the summed HK core strengths, as a measure of chromospheric activity. They compared the distribution of mean HK index values for the M67 solar-type stars with the variation of this index as measured for the Sun during the contemporary solar cycle. They found that the stellar distribution in the HK index is broader than that for the solar cycle. Approximately 17% of the M67 Sun-like stars exhibit average HK indices that are less than that found in our Sun at solar minimum. About 7%–12% are characterized by relatively high activity in excess of solar maximum values, while 72%–80% of the solar analogs exhibit Ca II HK strengths within the range of the modern solar cycle. Thus, according to these findings, the Sun is quite an average star for its type in terms of chromospheric activity. However, it has above-average variability in HK emissions.

What is not known is whether and how frequently Sun-like stars change cyclic behavior.

In a series of related papers (Lean and Foukal, 1988; Lean, 2000; Lean, Beer, and Bradley, 1995; Lean *et al.*, 1997, 1998; Lean, Skumanich, and White, 1992; Fligge *et al.*, 1998) Judith Lean and co-workers have estimated the variation of TSI over the past few hundred years based primarily on observations of Sun-like stars.

Lean and Foukal (1988) developed a simple model that included the reduction of total irradiance produced by the dark spots as well as the brightening caused by the faculae. Computation of the past behavior of the TSI with this model was limited by the available database of suitable indices of bright faculae. They were able to estimate both the sunspot darkening and the faculae brightening of the Sun from 1954 to 1984, and by subtraction, the net variation of the TSI over that time period. This amounted to a CQSM for this recent period.

It was desired to find a way to estimate the TSI for previous centuries, particularly going back to the earliest sunspot observations around the time of the Maunder Minimum (1645–1715). Lean, Skumanich, and White (1992) carried out a procedure for doing this based on several assumptions that in retrospect appear to this writer to be quite speculative. They noted that in the current solar cycles at SMIN, although sunspots and faculae are at a minimum (or absent), nevertheless a "quiet" network of bright magnetic elements remains on the Sun. While the current solar cycle produces an oscillatory TSI with the rise and fall of the appearance of sunspots and faculae, the network remains. Thus, Lean, Skumanich, and White (1992) postulated that in times past, this network might have disappeared, and if it did, that might have created a "grand minimum" TSI, below that currently experienced at SMIN. In order to estimate what that "grand minimum" TSI might have been, they used measurements of Ca II H and K lines from the Sun as a measure of magnetic activity. At the time they wrote their paper, extraterrestrial measurements of TSI were only available for one solar cycle and absolute calibration was not as refined as it is today (see Figure 4.1, color section). Therefore, their absolute values of TSI require some adjustment, but their method can still be discussed.

For the one solar cycle of TSI data, they carried out the following steps:

(a) They assigned a "quiet Sun" TSI (the TSI obtained at current SMIN) to be $S_Q = 1{,}366.9\,\mathrm{W/m^2}$. This was based on the minimum of ACRIM1 shown in Figure 4.1 around 1985. Based on Figure 4.2, we now believe that S_Q should have been about $1{,}365.5\,\mathrm{W/m^2}$.
(b) They used a previous estimate of the sunspot blocking effect to estimate the reduction in TSI caused by sunspots to be $(P_S \times S_Q)$, where P_S is a function of the number of sunspots, but P_S was not actually given in the paper. At SMIN, $P_S \sim 0$.
(c) At any level of magnetic activity on the Sun, the TSI will be enhanced by an amount S_C that increases with magnetic activity. They allowed S_C to remain non-zero at SMIN, thus providing for the possibility that a quiet network remains even at SMIN.

Thus, the actual measured TSI at any time is

$$\mathrm{TSI} = S_Q - (P_S \times S_Q) + S_C.$$

Therefore,

$$S_C = \mathrm{TSI} - S_Q + (P_S \times S_Q).$$

Lean and Foukal (1998) sought a relationship between S_C and the Ca II K index. However, inexplicably, they set

$$S_C = \mathrm{TSI} - S_Q - (P_S \times S_Q).$$

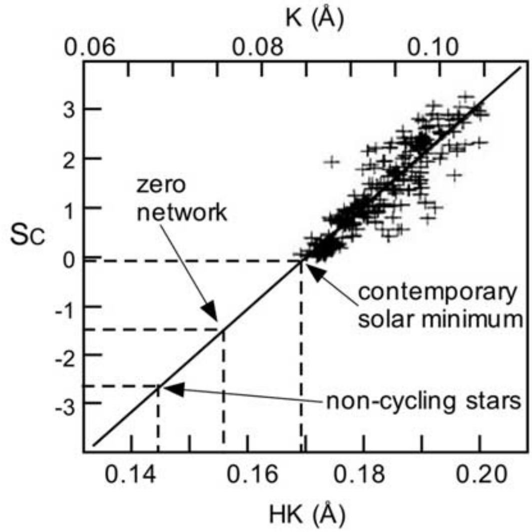

Figure 4.22. TSI data are plotted for ACRIM1 from 1978 to 1989 vs. Ca II H and K indices. (See text for note on the question of the sign of the term P_S.) The "zero network" point is an estimate for the Sun in the absence of magnetic activity. The "non-cycling stars" point is based on observation of non-cycling stars. Lean, Skumanich, and White (1992) extrapolated the data to "non-cycling stars" to estimate TSI during the MM.

This does not make sense to this writer (note the minus sign where a plus sign should exist).

For the ACRIM1 data from 1978 to 1989, they plotted their version of S_C vs. a measure of the Ca II H and K lines as shown in Figure 4.22. They found a linear relationship between the brightening due to faculae and the Ca II K index. However, had they used a + sign (rather than the − sign) in the above equation, it seems likely that the slope of the data in Figure 4.22 would have changed.

A theoretical model suggested an estimate for the Ca II K index of our Sun in the absence of magnetic activity as K = 0.076, and Lean, Skumanich, and White (1992) adopted this estimate for an estimate of our Sun when the entire surface is free of network brightening. In addition, they relied on studies of the Ca II K index from other stars. Some of these stars are non-cycling with reduced Ca II emission. Based on this work, an estimate was made of the mean Ca II emission for non-cycling stars, yielding K ~ 0.069. The implication is that in the absence of sunspots, faculae, and network, a non-cycling star will have further reduction (or elimination) of weak non-network magnetic fields. During the Maunder Minimum there were essentially no sunspots, and magnetic activity on the Sun was at a minimum. Lean, Skumanich, and White (1992) assumed that the state of non-cycling stars would be representative of the MM. They then extrapolated the line relating S_C to the Ca II K index to this lowest value of the K-index. This corresponds to the point marked "non-cycling stars" in Figure 4.22.

This process appears to this writer to be rather fragile for the following reasons:

(a) There is the question of the sign of the term ($P_S \times S_Q$) in the expression for S_C. If, as this writer believes, the sign is wrong, the slope of the putative line in Figure 4.22 will change.
(b) There is no guarantee that the extension of the data in Figure 4.22 to a lower K-index is linear.
(c) The use of non-cycling stars to estimate the K-index during the MM is a leap of faith.

This is not to diminish the imagination and innovation of Lean, Skumanich, and White (1992) who, in the absence of any firm ground to stand on, made some bold and intriguing assumptions to estimate TSI during the MM.

According to Figure 4.22, the TSI during the MM was about 2.8 W/m^2 lower than it is presently at SMIN ($\sim$1,365.5 W/m^2). Thus, the TSI during the MM was estimated to be about 0.24% lower than the current TSI at SMIN and about 0.33% lower than the current TSI at SMAX (1,367.2 W/m^2).

Lean, Beer, and Bradley (1995) was based on Lean, Skumanich, and White (1992). This required that the TSI during the Maunder Minimum be limited to a 0.24% decrease compared with the present TSI at SMIN. (This is in contrast to Reid's estimate of a 0.65% decrease during the MM.) Using their estimate for the reduction of TSI in the MM, Lean, Beer, and Bradley (1995) concluded that annual variations in TSI account for 74% of the variance in the Northern Hemisphere (NH) surface temperature anomalies from 1610 to 1800 and 56% of the variance from 1800 to the present. They further indicated:

> "About half of the observed 0.55°C warming from 1860 to the present may reflect natural variability arising from solar radiative forcing, although since 1970, less than one-third of the 0.36°C surface warming is attributable to solar variability."

They concluded:

> "Solar variability may have played a larger role in recent global temperature change than has hitherto been acknowledged."

Had Reid's model for TSI been used, for example, the solar contribution to temperature rise would have been much greater. However, Lean, Beer, and Bradley (1995) cautioned:

> "The longer term variability component [of TSI] is by necessity . . . speculative."

Solanki and Fligge (2000) also utilized a variant of the approach used by Lean *et al.* (1998).

Scafetta and West (2006) utilized an estimate of the TSI from 1900 to 2000 in climatological models to estimate the contribution of solar variations to climate

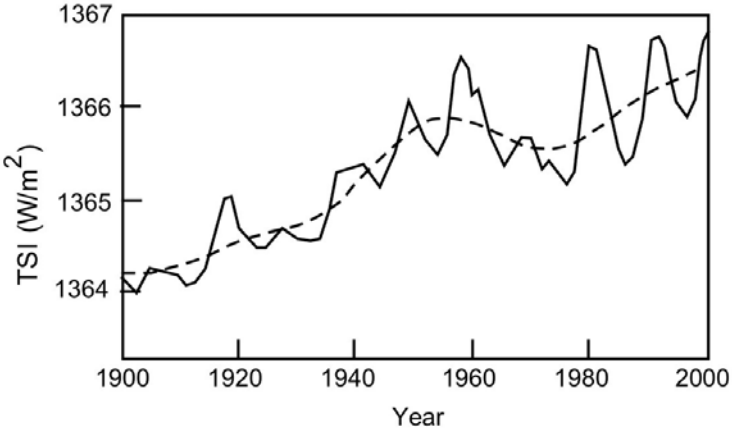

Figure 4.23. Estimated TSI for the 20th century. Adapted from Scafetta and West (2006).

change during the 20th century. Faced with a variety of reconstructions of past TSI with variable amplitude from 1900 to 2000, they had to choose one, and decided that the conservative thing to do was to choose a reconstruction with intermediate amplitude. Therefore, they chose the reconstruction of Lean, Beer, and Bradley (1995) (see Figure 4.23).

Their estimate of global surface temperature in the 20th century is shown in Figure 4.24. Based on this analysis, they arrived at the results shown in Table 4.1. Had they used a reconstruction of TSI with greater amplitude, the percentage rise due to TSI variation would have been higher. Nevertheless, they concluded that the

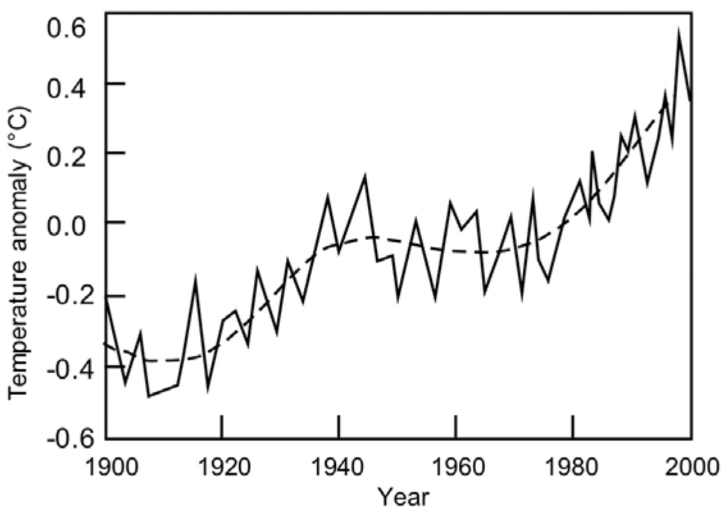

Figure 4.24. Global annual mean surface temperature anomalies (difference from mean) for the 20th century. Adapted from Scafetta and West (2006).

Table 4.1. Estimated TSI contribution to global warming. From Scafetta and West (2006).

Period	Total *T* rise (°C)	*T* rise due to TSI (°C)	Percent due to TSI
1900–2000	0.74	0.36	49
1900–1950	0.29	0.22	76
1950–2000	0.45	0.14	31
1980–2000	0.38	0.13	34

"impact of solar variation on climate seems significantly stronger than predicted by some energy balance models" (adapted from Lean, Beer, and Bradley, 1995).

Foukal, North, and Wigley (2004) reviewed stellar observations of Sun-like stars that have low-activity phases during which the magnetic activity is even lower than during present minima in the solar sunspot cycle. Extrapolation of the Sun's radiometrically observed irradiance (as in Figure 4.22) to this low-activity level suggested that solar irradiance in the 17th century may have been 0.24% lower than today. Reconstructions of irradiance variations based on stellar evidence have been used in several climate studies. Additional evidence for large multi-decadal solar luminosity variations came from photometric studies of Sun-like stars, some of which exhibited cyclic variations three to five times those observed radiometrically in the Sun. This finding suggested that similarly large luminosity variations may have occurred on the Sun in the recent past. However, Foukal, North, and Wigley (2004) raised concerns as to whether the stars that were studied "were truly Sun-like—that is, with very similar mass, age, and chemical composition to the Sun—because the high-dispersion data required for such identification are relatively difficult to obtain." According to Foukal, North, and Wigley (2004), "only 18 Scorpii (HR6060) seems to be a sufficiently close solar analog for comparison with the Sun's present irradiance behavior."

In Figure 4.25, a CQSM model of TSI and temperature variations since 1600 is compared with a model that assumes that TSI was 0.24% lower during the MM (as in Figure 4.22). While Foukal, North, and Wigley (2004) cast doubt on the 0.24% lower model, they did not discuss the fact that this leads to all sorts of logical difficulties. Even the 0.24% lower model during the MM is insufficient to account for inferred temperature variations during the past millennium. If the CQSM curve in Figure 4.25 is adopted, that would wipe out all temperature variations in the past 400 years, including the Little Ice Age, and probably the MWP as well.

Foukal, North, and Wigley (2004) raised a number of other objections to the process used by Lean and co-workers. Foukal, North, and Wigley (2004) concluded:

> "Data so far do not support the earlier conclusion that the Sun's irradiance variability of 0.08% is lower than that of similar stars ... Any relationship on longer time scales must therefore remain speculative."

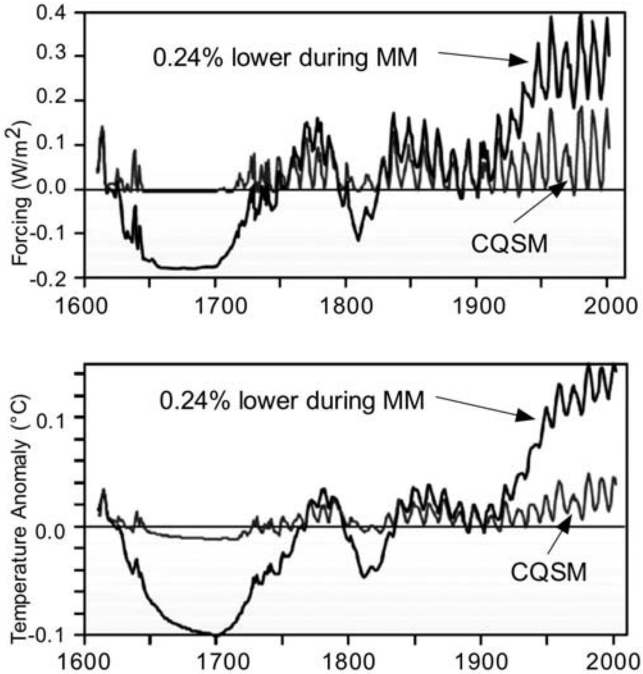

Figure 4.25. Illustration of the difference in modeled TSI and temperature variations since 1600 between a CQSM model and a model that assumes that TSI was 0.24% lower during the MM. Radiative forcing at the top of the atmosphere is one-quarter the change in TSI. Adapted from Foukal, North, and Wigley (2004).

Foukal, North, and Wigley (2004) mentioned that Lean, Wang, and Sheeley (2002) apparently "accepted that the long-term irradiance variations used in [their] climate models in the past decade may be a factor of ~5 larger than can be justified."

In a more recent publication Foukal *et al.* (2006) echoed the sentiments of their previous paper: "this study [i.e., Lean, Beer, and Bradley, 1995)] has since been retracted ... [by Lean, Wang, and Sheeley (2002)]. Foukal *et al.* (2006) also said "Recent reconstructions from ^{14}C records disagree on whether the Sun might have experienced extended episodes of very high activity in the past 10,000 years, much above that encountered in the recent past."

The issues raised by Foukal, North, and Wigley (2004) appear to be significant. However, that does not imply that there have not been long-term secular changes in the TSI over the past millennium. If the MWP and the LIA involved significant temperature excursions, and if these temperature fluctuations in the past millennium were driven by changes in TSI, then there had to be significant fluctuations in TSI. The upper curves in Figure 4.25 are likely to be an underestimate of the true variation; the lower curves are far worse. While previous studies of putative Sun-like stars may well be faulty, that does not lead to the conclusion that the Sun has been constant to within 0.1% for a thousand years.

4.4.5 Solar cycle duration model

4.4.5.1 The "Sun Melody"

> "Most reconstructions of TSI for the last 250 yrs have been based on solar activity data such as the sunspot number. To estimate the irradiance, the amplitude, the solar cycle duration (or frequency) are often used. Several reconstructions have been proposed. They differ in details but agree in the overall shape, the generally increasing trend with local minima during periods of low solar activity (Maunder minimum: 1645–1715; Dalton minimum: 1800–1820; 1900 minimum: 1880–1900), and a slight decrease between 1940 and 1970. A sharp maximum around 1830 is connected with high solar activity. Superimposed on this long-term trend are short-term fluctuations caused by the 11-year Schwabe cycle" (Beer, Mende, and Stellmacher, 2000).

The irradiance reconstruction of Beer, Mende, and Stellmacher (2000) was based on the frequency of the Schwabe cycle because they claimed a better fit to temperature data is obtained than with sunspot count if they assumed a linear relationship between solar cycle frequency and irradiance. They estimated the frequency change in time by complex demodulation. This provided a continuous frequency modulation function. For comparison with temperature records they used 14-year low-pass filtering in order to remove all periodic irradiance changes during one Schwabe cycle. This led to a relatively smooth frequency modulation function that they called the "Sun Melody".

Beer, Mende, and Stellmacher (2000) presented Figure 4.26 but no details are provided on how they obtained TSI from sunspot cycle duration (or its inverse: frequency).

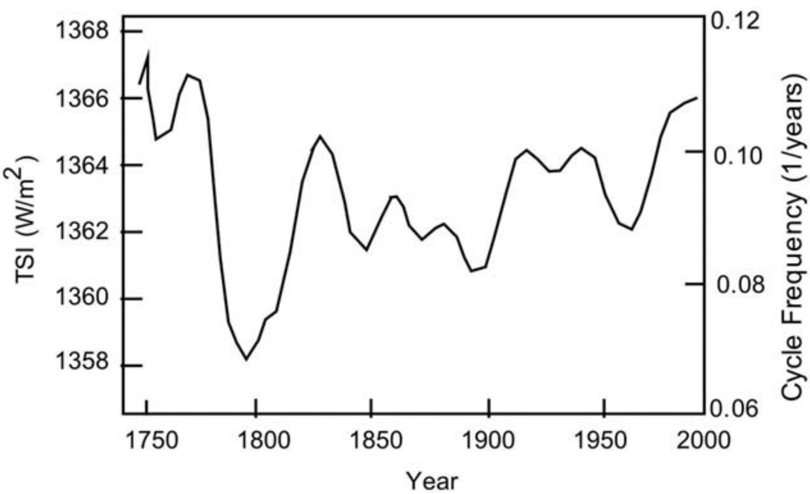

Figure 4.26. "Sun Melody." Estimate of TSI based on variable solar cycle duration. Adapted from Beer, Mende, and Stellmacher (2000).

It should be noted that the MM was not included in Figure 4.26 because solar cycle duration data were not available prior to about 1750. According to Figure 4.26, the low point in TSI just prior to 1800 was 0.6% lower than the current TSI. The MM was surely even lower. However, while the locations of ups and downs are fairly well correlated between sunspot numbers and inverse duration of the solar cycle, the amplitude of variation is much greater when based on solar cycle duration.

4.4.5.2 Danish Meteorological Institute studies

Friis-Christensen and Lassen (1991) presented Figure 4.27, taken from previous work. This figure compares the average temperature of the Northern Hemisphere with the average solar activity defined by the interval between successive sunspot maxima.

The more active the Sun, the shorter the interval: the solar cycle runs more intense. The dashed curve in Figure 4.27 illustrates the solar activity, which has generally increased over the past ~100 years, since the cycle duration has decreased from around 11.5 years to almost 10 years. Within the same interval the Earth's average temperature as indicated by the solid curve has increased by approximately 0.6°C.

Friis-Christensen and Lassen (1991) claimed that the varying length of the 11-year cycle is strongly correlated with long-term variations of the Northern Hemisphere land surface air temperature since the beginning of systematic temperature variations from a global network (i.e., during the past 130 years). Although direct temperature observations before this interval are scarce, the correlation has been extended back to the 16th century using various series of proxy temperature data. Reliable sunspot data do not exist before 1750, but Friis-Christensen and Lassen (1991) was able to derive epochs of minimum sunspot activity from auroral observations back to 1500 and combine them with direct observations to form a homogeneous series.

Based on Figure 4.27, Friis-Christensen and Lassen (1991) said:

"Whereas the sunspot number returns to near zero at each 11-year minimum, the 11-year geomagnetic activity variations are superimposed on a long-term varia-

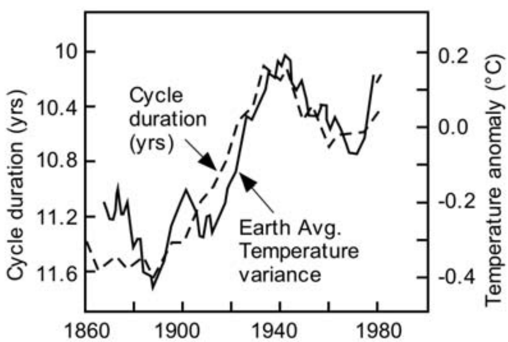

Figure 4.27. Comparison of solar cycle duration with temperature variance (measured from 1980) in the Northern Hemisphere. Adapted from Friis-Christensen and Lassen (1991).

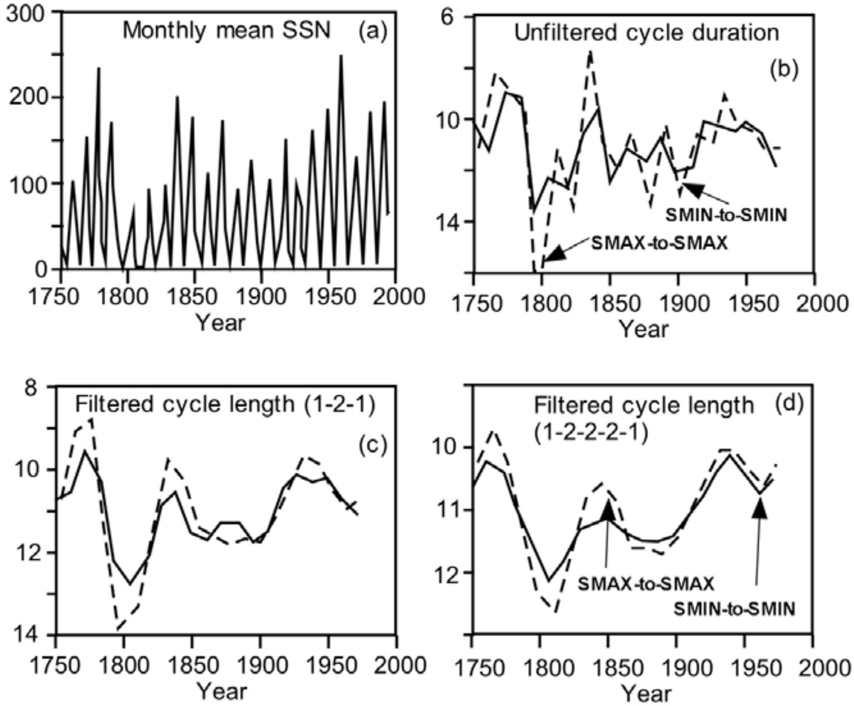

Figure 4.28. (a) Monthly mean of sunspot number; (b) unfiltered sunspot cycle duration (years) (SMIN to SMIN and SMAX to SMAX); (c) 1-2-1 filtered cycle duration data; and (d) 1-2-2-2-1 filtered cycle duration data. Adapted from Friis-Christensen and Lassen (1991).

> tion of similar amplitude including a nearly monatomic increase from 1900 to 1950. This has been interpreted as a signature of an increase in the solar wind velocity through the century. The observed long-term variation in solar energy output by means of the solar wind suggests that similar long-term changes in other manifestations of solar energy output may have occurred."

To estimate this putative long-term variation in TSI, they utilized changes in the length of the approximately 11-year sunspot cycle.

The sunspot cycle duration record is subject to "noise", due to the fact that the start of a cycle cannot be easily defined in time because of the presence of short-term fluctuations in solar activity that provide obscuration. This is the case when the minimum activity in the "11-year" cycle is regarded as the start of the cycle, but it is even more difficult to define the start of a cycle by means of the time of maximum solar activity. Therefore, the cycle duration record must be filtered as shown in Figure 4.28.

A comparison of filtered data from Figure 4.28c with Northern Hemisphere temperatures is given in Figure 4.29. The strong correlation between inverse sunspot cycle duration variations and variations in NH temperature suggests that solar

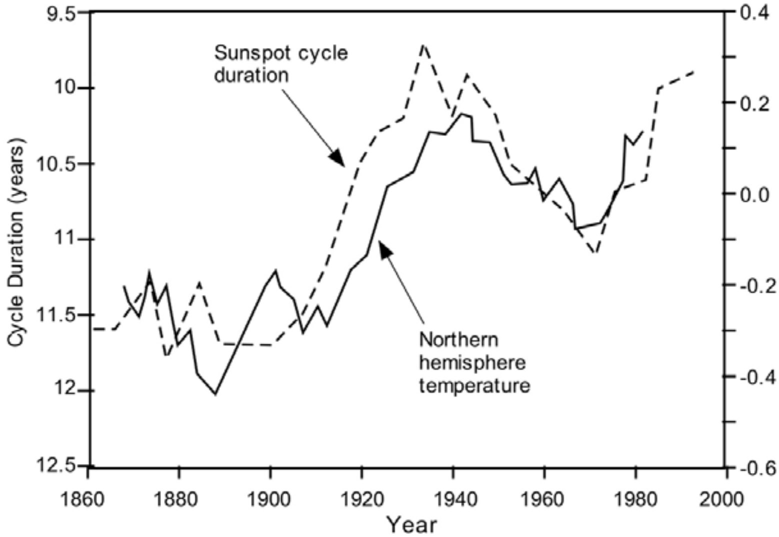

Figure 4.29. An 11-year running average of Northern Hemisphere temperature compared with 1-2-1 filtered sunspot cycle duration. Adapted from Friis-Christensen and Lassen (1991).

variations were the principal driver for temperature change since 1860. Friis-Christensen and Lassen (1991) also demonstrated a strong correlation between sunspot activity and frequency of aurora occurrence as shown in Figure 4.30.

Having demonstrated an inverse relationship between solar cycle duration and Northern Hemisphere temperature, Friis-Christensen and Lassen (1991) went on to

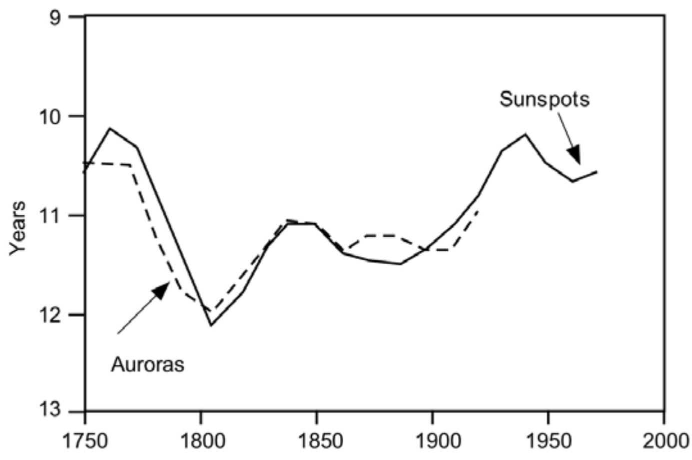

Figure 4.30. Comparison of sunspot cycle duration with frequency of aurora occurrence. The vertical scale for sunspots is the duration of the solar cycle and the vertical scale for auroras (scaled to fit) is the number of auroras seen per year. Adapted from Friis-Christensen and Lassen (1991).

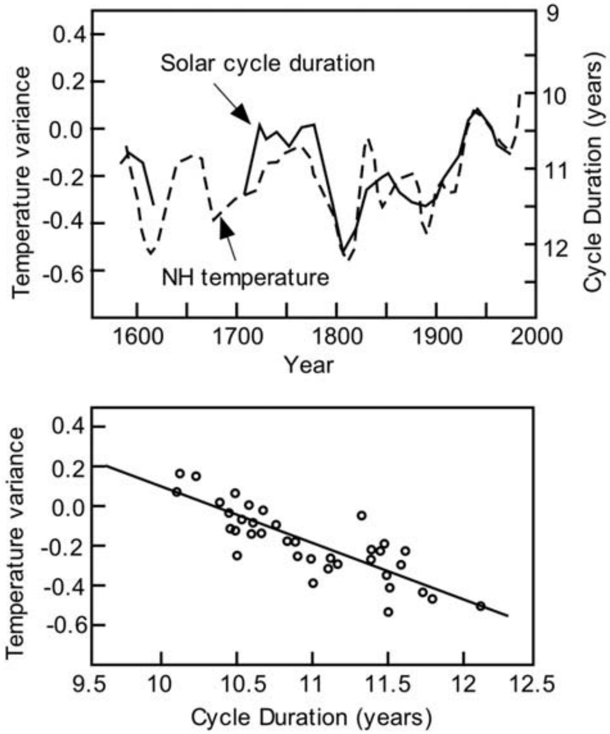

Figure 4.31. (a) Lower frame: dependence of Northern Hemisphere temperature variance on solar cycle duration. (b) Upper frame: an 11-year running average of the annual mean values of reconstructed NH temperatures from 1579 to 1860 connected to corresponding measured values for 1851 to 1987, together with the smoothed values of the solar cycle duration from 1564 to 1989, with the exception of the interval 1641–1674, for which reliable data are missing (plotted inversely). Adapted from Friis-Christensen and Lassen (1991).

define the relationship quantitatively and they compared the resultant estimated temperature since about 1579 with an estimate of the temperature record, as shown in Figure 4.31.

Lassen (1991) concluded that a comparison of the extended solar activity record with the temperature series confirms the high correlation between solar activity and Northern Hemisphere land surface air temperature and shows that the relationship has existed through the whole 500-year interval for which data exist.

A corresponding influence of solar activity was also demonstrated for both the date of arrival of spring in the Yangtze River Valley as deduced from phenomenological data and the extent of the sea ice in the Atlantic sector of the Arctic Sea that correlate well with the length of the sunspot cycle during the last 450 years.

Solanki and Fligge (2000) also presented a reconstruction of past TSI based on solar cycle duration correlations. However, few details were provided and it is not clear how they proceeded. Evidently, this work is derived from Solanki and Fligge (1999) as can be seen from Figure 4.17. However, that is a very compressed database.

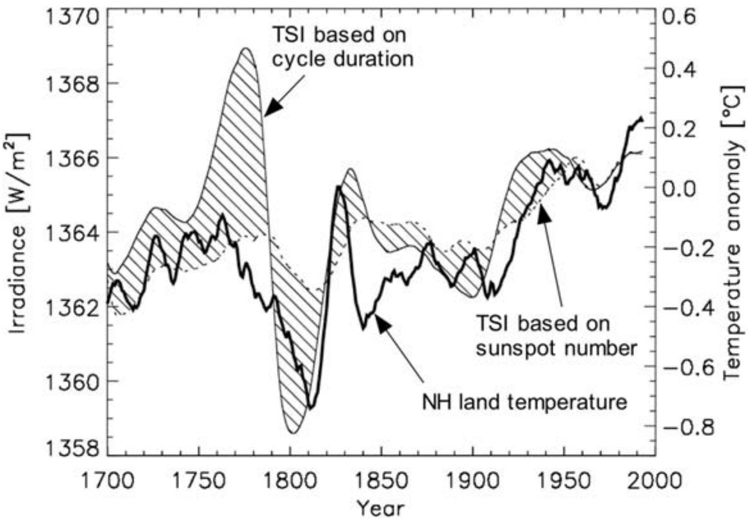

Figure 4.32. Reconstruction of TSI using cycle duration or sunspot indices. The shaded area shows the differential between reconstructions based on cycle duration and sunspot count. Adapted from Solanki and Fligge (2000).

Their result is shown in Figure 4.32. The large peak around 1760 and dip around 1800 seem to be anomalous.

4.4.5.3 Hoyt and Schatten model

Hoyt and Schatten (1993) took the approach that the various solar indices,

(1) fraction of spots that are penumbral
(2) solar cycle duration
(3) equatorial rotation rate
(4) decay rate of the solar cycle, and
(5) mean level of solar activity, but prior to the MM temperature model or the Ca HK model which are not included by Hoyt and Schatten (1993)

can be related to sunspot decay rates, and thus, the sunspot decay rate becomes the main determinant of TSI variations.

The results of their model are shown in Figure 4.33. For 1700–1874, three indices were used: cycle duration, cycle decay rate, and level of solar activity. For 1875–1978, two additional indices were employed: solar rotation and fraction of penumbral sunspots. For 1979 to 1992, they scaled their figures to Nimbus 7 measurements.

Although this correlation begins just around the end of the MM, extension of Figure 4.33 to earlier dates suggests that the TSI during the MM was more than 0.45% lower than it is today. If solar irradiance has varied with time as Hoyt and

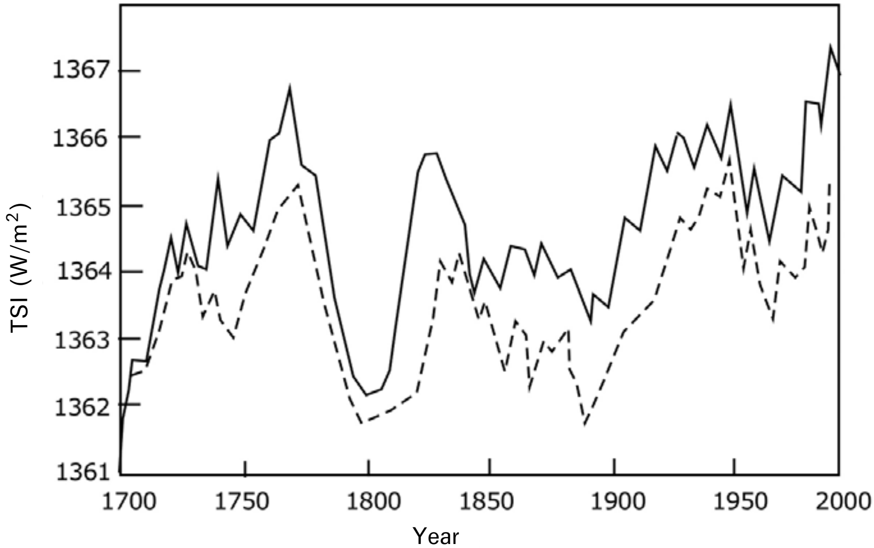

Figure 4.33. Modeled total solar irradiance based on sunspot decay rates. Solid line is upper estimate and dashed line is lower estimate. The vertical scale was scaled to fit the latest ACRIM measurements. Adapted from Hoyt and Schatten (1993).

Schatten (1993) estimated, it can be expected to have had some significant effect on the temperature of the Earth. They examined two questions.

(1) Is the Earth responding in a manner consistent with an external forcing?
(2) Do the Earth's temperature variations and the model TSI variations correlate with each other?

A solar forcing will tend to cause the two hemispheres of the Earth to vary in parallel. The amplitudes of the responses will differ because the two hemispheres have different amounts and distributions of land and ocean. Hoyt and Schatten (1993) separated the Northern and Southern Hemisphere temperature records. Then, they compared the temperature history in the Northern Hemisphere with the combined model for TSI history as shown in Figure 4.34; this figure suggests a close correlation of TSI with temperature. The modeled TSI and measured temperatures share many similarities. However, the temperature reconstruction used thermometer measurements predominantly from Europe, so the temperature reconstruction may not be fully representative of the NH.

Hoyt and Schatten (1993) claimed that on a decadal timescale, the TSI model can explain ~71% of the TSI variance during the past 100 years and ~50% of the variance since 1700. They concluded:

"There is plausible evidence for long-term changes in TSI."

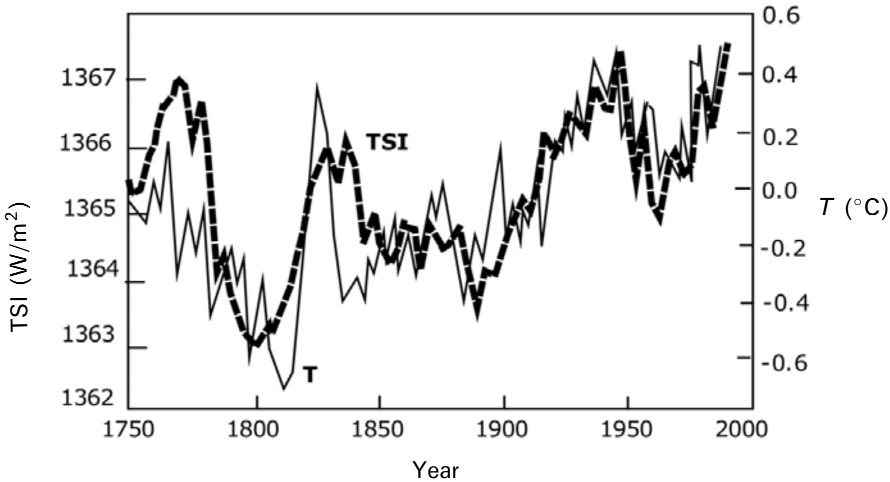

Figure 4.34. Comparison of 11-year moving mean of Northern Hemisphere temperature with modeled TSI. Adapted from Hoyt and Schatten (1993).

Based on the energy stored in the Sun's convective zone ($\sim 10^{45}$ ergs) a change in solar emission of, say, 0.2% for a whole century amounts to 1 part in 40,000 of the stored energy. Thus, there is no reason to rule out such variations based on energy. They also pointed out that from 1880 to 1940 the Earth warmed by about 0.5°C and climate models suggest that a change in TSI of 1% produces a change in temperature of about 1.67°C; therefore, a 0.5°C change should require a change in TSI of about 0.30%. They quoted some (QCSM) estimates that TSI changed by only 0.14% over this time interval and suggested that 0.14% is inadequate to account for the observed change in temperature.

4.4.6 Coronal source flux model

Lockwood and Stamper (1999) and Lockwood (2002) developed methods for estimating the coronal source flux, F_s. The coronal source surface occurs where the solar magnetic field becomes approximately radial and lies at a heliocentric distance of about 2.5 solar radii. The total magnetic flux leaving the Sun, and thereby entering the heliosphere by threading this surface, is the coronal source flux, F_s. One method depends on measurements of the geomagnetic *aa* index and another depends on measurements of the near-Earth interplanetary magnetic field (IMF). They studied the correlation of F_s with TSI. Lockwood (2002) said (regarding correlation of F_s with TSI):

> "Were it to reveal a real physical connection between TSI and F_s, this correlation would be very important—even though it is unlikely to be the result of a direct causal relationship."

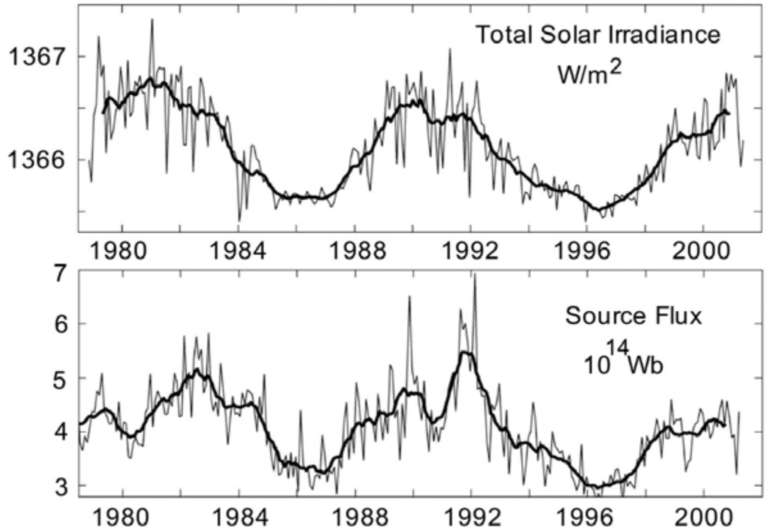

Figure 4.35. Variation of measured extraterrestrial TSI and calculated F_s since 1978. Thin lines are monthly means and thick lines are 12-month averages. Careful comparison of the peaks and valleys of the two monthly curves reveals that TSI tends to lag F_s by about a month or so. Adapted from Lockwood (2002).

A comparison of recent TSI data with F_s data is shown in Figure 4.35.

Lockwood (2002) developed a scatter plot of 12-month average F_s vs. 12-month average TSI and fitted a straight line to the scattered data resulting in

$$\text{TSI} = 1363.5 + 0.645F_s \quad (\text{W/m}^2)$$

although they found a best fit with the TSI data lagging by 6 months. Using this relationship, the predicted 12-month average TSI (from F_s) is compared with the actual 12-month average TSI in Figure 4.36. Note that according to this algorithm, the TSI can never drop below 1,363.5 W/m^2 under any circumstances. Thus, this model is somewhat analogous to QCSM models in that it assumes that past variations in TSI are due only to factors discernible in the present solar cycle.

In an earlier paper, Lockwood and Stamper (1999) estimated F_s over a much longer time period, from about 1870 to the present. The lowest values of F_s occurred around 1880 and 1900 when F_s dipped to about 1.4×10^{14} Wb. According to the above algorithm, this would imply that the minimum TSI in those years was about $(1{,}363.5 + 0.645 \times 1.4) = 1{,}364.4$ W/m^2, which is about 0.15% lower than the present TSI at SMAX. In essence, this is another QCSM except that the transducer for predicting TSI is F_s instead of sunspot number. This model does not account for any long-term secular changes in solar output independent of solar magnetic activity within the framework of current solar behavior.

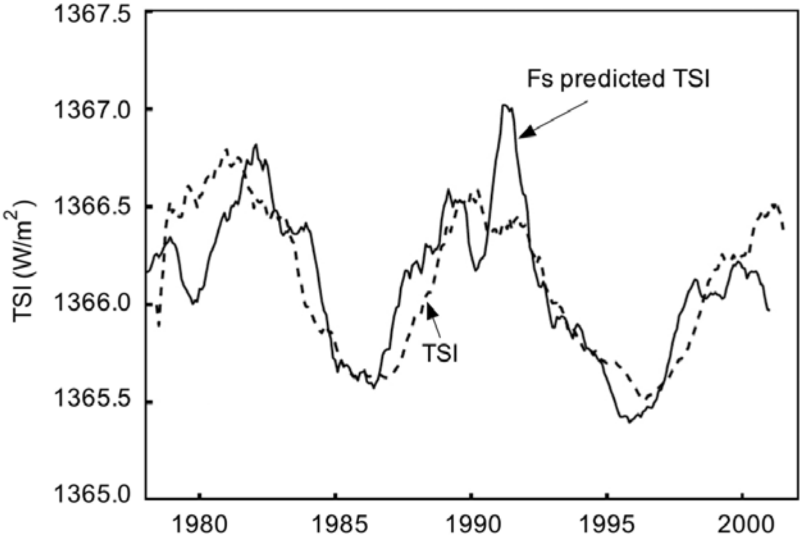

Figure 4.36. Comparison of the predicted 12-month average TSI (from F_s) with the actual 12-month average TSI. Adapted from Lockwood (2002).

4.5 TSI RECONSTRUCTIONS BASED ON COSMOGENIC ISOTOPE PROXIES

4.5.1 Introduction

Galactic cosmic rays are continually impinging on the Earth's atmosphere, producing nuclear reactions that generate radioactive isotopes. These isotopes gradually settle through the atmosphere and may be incorporated into biota, ice deposits, and other media that preserve the "cosmogenic isotopes" for long periods of time. Of particular interest is the occurrence of ^{14}C in tree rings and ^{10}Be in high-latitude ice cores. The interpretation of such proxies has mainly been in reference to historical surface temperatures as discussed in Section 2.4, but proxies have also been used in a few instances to infer aspects of historical variation of TSI.

As Muscheler *et al.* (2005) pointed out:

> "The Sun influences the production rate of ^{14}C in the Earth's atmosphere by modulating the galactic cosmic-ray flux through its magnetic field. Increased magnetic field in the solar wind causes a stronger deflection of galactic cosmic rays and lower radionuclide production rates in the atmosphere, and vice versa."

Thus, the historical record of annual isotope production would have been influenced by the historical variation in the activity of the Sun. However, Muscheler *et al.* (2005) also pointed out:

> "The atmospheric ^{14}C concentration also depends nonlinearly on the geomagnetic field intensity and the global carbon cycle. These factors and their uncertainties need to be carefully included in the reconstruction of solar activity."

Similar considerations apply to other proxies such as ^{10}Be in ice cores. Thus, the historical isotope record contains information about past solar activity, but unraveling that information is difficult due to a number of confusing factors.

The use of cosmogenic radioisotopes as proxies for TSI variation introduces uncertainties. The radioisotopes are not produced in the Earth's atmosphere directly by the Sun's flux of energetic particles. They are produced mainly by high-energy galactic cosmic rays, from outside the Solar System. Their modulation with the solar cycle is due to changes in the way these cosmic rays are shielded by the heliosphere (the solar wind). The efficiency of this shielding depends on solar plasma outflows from open magnetic fields in quiet regions and individual events such as flares and coronal mass ejections. Although this shielding increases roughly with the general level of solar activity, it is only very loosely proportional to the areas of the dark and bright magnetic structures that drive TSI. In view of this, it is unrealistic to expect a fixed relation between variations in ^{10}Be or ^{14}C production rate and TSI over the past millennium. The relation is complicated further by possible climate influences on the ^{10}Be and ^{14}C deposition rates, causing errors in the inferred ^{10}Be and ^{14}C formation rates (Foukal *et al.*, 2006).

Lean, Wang, and Sheeley (2002) revisited the question of reconstructing TSI for the past based on models developed for solar magnetic fields (Wang, Lean, and Sheeley, 2002). While the Sun's total magnetic flux (sunspots, faculae, network, etc.) has a significant effect on TSI, a relatively small fraction of the Sun's magnetic flux (whose footprint regions are observed as coronal holes) extends into the heliosphere. Open magnetic fields have a negligible effect on solar irradiance, but they are the source of the interplanetary magnetic field (IMF). IMF variations modulate the terrestrial flux of cosmic rays that produce cosmogenic isotopes, and they also affect geomagnetic activity. When these fields are high, production of cosmogenic isotopes is reduced. In the model developed by Wang, Lean, and Sheeley (2002) and Lean, Wang, and Sheeley (2002), a hypothetical 110-year build-up of solar magnetic dipoles was simulated (with an 11-year solar cycle superimposed) and the consequences for the total magnetic flux and the open flux were estimated.

The main conclusion drawn by Lean, Wang, and Sheeley (2002) was that the open flux can build up with time due to an increase in dipoles, but the total surface flux may remain constant. Thus, they say:

> "Secular changes in terrestrial proxies of solar activity (such as the ^{14}C and ^{10}Be cosmogenic isotopes and the *aa* geomagnetic index) can occur in the absence of long-term (i.e., secular) solar irradiance changes. Increasing solar cycle amplitudes produce a secular increase in open flux and interplanetary magnetic field (IMF), and can therefore explain variations like the cosmogenic isotope decrease from 1922 to 1965. Total magnetic flux, however, does not have an equivalent secular trend during minima. Since the primary sources of the total flux

are features that modulate solar irradiance, this suggests that total solar irradiance may also lack significant secular trends.''

In essence, Lean, Wang, and Sheeley (2002) argued in favor of a CQSM model for long-term solar variation. Foukal *et al.* (2006), building upon Lean, Wang, and Sheeley (2002), concluded:

> ''Overall, we can find no evidence for solar luminosity variations of sufficient amplitude to drive significant climate variations on centennial, millennial and even million-year timescales.''

In keeping with current trends in ''political correctness'' that have wiped out temperature variations for the past thousand years with *hockey stick* figures, Foukal *et al.* (2006) and Lean, Wang, and Sheeley (2002) have attempted to eliminate TSI variations as well. However, there are several gaping holes in their arguments. One that stands out is that if there were no ''solar luminosity variations of sufficient amplitude to drive significant climate variations on centennial, millennial and even million-year timescales'', that would seem to imply that there have been no ''climate variations on centennial, millennial and even million-year timescales,'' unless they believe that all the past climate changes were due to variations in the Earth's orbit around the Sun, which seems unlikely.

4.5.2 Reconstruction of TSI from cosmo-nuclide production proxies

Bard *et al.* (2000) pointed out that previous reconstructions of historical TSI exhibited similar fluctuations, but they differed significantly in amplitude. The main differences are best illustrated by comparing the TSI decrease estimated or extrapolated for the deepest part of the Maunder Minimum: ranging from 0.24% (Lean, Beer, and Bradley, 1995), to 0.3% (Hoyt and Schatten, 1993), to 0.4% (Solanki and Fligge, 1999), to 0.5% to 0.65% (Reid, 1997). The estimate of 0.24% by Lean, Beer, and Bradley (1995) is often used as a conservative view of TSI changes during the Maunder Minimum. Nevertheless, if there were no long-term trend, the TSI during the Maunder Minimum would obey a CQSM and be comparable with the current TSI at SMIN.

Bard *et al.* (2000) emphasized that it is possible to use the high-frequency component of the solar magnetic variability as a proxy for production of cosmogenic nuclides such as ^{14}C and ^{10}Be. Magnetic fields of the solar wind deflect the primary flux of charged cosmic particles, which leads to a reduction of cosmogenic nuclide production in the Earth's atmosphere. In particular, it is claimed that the 11-year cycle modulates ^{10}Be production recorded in well-dated polar ice from Greenland and Antarctica. Very high cosmo-nuclide production (30%–50% above the modern value) has also been confirmed for the Maunder Minimum based on high ^{14}C content in tree rings and ^{10}Be in polar ice.

The results of the work by Bard *et al.* (2000) provided a profile of variation of ^{10}Be and ^{14}C during the past millennium. Their result is shown in Figure 4.37. The

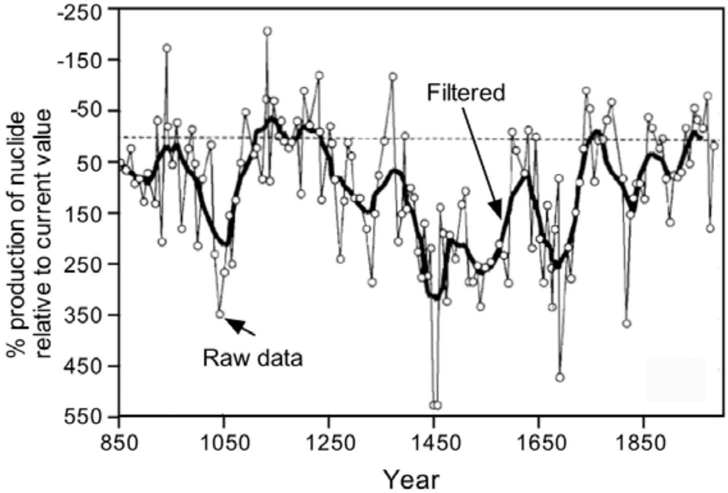

Figure 4.37. Cosmo-nuclide production as percent of present production based on ^{10}Be in polar ice and ^{14}C in tree rings. Adapted from Bard *et al.* (2000).

TSI is inversely related to cosmo-nuclide production, so the vertical scale is plotted inversely. The curve in Figure 4.37 is representative of the TSI, but the quantitative relationship of nuclide production to TSI is not obvious.

Bard *et al.* (2000) scaled the nuclide data by setting TSI equal to the known value (~1,367 W/m^2) in the 1990s, and then using a parameterized decrease in TSI during the MM to generate a family of curves for TSI over the past millennium for each assumed minimum during the MM (see Figure 4.38, color section). However, in doing this, apparently, Bard *et al.* (2000) only scaled the nuclide production rate during periods of low TSI (high nuclide production) and assumed that during periods of high TSI (low nuclide production) no scaling was needed. That is one possibility; it assumes that prior to (and after) the MM, during periods of relatively high TSI, the Sun acted as it does today. This model is the antithesis of the CQSM because in this model, the maximum TSI is fixed and the minimum TSI is varied and unbounded.

4.5.3 Projections for the Holocene

Solanki *et al.* (2004) carried out a reconstruction of the sunspot number over 11,000 years back in time, based primarily on archival concentration of cosmogenic isotope ^{14}C activity in the atmosphere obtained from high-precision ^{14}C analyses on decadal samples of mid-latitude tree ring chronologies, but also including some comparison with ^{10}Be in ice cores from Antarctica and Greenland since 850.

The original data set used by Solanki *et al.* (2004) for sunspot number reconstruction is represented by the "wiggly" black line in Figure 4.39, based on ^{14}C data. The ^{14}C measurement precision is claimed to be generally 2%–3%, although in the earlier part of the time series it can reach up to 4%–5%. The long-term decline (indicated by the smooth curve) is caused by a reduction in ^{14}C production rate due mainly to an increase in the geomagnetic shielding of the cosmic ray flux and does not necessarily indicate any changes in TSI. The short-term fluctuations (duration one to two centuries) are assumed to reflect changes of the production rate due to solar variability.

According to Anon. (E, p. 36):

> "Whereas the long term trend in records of cosmogenic isotopes such as ^{14}C and ^{10}Be reflects, primarily, changes in the Earth's magnetic field that affect the interaction of cosmic rays with the Earth's atmosphere, the 'wiggles' superimposed on the smooth long term trend are believed to occur because of the modulation of the local cosmic-ray intensity by magnetic fields embedded in the solar wind, which varies in response to solar activity. Thus, enhanced solar activity corresponds to ^{14}C minima, and the mechanism proposed by Eddy (1976) for the apparent relationship between climate and the ^{14}C 'wiggles' involved changes in the total solar irradiance linked to the long term envelope of the 11-year sunspot cycle and reflected in the ^{14}C record."

This seems to imply that most of the secular long-term variation in Figure 4.39 is due to changes in the Earth's magnetic field, and the smaller "wiggles" in Figure 4.39 represent the ups and downs due to changes in solar activity. On this basis one could treat the smooth curve in Figure 4.39 as a reference and measure deviations in ^{14}C from this reference as the main signal. However, as Eddy (1976) suggested, there may also be a solar component to the secular long-term change in the ^{14}C signal, and it is not clear how Solanki *et al.* (2004) determined this component.

Thus, in order to estimate variability of TSI one would have to flatten out the

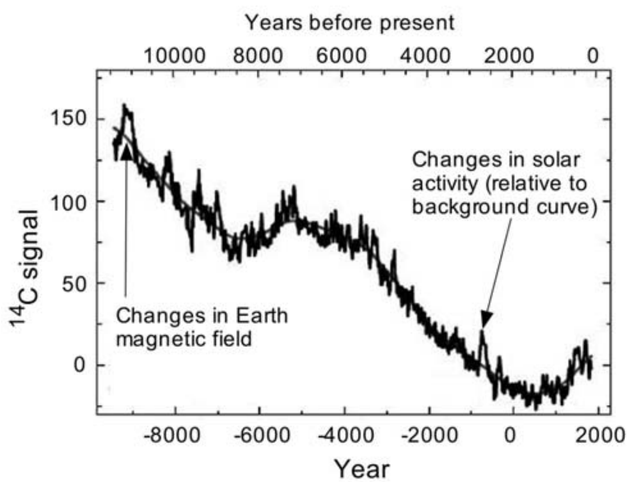

Figure 4.39. Atmospheric radiocarbon level ^{14}C (expressed as deviation, in ‰, from the AD 1950 standard level) derived from mostly decadal samples of absolutely dated tree-ring chronologies. Adapted from Solanki *et al.* (2004).

smooth curve in this figure to horizontal and deal only with variations about this horizontal line. Since the accuracy of the basic $\Delta^{14}C$ measurement is several percent, and the signal ("wiggles" about the trend line) amounts to only a fraction of the $\Delta^{14}C$ measurement, the accuracy of the signal will be limited.

As Solanki *et al.* (2004) pointed out,

> "The atmospheric ^{14}C level may also be affected by changes in the partition of carbon between the major reservoirs, that is, deep ocean, ocean mixed layer, biosphere and atmosphere. Variations in ocean circulation could influence ^{14}C via a variable uptake of CO_2 into the ocean or by the exchange of ^{14}C-depleted carbon from the deep ocean, but, owing to the rather small ^{14}C gradients among the reservoirs, strong changes in these processes need to be invoked."

For the Holocene, Solanki *et al.* (2004) claimed that

> "there is no evidence of considerable oceanic variability, so we can assume that the short- and mid-term fluctuations of ^{14}C predominantly reflect solar variability. This is supported by the strong similarity of the fluctuations of ^{10}Be in polar ice cores compared to ^{14}C, despite their completely different geochemical history."

However, Anon. (E) claims that

> "the extent to which cosmogenic isotope variations really indicate terrestrially relevant variations in solar energy outputs, either radiative or particle, and the scaling of the relationship over long times is poorly known; the paleo-climate record is similarly somewhat uncertain."

It is not clear to this writer how Solanki *et al.* (2004) processed Figure 4.39. It appears possible that they simply flattened out the smooth curve to make it horizontal and took only variations about this line. However, later results do not necessarily agree with this interpretation. Solanki *et al.* (2004) used a rather involved procedure in multiple steps to estimate historical sunspot numbers from the ^{14}C production rate in Figure 4.39. This reconstruction method was previously applied to ^{10}Be data from Greenland and Antarctica. A comparison of their results with ^{10}Be results since 850 and observed group sunspot numbers since about 1600 is shown in Figure 4.40 (color section). Solanki *et al.* (2004) claims that the similarity of the curves provides some measure of validation of the process. However, it is difficult to understand how they arrived at their results. These results suggest that the sunspot number is higher today than at any previous time in the past 1,000 years.

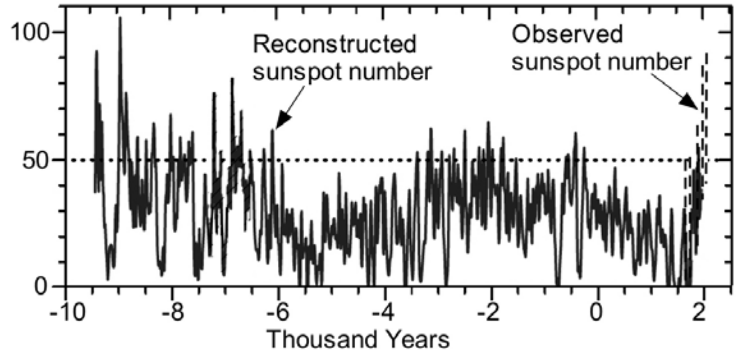

Figure 4.41. Reconstructed sunspot number and its uncertainty for the whole interval of time considered. (a) 10-year averaged SN reconstructed from ^{14}C data since 9500 BC and 10-year averaged group sunspot number (GSN) obtained from telescopic observations since 1610 (dashed lines). Adapted from Solanki *et al.* (2004).

The results of Solanki *et al.* (2004) over a longer time period are shown in Figure 4.41. As before, it is difficult to understand how this figure follows from Figure 4.39. Presumably, each peak in Figure 4.41 should be associated with a down-wiggle in Figure 4.39 and the height of each peak in Figure 4.41 should be determined by the depth of the wiggle in Figure 4.39. It is difficult to make this connection. If the results presented in Figure 4.41 were correct, it would imply that current sunspot numbers are the highest they have been in the past 8,000 years.

An extension of the work of Solanki *et al.* (2004) was carried out by Muscheler *et al.* (2005). Solanki *et al.* (2004), like most ^{14}C studies, excluded the most recent 100 years of the ^{14}C record, because they are influenced by ^{14}C-depleted fossil fuel emissions and atomic bomb tests conducted since 1950. However, Muscheler *et al.* (2005) claimed that they extended the analysis of the radiocarbon record from Solanki *et al.* (2004) to 1950, which allowed them to link the ^{14}C-based solar reconstruction to instrumental measurements of solar magnetic modulation that cover the past 68 years. Muscheler *et al.* (2005) said:

> "It is standard practice to model the observed dilution of the atmospheric isotope ratios caused by the addition of isotopically depleted carbon from fossil and land-use sources. Emissions from fossil sources are prescribed, emissions from land-use sources are inferred from the atmospheric carbon budget, and the two-way exchange fluxes between reservoirs are simulated. The dilution of ^{14}C is governed by the same processes that affect ^{13}C. The good agreement between modeled ^{13}C and ice-core data supports the reconstructed rate of ^{14}C production."

However, this description is too vague for this writer to understand how Muscheler *et al.* (2005) took into account the ^{14}C-depleted fossil fuel emissions and atomic bomb tests conducted since 1950.

According to Muscheler *et al.* (2005), the ^{14}C production record was transformed into a record of the solar modulation parameter that describes the solar influence on galactic cosmic ray deflection by normalizing it to neutron monitor and ionization chamber data covering the recent decades. Alternatively, balloon-borne estimates of galactic cosmic ray deflection were used instead of the ionization chamber data. Like Solanki *et al.* (2004), Muscheler *et al.* (2005) assumed that natural variations in the carbon cycle were small during the past millennium, which is consistent with ice core CO_2 and $^{13}CO_2$ data and models. However, the entire procedure for data reduction and modeling remains obscure to this writer.

The results of Muscheler *et al.* (2005) indicate that the ^{14}C-production rate tracks the group sunspot number fairly well although the large peak in the late 18th century ^{14}C production rate curve appears to be anomalous. Variations in ^{14}C production rate appear to be well correlated with solar magnetic activity. Similar results for the solar modulation parameter were obtained. However, Muscheler *et al.* (2005) cautioned:

> "The link between the visually based sunspot numbers and solar-modulation parameter is neither straightforward nor yet understood, and also that solar modulation must have reached or exceeded today's magnitudes three times during the past millennium."

Considering that the sunspot numbers are observed directly and the ^{14}C production rate depends on assumptions and intricate models, it appears likely that the sharp peaks in the ^{14}C production rate may be artifacts.

Muscheler *et al.* (2005) argued that the reconstruction by Solanki *et al.* (2004) implies generally less solar forcing during the past millennium than in the second part of the 20th century. However, Muscheler *et al.* (2005) then went on to provide the "politically correct" assurance:

> "In any case, as noted by Solanki *et al.* (2004) solar activity reconstructions tell us that only a minor fraction of the recent global warming can be explained by the variable Sun."

There is no known way to prove such an assertion.

4.6 TEMPERATURE CHANGES DRIVEN BY THE SUN

4.6.1 Global climate models

The impact of a change in TSI on the Earth is bound to be very complex. A number of groups have developed global climate models that analyze such effects (e.g., Meehl *et al.*, 2002; Doran *et al.*, 2002; Turner *et al.*, 2005). These studies typically examine the extent to which estimated solar, volcanic, and greenhouse forcing can account for past variations in temperature, as well as recent temperature rises in the late 20th century. Typically, such studies are mainly concerned with the potential impact of increased CO_2 emissions on global temperatures in the 21st century. Unfortunately, published estimates of historical TSI that are needed by these models suffer from a number of maladies as summarized in Section 4.7.

Ammann *et al.* (2007) employed a sophisticated global climate model to estimate the Earth's temperature history over the past 1,150 years. The time dependence of historical TSI was defined by an Antarctic ^{10}Be record. However, it was recognized that there exist a range of estimates for past absolute variation of TSI and the essential unknown is how much lower the TSI was during the MM than it is at the current time? Ammann *et al.* (2007) treated this parametrically. Three cases were considered where TSI during the MM was lower by 0.65% (high), 0.25% (medium), and 0.1% (low) than at the present time (see Figure 4.38, color section). Account was also taken of greenhouse gases and volcanism. Several sharp cooling episodes mark the response to very large volcanic forcing (e.g., 1258, 1453, 1815). The largest volcanic forcing was estimated for 1258 after what was probably the largest explosive eruption of the past few thousand years. Greenhouse gas forcing was based on a CO_2 equivalent of about 275 ppm in pre-industrial times, rising in the 20th century to about 425 ppm in 2000.

Figure 4.42 shows the three parameterized TSI functions. The procedure by which Ammann *et al.* (2007) scaled the historical TSI to obtain high, medium, and low profiles of TSI vs. time over the past 1,150 years (Figure 4.42) was based on Figure 4.38 (color section) that was generated by Bard *et al.* (2000).

Figure 4.43 (color section) shows the resultant temperature histories that result from the models.

As in the case of Figure 4.42, the relationship between curves in Figure 4.43 (color section) is confusing. How can the "high" curve ever exceed the "medium" curve? Common sense would dictate that the curves would be similar with the "high" curve lying below the "medium" curve and the spacing between the two diminishing toward the 20th century. This is not the case in Figure 4.43 (color section).

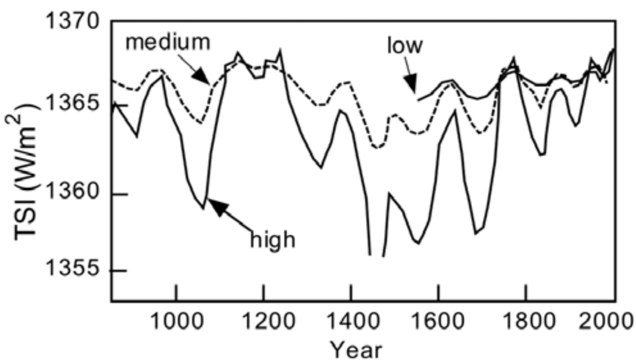

Figure 4.42. Estimated historical variation of TSI for three assumed differences between TSI at the MM vs. TSI today (high = 0.65%, medium = 0.25%, low = 0.1%). Adapted from Ammann *et al.* (2007).

One result that can be derived from Figures 4.42 and 4.43 (color section) is that at the depth of the MM, the difference between the "high" and "low" curves for TSI is about $8\,\text{W/m}^2$, while the difference in temperature anomaly is about 0.5°C. This would suggest a climate sensitivity parameter (see Section 4.6.2) of $\lambda_S \sim 0.5/8 = 0.06$°C per W/m^2, or $\lambda \sim 0.06 \times 4 \sim 0.24$°C per W/m^2. This is a very low value. The model of Ammann *et al.* (2007) is relatively insensitive to solar forcing but is highly sensitive to greenhouse forcing. Hence, it is inevitable that a *hockey stick* result should be obtained. In this model, 20th-century warming eclipses the temperature variations of the MWP and the LIA.

Goosse *et al.* (2005) used the TSI history estimates of Lean, Beer, and Bradley (1995) (basically, the "medium" case of Ammann *et al.* (2007) with 0.25% reduction in TSI during the MM) in a global coupled atmosphere–ocean–sea ice–land surface model of the Earth's climate. The model was forced over the period from 850 to 2000 using modeled time histories of solar irradiance, spatially explicit aerosol loading from explosive volcanism, the greenhouse gases (CO_2, CH_4, N_2O, CFC-11, and CFC-12), and anthropogenic sulfate aerosols with a recurring annual cycle of ozone and natural sulfate aerosol. The model's sensitivity to CO_2 doubling is a 1.8°C temperature rise which is in the low range of coupled atmosphere–sea ice–ocean general circulation models (in fact, some models predict about double that temperature rise). Goosse *et al.* (2005) admitted (as they should): "large uncertainties exist on forcing variations [i.e., variations in TSI] during the last millennium with consequences on simulated temperatures."

The result of running the model is shown in Figure 4.44. There is evidence of an MWP, an LIA, and a 20th-century warming beyond the warmth of the MWP. The estimated variations during the MWP and the LIA are small.

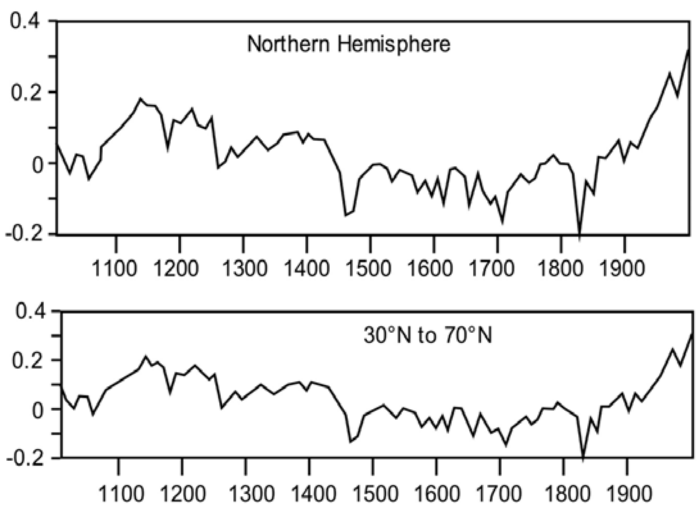

Figure 4.44. Estimated temperature anomaly for the last millennium (vertical scale = °C). Adapted from Goosse *et al.* (2005).

4.6.2 Climate sensitivity parameter

We are concerned here with approximations for the rise in global average temperature ΔT (°C) that is expected to result from an increase in TSI (W/m^2). It is common practice to define the resulting temperature change when an annually and globally averaged mean forcing function ΔF (W/m^2) is applied to the Earth at the *top of the atmosphere*

$$\Delta T = \lambda \Delta F$$

where λ is the so-called *climate sensitivity parameter*.

Most papers that deal with forcing are mainly concerned with forcing due to greenhouse gases. In this case, the forcing takes place within the Earth's atmosphere, and the area used to estimate ΔF is the surface area of the Earth ($4\pi R^2$). Occasionally, some papers also deal with forcing of Earth temperatures caused by changes in TSI. However, there may be some ambiguity that needs to be resolved as to whether they refer to forcing at the TSI level ($\sim$1,366 W/m^2) based on a plane in space facing the Sun, or at the Earth-input level (1,366/4 $\sim$ 342 W/m^2) based on the spherical surface area of the Earth. The factor of 4 arises because the area of the Earth as a disk facing the Sun is πR^2 whereas the spherical surface area of the Earth is $4\pi R^2$, so the TSI input of 1,366 W/m^2 is reduced to 342 W/m^2 when spread over the Earth's surface. In what follows, we will be concerned with ΔF representing a change in TSI at the in-space level. The difference between the two is that for TSI

$$\Delta T = \lambda_S \Delta \text{TSI}$$

and

$$\lambda_S = \lambda/4.$$

Beer, Mende, and Stellmacher (2000) used a simplistic radiation model to estimate that an increase in spherical forcing of 1 W/m^2 (at the top of the atmosphere) would cause an increase of the mean global temperature of 0.26°C. They claimed that this forcing of the Earth energy balance by 1 W/m^2 (top of atmosphere) is equivalent to a 5.7 W/m^2 change in TSI. This was based on the area ratio (4) coupled with an assumed Earth albedo of 0.3. However, this is overly simplistic because the energy transfers with the Earth environment are complex and simply dividing by (1 – albedo) does not make sense to this writer. Hence, my interpretation of Beer, Mende, and Stellmacher (2000) is that it suggests that

$$\lambda_S = 0.26/4 \sim 0.065°\text{C per W/m}^2.$$

[Reid (1997)] estimated that a reduction of $\sim$8 W/m^2 in TSI could have produced a global temperature change of $\sim$0.45°C (i.e., $\lambda_S \sim 0.45/8 \sim 0.06$°C per W/m^2).

Ramanathan *et al.* (1985) is an early paper that provided a summary of estimates of λ available in 1985. Eight estimates are listed that vary in a narrow range from 0.47°C to 0.53°C per W/m^2. For TSI, these values should be divided by 4, so $\lambda_S \sim$ 0.12°C to 0.13°C per W/m^2.

Gerard and Hauglustaine (1991) indicated that: "A temperature response range of 1.1°C to 2.3°C for a 1% solar total irradiance increase is predicted by climate models." This would suggest that

$$\lambda_S \sim (1.1 \text{ to } 2.3)/13.7 \sim 0.08 \text{ to } 0.17°\text{C per W/m}^2.$$

Gerard and Hauglustaine (1991) also said in another paragraph that an abrupt atmospheric CO_2 doubling would produce a 3.2°C global mean temperature response, and that the climate sensitivity parameter equals 0.8°C per (W/m^2) at the tropopause (referencing Ramanathan, 1988). This would appear to correspond to a value of $\lambda_S = 0.8/4 = 0.2$°C/(W/m^2) for TSI forcing. Senior and Mitchell (2000) estimated that a doubling of CO_2 would produce a downward forcing of ~3.5 W/m^2, leading to a global temperature increase of ~4°C suggesting a value of $\lambda_S \sim (4/3.5)/4 = 0.29$°C per W/m^2 for TSI forcing.

Gregory *et al.* (2004) appears to be an authoritative source for estimation of climate parameters. However, they were mainly concerned with CO_2 forcing and gave less emphasis to solar forcing. Nevertheless, their study is instructive. They used a relationship

$$\Delta F = \Lambda \Delta T$$

where Λ, the *climate feedback parameter*, is actually the reciprocal of the *climate sensitivity parameter*, λ. Thus, $\Lambda = 1/\lambda$.

Gregory *et al.* (2004) assumed a positive forcing agent that is constant in time, generating an increased downward flux ΔF (W/m^2) at the tropopause. They assumed that the Earth environment responds to this perturbation with gradually increasing temperature and thereby generating a gradually increasing upward flux $\Delta H(t)$ that is time-dependent. They assumed that $H(t)$ is proportional to the temperature change $\Delta T(t)$ with $\Lambda = 1/\lambda$ being the proportionality constant. Thus, as time proceeds, the change in net flux downward is

$$\Delta N(t) = \Delta F - (1/\lambda)\Delta T(t).$$

At $t = 0$,

$$\Delta T(0) = 0 \quad \text{and} \quad \Delta N(0) = \Delta F.$$

At some future time (t_F), a steady state is reached when $\Delta N(t_F) = 0$. At that point,

$$\Delta T(t_F) = \lambda \Delta F.$$

For our purposes here, we don't much care what t_F is; we are mainly interested in the ratio of the value of ΔT to ΔF (at the point where $\Delta N \Rightarrow 0$). Thus, Gregory *et al.* (2004) utilized a procedure in which they applied a constant forcing ΔF at the top of the troposphere, and used an atmosphere–ocean global climate model to calculate ΔN vs. ΔT for various times after the start. The slope of this line yields $(1/\lambda)$ and the y-intercept is ΔF.

For a forcing produced by doubling the CO_2 concentration in the atmosphere, Gregory *et al.* (2004) found that, depending on the specifics of the model used, the values of $\Lambda = (1/\lambda)$ were in the range 1.0 to 1.2 (W/m^2 per °C) and the value of ΔT was in the range 3.0°C to 3.8°C.

For solar forcing Gregory *et al.* (2004) found values of $(1/\lambda)$ in the range 1.3 to 2.0 (W/m^2 per °C) based on forcing from the troposphere. The equivalent values of λ_S for TSI would then be in the range 0.125°C to 0.19°C per W/m^2 although it appears from Gregory (2004) that the value 0.125 is preferred.

Nozawa *et al.* (2007) provided a very brief discussion of climate feedback parameters. Using their climate model ("MIROC3.2") they found that the appropriate values of $\Lambda = 1/\lambda$ for solar forcing (1.07 W/m^2 per °C) and for CO_2 forcing (1.13 W/m^2 per °C) were "consistent". However, the model used by Gregory *et al.* (2004) ("HadCM3") is claimed to lead to "inconsistent" results: $\Lambda = 2.0$ W/m^2 per °C for solar and 1.26 W/m^2 per °C for greenhouse gases. Using the value of $\Lambda = 1.07$ W/m^2 per °C provided by Nozawa *et al.* (2007), the implied value of λ_S is then (1/1.07)/4 $\sim$ 0.23°C per W/m^2.

Gregory (2004) provided a review of climate sensitivity and feedback parameters. He compared values of λ for various kinds of forcing. One model predicted that λ for CO_2 forcing is ~1.26 times λ for solar forcing. However, Gregory (2004) implied that this may be due to uncertainties in models and the two values of λ should be equal (note: as usual $\lambda_S = \lambda/4$). The value of λ_S was estimated to be about 0.125 °C per W/m^2.

Cubasch *et al.* (2002) quoted a paper by Zorita *et al.* (2003) that provided four estimates of λ for TSI. The four estimates were made by comparing estimates of TSI with estimates of surface temperature over the period 1600–1900. Unfortunately, neither the reconstructions of TSI nor those of temperature that underlie these estimates of λ appear to be trustworthy. However, for what they are worth, the four estimates of λ_S were

1. NCEP: 0.13°C per W/m^2
2. Jones *et al.* (1998): 0.13°C per W/m^2
3. ECHO-G: 0.11°C to 0.17°C per W/m^2
4. MBH99: 0.015°C to 0.08°C per W/m^2.

Ammann *et al.* (2007) mentioned that their "climate model results exhibited a response of 0.066°C in global temperature for each Watt per square-meter change in solar input" (i.e., $\lambda_S = 0.066$°C per W/m^2). The supplemental materials to this paper indicate that the calculation range was 0.062°C to 0.071°C per W/m^2, which is a low value.

Bony *et al.* (2006) summarized a number of estimates of λ based on water vapor in the atmosphere. The values of λ range from about 0.45°C to 0.8°C per W/m^2 with a mean value of about 0.6°C per W/m^2 which implies that $\lambda_S \sim 0.15$°C per W/m^2.

Hansen *et al.* (2005) discussed the climate sensitivity parameter briefly. This reference points out that there is always a lag between sudden application of a steady climate forcing and the appearance of the full equilibrium Earth temperature rise. Indeed, as we pointed out previously, Gregory *et al.* (2004) estimated λ by using global models to infer the (linear) rate of change of net forcing (constant forcing – reaction to forcing) and extrapolating to zero. Hansen *et al.* (2005) claimed that this time lag depends on the rate of heat exchange between the ocean's surface mixed layer and the deeper ocean, and is a "sensitive function of the equilibrium climate sensitivity" (i.e., a sensitive function of λ) varying approximately as the square of λ. Hansen *et al.* (2005) said:

> "The lag could be as short as a decade, if climate sensitivity is as small as 0.25°C per W/m^2 of forcing, but it is a century or longer if climate sensitivity is 1°C per W/m^2 or larger. Evidence from the Earth's history and climate models suggests that climate sensitivity is $\lambda = 0.75 \pm 0.25$°C per W/m^2, implying that 25 to 50 years are needed for the Earth's surface temperature to reach 60% of its equilibrium response."

If we can deduce an appropriate value of λ_S, we can convert any of the temperature reconstructions (prior to the 20th century) into equivalent variations in TSI, assuming the temperature changes prior to 1900 were caused mainly by variations in TSI (taking account of land clearing and volcanic eruptions). Similarly, we can reverse this process and convert reconstructions of past variations in TSI into equivalent changes in temperature. A number of estimates of λ_S have been made, as previously discussed. At the troposphere level, a reasonable guess for λ is 0.6°C per W/m^2, which would imply that for TSI, the effective $\lambda_S \sim 0.15$°C per W/m^2.
Hansen (2004) said:

> "The composition of the ice age atmosphere is known precisely from air bubbles trapped as the Antarctic and Greenland ice sheets and numerous mountain glaciers built up from annual snowfall. Furthermore, the geographical distributions of the ice sheets, vegetation cover and coastlines during the ice age are well mapped. From these data we know that the change of climate forcing between the ice age and today was about 6.5 watts/m^2. This forcing maintains a global temperature change of 5°C, implying a climate sensitivity of 0.75 ± 0.25°C per watt per square meter. Climate models yield a similar climate sensitivity. The empirical result is more precise and reliable, however, because it includes all the processes operating in the real world, even those we have not yet been smart enough to include in the models."

While there is some significant divergence of opinion, it appears that a reasonable estimate for λ is 0.6°C per watt per square meter and $\lambda_S \sim 0.25\lambda \sim 0.15$°C per watt per square meter. However, Schwartz (2007) deduced a lower value: $\lambda = 0.3$°C per watt per square meter from heat capacity arguments. But if Schwartz's Earth time constant (5 years) is doubled, his value of λ also doubles.

4.7 CONCLUSIONS ON TSI

Scientists abhor a vacuum. They can't seem to shrug their shoulders and admit that we just don't know the answers to important questions. They demand explanations, however speculative. Thus, we have theories on how life started on Earth, how life begins from inanimate matter, how the universe began, and how the TSI varied over past millennia. There are many reconstructions of past TSI. Some are far from credible. Even the best of these are quite speculative. It could be argued that in the absence of firm data on historical variations in TSI, even speculative models are better than nothing. As the saying goes: "In the land of the blind, a one-eyed man is king." And there is some merit to this argument. The one danger is we may unwittingly rely too heavily on speculations.[2] Thus, speculations tend to acquire a life of their own. The truth is that we just don't know how the Sun behaved in the past, although we have a few inklings.

One basic point is that if significant temperature variations occurred on the Earth over the past millennium (MWP and LIA), it seems likely that such temperature changes were driven mainly by changes in TSI, land clearing, and volcanic eruptions, since these events occurred prior to industrialization. The largest volcanic eruptions undoubtedly had a significant short-term impact, but overall, the variations in TSI likely guided the temperature changes experienced by the Earth prior to recent times. Thus, the histories of TSI variation and temperature changes are intimately entwined. On the other hand, some scientists have derived a *hockey stick* picture of past temperature variations which would minimize temperature variations during the MWP and the LIA. While there are good reasons for believing that the *hockey stick* result is fallacious (see Section 2.2.3), nevertheless controversy surrounds the uncertainty in historical temperatures as well as historical TSI. A necessary consequence of the *hockey stick* temperature profile is that past variations of TSI would have to be small. Thus, one can either believe the *hockey stick* temperature profile in which case variations of TSI must have been very small during the past millennium, or one can believe that there were significant temperature excursions in the MWP and the LIA, driven primarily by significant variability of TSI.

In attempting to reconstruct the TSI over the past several hundred years, or the past millennium, we only have bits and pieces of fragmentary evidence. Like a detective seeking to solve a crime from limited evidence, scientists have attempted to create models of past TSI based on fragmentary data. Unfortunately, although

[2] I am reminded of an event that occurred in the 1970s. At that time, there was some controversy regarding the altitude where the Earth's ionosphere transitioned from mainly O^+ to H^+. This was dependent on the rate of the reaction $O^+ + H \rightarrow O + H^+$. On the first day of a national meeting, a leading expert, Alec Dalgarno made a presentation on this topic. At the end of his talk, someone asked him what the rate of the charge exchange reaction was. He said he didn't know. They pressed him to make a guess. So, he guessed. Three days later at the meeting wrap-up, Dalgarno was asked to present a summary. In doing this, he used the aforesaid reaction rate. Someone asked him where he obtained that figure. He replied: "I don't know. Someone provided it on the first day of the meeting!"

these models are often interesting and imaginative, they tend to be quite speculative and impossible to verify.

However, there are a few things that we can be fairly sure of.

1. We have extraterrestrial measurements of TSI since about 1978. The Sun presently goes through periodic cycles of variable length, but approximately every 11 years. The TSI varies by about 0.1% during the $\sim$11-year solar cycle. At SMAX there are presently typically $>$100 sunspots and at SMIN there are typically $<$10 sunspots.
2. We have visual observations of sunspots that date back about two hundred years. Sunspot data are characterized as (i) reliable from 1848 to the present, (ii) good from 1818 through 1847, (iii) questionable from 1749 through 1817, and (iv) poor from 1700 through 1748. In addition, there is anecdotal evidence that the number of sunspots was minimal (or zero) for much of a 70-year period from 1645 to about 1715.
3. The sunspot data clearly show that sunspot activity has been increasing since the start of the 20th century except for a brief dip around 1960, and furthermore, sunspot activity is higher today than at any time in the past 400+ years, and possibly a lot longer. This shows that there have been significant changes in the behavior of the Sun, although it is not clear how this is reflected in changes in TSI.
4. We have visual observations of the duration of the solar cycle that varied considerably since measurements were begun around 1750. Unfiltered cycle durations have swung widely from 8 to 14 years, and filtered cycle durations vary from roughly 10 to 12 years.

Another potential source of information is observations of putative Sun-like stars. Such studies indicate that the Sun's variability is slightly above average in regard to HK variations, but is well below average in regard to TSI variations. Attempts were made to estimate the TSI during the MM by comparison with the behavior of Sun-like stars. This required assumptions and extrapolation. A rather speculative approach for estimating the TSI of the Sun in the past was utilized by one group. In this approach, the HK index was correlated against recent measurements of TSI since 1978 and the regression line was extrapolated to the lowest HK index observed for non-cycling stars. With this assumption, the TSI during the MM was estimated to be 0.24% lower than the TSI at SMIN in 1980. This work has had considerable influence and a number of climate studies adopted this value. Some stars do not cycle. It is not clear whether they are cyclic stars that have temporarily entered an MM-like period or whether they simply do not cycle. No definite conclusions can be drawn, although evidence exists for greater TSI variability in some stars. However, a recent paper has cast doubt on several aspects of these studies, including concerns that putative Sun-like stars may not resemble the Sun as closely as was thought.

A number of approaches have been used to reconstruct the past TSI over the last millennium. One approach that has been used by a number of investigators is called a "constant quiet Sun model" (CQSM) which is based on the current solar cycle.

Reasoning that the TSI is presently ~1,367 W/m^2 at SMAX when there are >100 sunspots, and TSI ~ 1,365.5 W/m^2 at SMIN when there are very few sunspots (see Figure 4.2), one can assume a linear scale of TSI vs. number of sunspots, and use the sunspot observations of the past to estimate TSI in the past. In this approach, the past TSI can never drop below ~1,365.5 W/m^2 because that corresponds to ~0 sunspots. Thus, the lowermost possible TSI is defined, and TSI can increase slightly above this value in proportion to the sunspot count. This approach is implicitly based on the assumption that the Sun has behaved in the past as it does today, and no long-term secular changes have occurred. The only variations allowed to the Sun are those bounded by what we presently observe in the current solar cycle. A major problem with this approach is that variations in TSI are limited to about 0.1%, and that is not sufficient to account for temperature fluctuations that appear to have occurred over the past thousand years or more unless perhaps you believe the *hockey stick* model for historical temperatures.

At the other extreme, Reid (1997) assumed that the Earth was about 1°C cooler during the MM, and attributed this as due to a lower TSI. His climate model indicated that in order to achieve a 1°C temperature drop during the MM compared with recent times, the TSI must have been about 0.65% lower in the MM (about 1,358 W/m^2) than it was in 1980 (1,366.5 W/m^2). He then assumed that regardless of the small ~0.1% fluctuations in TSI that occur during solar cycles, there was a secular change in TSI in proportion to a 15-year moving average of sunspot number. He was thus able to estimate TSI for all years from the MM to the present. His estimates of variability of TSI are much greater than those of other models. Reid found that the TSI bottomed out at around 1,358 W/m^2 during the MM, rose after 1700, dipped down to about 1,359 W/m^2 just after 1800, and then rose back up and eventually increased during the 20th century. It is noteworthy that Reid used a climate sensitivity parameter $\lambda_S \sim 0.12$°C per W/m^2.

It turns out that the duration of the solar cycle has varied considerably since measurements were begun around 1750. Unfiltered cycle durations have swung widely from 8 to 14 years, and filtered cycle durations vary from roughly 10 to 12 years. By developing a relationship between observed TSI and filtered cycle duration since 1978 some investigators have estimated TSI back to 1750 from the historical filtered cycle duration over that period. Solanki and Fligge (2000) did this but their procedure was not clearly defined, and the results seem to contain anomalies, although it does produce the dip expected shortly after 1800. The main problem appears to be that the database for TSI since 1978 is too short to arrive at a firm correlation with filtered cycle duration. This approach is limited by the same factors that limit constant quiet Sun models: there is no allowance for long-term secular changes in the Sun independent of changes in cycle duration.

Some estimates of TSI in the past have been made from measurements of cosmogenic isotopes. A good example is Bard *et al.* (2000). A curve for cosmogenic isotope production rate vs. year is derived for the past millennium or so. The question is how to convert isotope production rate to TSI? Clearly, the isotope production rate is related inversely to TSI. Bard *et al.* (2000) converted the isotope production rate to TSI by setting TSI equal to the current value for the most recent production rate, and using the reduction in TSI during the MM compared with the current TSI as an adjustable parameter to create a family of TSI vs. year curves for various assumed reductions in TSI during the MM (0.25%, 0.40%, 0.65%). This seems to be a reasonable procedure, but we still don't know which curve to choose.

In summary, it is clear that the Sun has varied over the past millennium as evidenced by visual observations of sunspots and cycle duration, observations of Sun-like stars, and studies of cosmogenic isotopes. Unfortunately, it is not at all clear what these changes imply quantitatively for the range of variation of TSI.

5

The Earth's heat balance and the greenhouse effect

5.1 THE GREENHOUSE EFFECT

5.1.1 Terrestrial examples

This section was abstracted from Gerlich and Tscheuschner (2007).

Radiation is the only means of heat transfer between bodies in the vacuum of space. Ideally, the radiation emitted by a blackbody plane surface is a spectrum over many wavelengths. When integrated over all wavelengths, the emitted irradiance is:

$$I = \sigma T^4$$

where $\sigma = 5.67 \times 10^{-8}$ W/(m^{2}K^4).

This integrated form of the radiation equation is only correct for an ideal blackbody. In the real world, radiation depends on geometry, and most bodies exhibit deviations from blackbody behavior, in that their emissivities and absorptivities deviate from unity in at least some parts of the spectrum. In many cases, the deviations are large.

In an atmosphere, heat can be transmitted between bodies via radiation, conduction, or convection. On Earth, in the atmosphere at moderate temperatures, heat transfer between bodies and the atmosphere is typically dominated by convection, and radiation usually plays a secondary role.

The standard explanation for why a greenhouse (or equivalently, an automobile parked in the Sun) heats up is based solely on radiation. Gerlich and Tscheuschner (2007) provide many examples of these often used descriptions from books and articles. These descriptions go something like the following. Incident sunlight passes through the glass enclosing the greenhouse, and is absorbed by the interior, thus heating the interior. As the interior heats up, it radiates in the IR. However, the glass absorbs IR and thereby prevents the IR from passing through. Thus, the IR irradiance is trapped in the glass, which restricts the ability of the greenhouse to lose heat to the environment.

In actuality, the standard explanation for the heating of a greenhouse or an automobile in the Sun is fallacious. A greenhouse or an automobile gains heat from solar irradiance but loses heat to the surroundings mainly by convection to air surrounding the exterior glass. The reason that the greenhouse (or an automobile in the Sun) heats up is because the thermal conductivity of the glass is sufficiently low that heat transmission from the hot air within the greenhouse through the windows to the exterior is slow, and the interior temperature must rise sufficiently so that the temperature difference across the window glass is high enough that conduction through the glass provides enough heat loss to balance the heat input from the Sun. Hence, the IR absorptivity of the glass has very little to do with why a greenhouse or an automobile in the Sun gets hot. In fact, the glass does not get hot.

Gerlich and Tscheuschner (2007) refer to examples where two insulated black boxes were placed in the Sun. One had a cover made of IR-absorbing glass and the other had a cover made of an IR-transmitting NaCl crystal. In order to make the two cases as compatible as possible, a glass was placed above both boxes, because otherwise the NaCl cover would transmit more of the incident solar IR into the box. The two boxes reached the same temperature ($\sim$55°C). The IR absorptivity of the cover had nothing to do with the interior temperature. If this experiment could be repeated with both boxes surrounded by a vacuum instead of the Earth's atmosphere, the boxes could only lose heat to the surroundings by radiation. In this case, the box covered with NaCl would be cooler since it can transmit IR through its transparent window and there would indeed be a greenhouse effect with the glass cover.

Gerlich and Tscheuschner (2007) provided the data shown in Table 5.1. Within a car parked in the Sun, surfaces exposed to the Sun heat up to $\sim$71°C. This generates air currents within the car that warm the shaded areas within the car to about 39°C. Outside the car, the difference between being in the Sun or the shade is minimized by convective air currents. As Gerlich and Tscheuschner (2007) pointed out:

> "One can touch the car's windows and notice that the panes, which absorb the infrared light, are rather cool and do not heat the inside of the car in any way.

Table 5.1. Measured temperatures in and around a car parked in the Sun.

Location	*Temperature* (°C)
Inside the car, in direct Sun	71
Inside the car, in the shade	39
Next to the car, in direct Sun	31
Next to the car, in the shade	29

If one holds his hand in the shade next to very hot part of the dashboard that lies in the Sun, one will practically feel no thermal radiation despite the high temperature of ~70°C, whereas one clearly feels the hot air."

5.1.2 Simplistic models of the Earth

The Earth can only lose heat to its surroundings by radiation. If the Earth had no atmosphere, its surface temperature would resemble that of the Moon. In the daytime, the mid-latitude temperature would rise to perhaps 100°C, and at night it would drop to perhaps −150°C. Temperatures at the poles would be decidedly lower than at the equator.

To illustrate the greenhouse effect, a number of books and websites present a simplistic *average* picture of the Earth without an atmosphere as a baseline, as shown in Figure 5.1.

The solar power approaching the Earth is about 1,367 W/m^2 passing through a plane above the Earth, facing the Sun. Since the area of this plane projected by the Earth is πR^2, where R is the radius of the Earth, and the surface area of the Earth is $4\pi R^2$, the solar power falling on the Earth would be 1,367/4 ~ 342 W/m^2 per unit surface area of the Earth, if it impinged uniformly on all areas of the Earth. The Earth's albedo (reflection coefficient for solar irradiance) is estimated to be roughly 30%. If ~30% of the solar irradiance on the Earth is reflected back into space, the net solar irradiance absorbed by the Earth (per unit surface area) is $0.7 \times 342 = 239$ W/m^2. This hypothetical Earth would warm up and radiate until the power radiated is equal to the power input from the Sun, whereupon equilibrium will be established. Thus, the temperature is calculated from

$$239\ \mathrm{W/m^2} = \sigma T^4 = 5.67 \times 10^{-8} (\mathrm{W/m^2\text{-}K^4}) T^4$$

where $T = 255$ K $= -18$°C.

In this artificial model, the daily average solar input to an average element of Earth surface area is treated as a constant, whereas in reality, it will vary widely from day to night. Nevertheless, the calculation is instructive. It suggests that the Earth

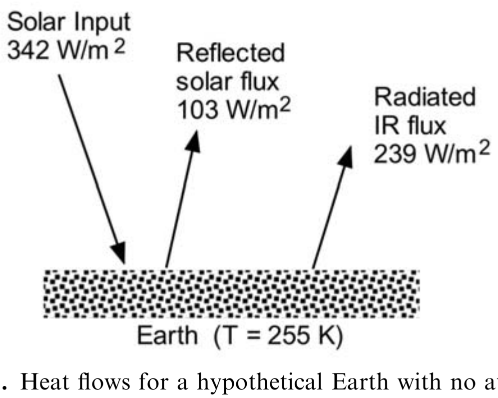

Figure 5.1. Heat flows for a hypothetical Earth with no atmosphere.

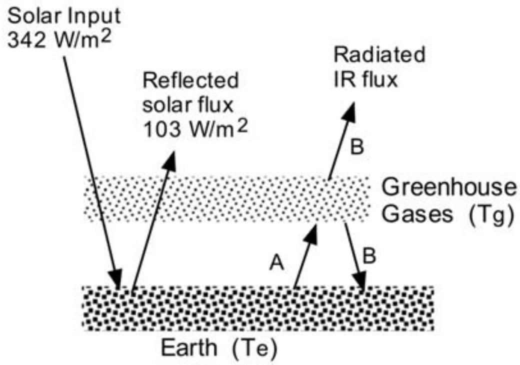

Figure 5.2. Simplistic model of effect of greenhouse gases on Earth temperature.

would be (on average) a relatively colder place if it had no atmosphere. Actually, this model is very artificial because the atmosphere plays a major role as an intermediary between the Earth's surface and space.

An artificial, simplistic averaged model is often used in books and websites to illustrate the "greenhouse effect" by introducing a simplistic atmosphere between the Earth and space that does nothing else but (a) transmit incident solar radiation, (b) absorb long-wavelength IR emitted by the Earth, and (c) reradiate long-wavelength IR both upward to space, and downward to Earth. This model is illustrated in Figure 5.2.

The solar input to Earth remains at 342 W/m^2 and is (according to this model) unimpeded by the fictional atmosphere. Of this, 103 W/m^2 is reflected back to space. The Earth radiates a flux A (W/m^2) that depends on its temperature (T_e), and the atmosphere absorbs all of this radiation reaching temperature T_g, and re-emits a flux B upward and a flux B downward, where $A = 2B$.

At equilibrium, the Earth and its atmosphere must emit as much radiation flux as it receives. Thus:

$$B = (342 - 103) = 239\ \text{W/m}^2.$$

Thus

$$T_g = 255\ \text{K}.$$

In this model, the surface that radiates to space has been moved from the Earth's surface to the top of the atmosphere. Since $A = 2B$, we find that $A = 478$ W/m^2 and therefore

$$T_e = (478/\sigma)^{1/4} = 303\ \text{K}.$$

This is considerably warmer than the previous baseline case with no greenhouse effect. According to this admittedly overly simplistic model, the presence of greenhouse gases provides significant heating to the Earth's surface, and without the greenhouse effect, the Earth would be a very cold planet. The simple greenhouse effect provides a temperature increase of 48°C over the simple model without the greenhouse effect. This simple greenhouse effect is based on the assumption that there is an intermediate level between the Earth and space that absorbs radiation emitted by the Earth and reradiates upward and downward. However, the atmosphere is far more complex than this model allows for, and the transfer of heat between the surface and the atmosphere includes a major contribution from convection and latent heat of water vapor. In addition, the transmission of various wavelength bands through the atmosphere at different levels is quite variable and not amenable to simple description. It should also be noted that most of the greenhouse effect is produced by water vapor, not the so-called greenhouse gases.

5.2 THE EARTH'S HEAT BALANCE

5.2.1 Major heat flows

The net energy input at the top of the atmosphere is determined by the incident irradiance from the Sun minus the reflected irradiance. However, note that while many notable papers refer to the incident solar irradiance as "short-wave radiation", a significant portion of the Sun's spectrum extends into the IR. The net solar input flux at the top of the atmosphere is the difference between incident and reflected fluxes. When the Earth is in balance, this inflow of solar irradiance is equal to the flux of long-wave IR radiation emitted to space by the surface–atmosphere system. The outward-bound long-wave radiation that reaches the top of the atmosphere derives from the absorption and emission of long-wave radiation by gases throughout the atmosphere as well as convection and latent heat in the troposphere. Thus, very little of the long-wave energy that escapes to space represents emission directly from the surface.

The heat flows in the Earth–atmosphere system were estimated by Kiehl and Trenberth (1997) to be those shown in Figure 5.3. This assessment of heat flows was based on use of the 1976 U.S. standard atmosphere (but the humidity profile was reduced by 12%) and 1990 IPCC estimates for concentrations of greenhouse gases. Kiehl and Trenberth (1997) adopted the best measurements and analyses available to produce a balanced heat flow chart. However, there are considerable variations in specific estimates of individual heat flows by various investigators. Hence the data in Figure 5.3 contain significant implicit uncertainty. The figures shown are for average levels of cloudiness (about 62%). In clear weather the outgoing long-wave radiation increases to about 265 W/m^2. Thus, the effect of clouds in this model is a downward forcing (i.e., a cooling) of about 30 W/m^2.

The solar input to the Earth is 342 W/m^2 when averaged over the Earth's area. Of this, 77 W/m^2 is reflected back into space by the atmosphere, clouds, and aerosols, and 67 W/m^2 is absorbed by the atmosphere and clouds. The remaining 198 W/m^2 reaches the surface, where 30 W/m^2 is reflected back to space and 168 W/m^2 is absorbed. Thus, the net heat input from the Sun is 67 W/m^2 to the atmosphere and 168 W/m^2 to the surface.

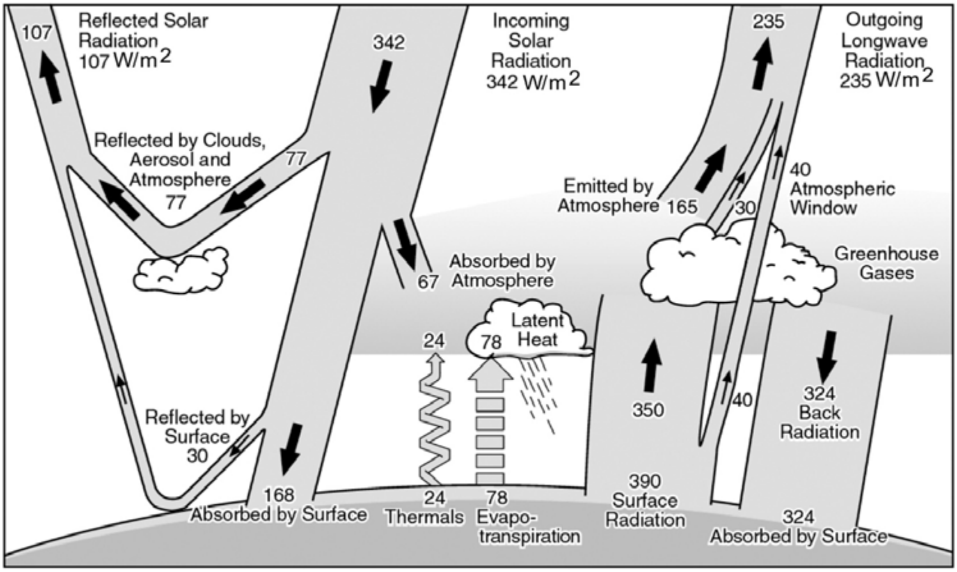

Figure 5.3. Heat flows in the Earth–atmosphere system during average cloudiness. From Kiehl and Trenberth (1997) by permission of the *Bulletin of the American Meteorological Society*.

5.2.2 Greenhouse gas effects and water vapor

5.2.2.1 Absorption by greenhouse gases

A variety of climate models have been developed (see Section 5.4) with the primary purpose of predicting the effect of future greenhouse gas emissions on the climate in the 21st century. Most of this work has been carried out by climate alarmists, and it is not clear to what extent the findings influenced the scientists, or the extent to which scientists influenced the findings.[1]

The 2001 IPCC Report provides data on the various greenhouse forcings due to CO_2, CH_4, N_2O, halocarbons, stratospheric O_3, tropospheric O_3, aerosols, sulfate, carbon, biomass burning, mineral dust, aerosol indirect, contrails, land use, albedo, and solar variations. However, there does not seem to be much mention of water vapor or feedbacks, and it is not clear what to do about clouds. For each greenhouse gas, the IPCC has tabulated pre-industrial and current concentrations in the troposphere, lifetime of gases in the atmosphere, current rates of emission, and global-warming potential. The global-warming potential is a function of the absorptivity (per unit concentration of greenhouse gas) of IR radiation emitted by the Earth. The principal greenhouse gases are water vapor, carbon dioxide, and methane, although the combination of nitrous oxide plus a wide variety of halocarbons produces an effect comparable with that of methane. Methane has a lifetime in

[1] Just as earthquake specialists always seem to predict that "the big one" is coming, so one must wonder about the climatologists who predict a dire future for the planet.

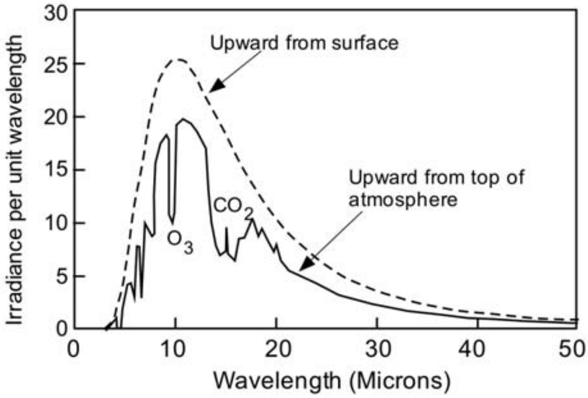

Figure 5.4. Comparison of spectral distribution of upward irradiance from the surface with that at the top of the atmosphere showing CO_2 and O_3 bands for assumed global cloudy conditions. Water absorption occurs throughout the spectrum in various amounts. Adapted from Schimel *et al.* (2001).

the atmosphere of about ten years and is more effective than carbon dioxide (by about a factor of 40 per unit concentration) at absorbing IR emitted by the Earth. Fortunately, the concentration of methane is about 200 times lower than that of carbon dioxide. But both are increasing with time. Nevertheless, the rate of increase of atmospheric methane has slowed down considerably. From 1982 to 1992, the methane concentration increased by 1% per year, whereas from 1992 to 2005 it increased by only $\sim$0.3% per year (Robinson, Robinson, and Soon, 2007; Khalil, Butenhoff, and Rasmussen, 2007; Idso and Idso, 2007). Figure 7.2 shows that the most recent measurements indicate that the methane concentration has reached a plateau and is no longer increasing.

Figure 5.4 shows a comparison of spectral distribution of upward irradiance from the surface with that at the top of the atmosphere showing CO_2 and O_3 bands for assumed global cloudy conditions.

The term "radiative forcing" has been used in several contexts. According to Kiehl and Trenberth (1997):

> "The difference between the surface emission and the top-of-atmosphere emission defines the long-wave radiative forcing, which clearly illustrates that strong atmospheric absorption occurs at 15 microns by carbon dioxide and 9 microns by ozone, while the effects of water vapor are distributed throughout all wavelengths. Note that the radiative forcing centered at 15 microns extends from 12 to 18 microns, owing to numerous absorption bands of the vibration mode of the CO_2 molecule. Indeed, it is this series of bands centered at 15 microns that ensures that this band is not near saturation for present and future projected amounts of CO_2, although it further means that long-wave radiative forcing from increases in CO_2 is not linear but more closely approximates a logarithmic increase."

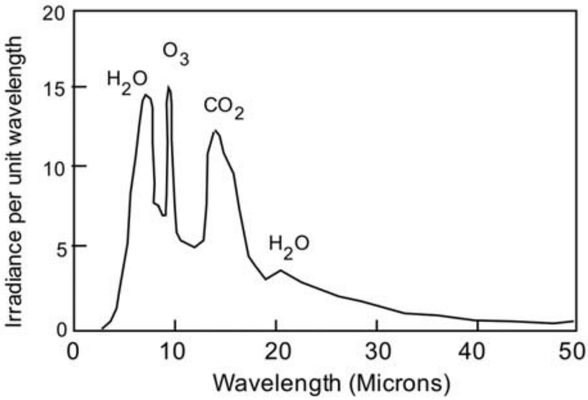

Figure 5.5. Downward radiant forcing (difference between curves in previous figure) for assumed global cloudy conditions. Adapted from Kiehl and Trenberth (1997).

However, in most papers in the literature, a different definition is used in which *forcing* refers to the added downward flux at the top of the atmosphere due to a change in a quantity that affects the Earth's heat balance, such as a change in greenhouse gas concentration, a change in solar irradiance, a change in aerosol concentration, etc.

Figure 5.5 shows the downward radiant forcing (difference between curves in Figure 5.4) for assumed global cloudy conditions. Integrating over all wavelengths leads to a total long-wave radiative forcing of 155 W/m^2. As stated previously, the long-wave cloud forcing is 30 W/m^2. Thus, clear-sky radiative forcing is estimated to be 125 W/m^2. The contribution of each absorber to downward forcing was estimated by Schimel *et al.* (2001) as shown in Table 5.2.

Table 5.2. Percentage of downward forcing due to each absorber. From Schimel *et al.* (2001).

Absorber	*Clear skies*	*Cloudy conditions*
Clouds	0	19
Water vapor	60	
CO_2	26	
Ozone	8	
Other gases	6	

5.2.2.2 Water vapor as a greenhouse gas

Water vapor is by far the most important greenhouse gas, in the sense that it absorbs more irradiance from the Earth than all other greenhouse gases combined. As we showed in Table 5.2, Schimel *et al*. (2001) estimated that water vapor accounts for 60% of the total greenhouse effect. Leroux (2005) suggested the much higher value of "95.00%" but provided no basis for this figure and it is probably not credible.

A number of naysayer blogs have criticized the global climate modelers and alarmists (often the same people) who typically do not list water vapor as a greenhouse gas. For example, Leroux (2005) said that IPCC (2001) underemphasized the role of water vapor, and did not even include water vapor in its tables and figures depicting the effects of greenhouse gases. However, the reason for this is that climate modelers are not interested in the steady-state relatively unchanging role of water vapor as a greenhouse gas, but rather, they are interested in the changes induced by human activity.

Thus, according to the realclimate.com blog:[2]

> "Whenever three or more contrarians are gathered together, one will inevitably claim that water vapor is being unjustly neglected by IPCC scientists. 'Why isn't water vapor acknowledged as a greenhouse gas?' 'Why does anyone even care about the other greenhouse gases since water vapor is 98% of the effect?' 'Why isn't water vapor included in climate models?' 'Why isn't water vapor included on the forcings bar charts?' etc. Any mainstream scientist present will trot out the standard response that water vapor is indeed an important greenhouse gas, it is included in all climate models, but it is a feedback and not a forcing."

The point here is that water vapor concentrations are not being considered by modelers to increase directly by injection from anthropogenic sources, but rather, as a consequence of indirect processes due to feedback from other greenhouse gases. If climate models properly include such feedbacks,[3] then water vapor would be properly accounted for by climate models. However, widespread changes in land use with irrigation appear to be changing water vapor inputs to the atmosphere over wide regions, so there may be some changes in water vapor aside from the feedback effect from greenhouse gas warming. Furthermore, water vapor is the predominant greenhouse gas and whether it increases directly, or as a result of warming produced by other greenhouse gases, its action is still important.

Realclimate.com admits that water vapor is the single most important absorber but suggests that it accounts for "between 36% and 66% of the greenhouse effect," and "together with clouds makes up between 66% and 85% of the temperature change induced [by greenhouse gas emissions]. CO_2 alone makes up between 9 and 26% ..." Realclimate.com goes on to conclude that:

> "The maximum supportable number for the importance of water vapor alone is about 60–70% and for water plus clouds 80–90% of the present day greenhouse

[2] *http://www.realclimate.org/index.php?p=142*

[3] A consummation devoutly to be wished.

> effect. (Of course, using the same approach, the maximum supportable number for CO_2 is 20–30%, and since that adds up to more than 100%, there is a slight problem with such estimates!).''

Realclimate.com could not find any support for the 98% figure, nor could this writer. Nevertheless, the degree of uncertainty regarding the relative importance of water vapor and carbon dioxide is rather unsettling.

Estimates in the literature vary widely. According to Marsh (2002), estimates range from water vapor accounting for 64% of the greenhouse effect, carbon dioxide 21%, ozone 6%, and other trace gases 9%, to water vapor being responsible for 90% of the greenhouse effect, leaving 10% for carbon dioxide and the other greenhouse gases.

Leroux (2005) claims that the greenhouse effect cools the atmosphere. This reference also claims that the ''so-called 'greenhouse effect' is fundamentally a 'water' effect,'' and chastises the IPCC ''water vapor-free greenhouse effect''. But ignoring these meanderings, it is noteworthy that Leroux (2005) quoted some relevant figures from the IPCC 2001 Technical Summary of Group I,[4] which claimed that the following changes have occurred:

1. Lower stratosphere (above 18 km): 20% increase in water vapor since 1980.
2. Upper troposphere: no significant global trends since 1980; 15% increase in water vapor in tropics (10°N–10°S).
3. Troposphere: many regions with increased water vapor since 1960.
4. Near surface: widespread significant increases in water vapor in the NH from 1975 to 1995.

These are significant changes. Leroux (2005) went on to criticize the IPCC by suggesting that it was these increases in water vapor (and not increases in CO_2) that may be producing putative global warming. But the viewpoint of the IPCC (and indeed all global-warming alarmists and modelers) is that these increases in atmospheric humidity are claimed to be a result of global warming induced by non-H_2O greenhouse gases, with the increases in H_2O acting as a feedback mechanism to amplify the effect of non-H_2O greenhouse gases.

According to Hall and Manabe (1999):

> ''The latest IPCC assessment indicates that the likely equilibrium global-mean temperature response to a doubling of CO_2 ranges from 1.6 to 4.6°C. The source of this uncertainty is our inability to quantify the role of feedback mechanisms in the climate system, including water vapor, cloud, lapse rate, and albedo feedback. Water vapor feedback, has long been thought to be a positive feedback mechanism. This is due to the dependence of the saturation water vapor mixing ratio on temperature, as predicted by the Clausius–Clapeyron equation. Thus a CO_2-induced warming of the surface–troposphere system will lead to a water vapor

[4] *http://www.ipcc.ch/pub/wg1TARtechsum.pdf*

increase in the atmosphere. Since water vapor is itself a greenhouse gas, this increase will . . . make the warming larger than it would be otherwise. While there is a consensus that water vapor feedback is positive in the context of global warming, it remains unclear exactly how strong the effect is. Large uncertainties also exist regarding the magnitude (and sign, in the case of cloud feedback) of the other feedback mechanisms.''

Hall and Manabe (1999) carried out long-term (500-year) GCM analyses of a modeled Earth's climate in two ways: not allowing, or allowing water vapor to increase as greenhouse gases warm the Earth. In the former case, amplification by water vapor is eliminated, and in the latter case, it is included. They presented arguments in favor of a model that assumes that the relative humidity will not change as the Earth warms, resulting in a sizable increase in absolute humidity with temperature. The results of Hall and Manabe (1999) indicated that without amplification by water vapor, the global temperature rise due to a doubling of CO_2 was 1.1°C, but with amplification by water vapor, it rose to 3.4°C. They also distinguished between two cases that might induce a warm anomaly in the surface–troposphere system: (i) greenhouse gas absorption, referred to as ''external'' forcing, and (ii) ''internally'' generated forcing, such as a change in net cloud cover associated with atmospheric disturbances. They found that the amplification was greater for the greenhouse gas absorption case and explained why at some length; however, their explanation was not convincing to this writer.

Held and Soden (2000) discussed water vapor feedback effects at some length. They derived an equation of the form:

$$\frac{dT}{d\log[CO_2]} = \frac{A}{(1 - B - C)}$$

in which the surface temperature (T) depends logarithmically on the CO_2 concentration in the troposphere with a coefficient A. To the extent that surface warming generates additional water vapor, and the water vapor contributes a feedback to more surface heating, the parameter B is inserted. In addition, surface heating could reduce the ice/snow albedo of the Earth, and the term C is included for this effect. Held and Soden (2000) pointed out that the combined effect of B and C could have much greater impact than either term alone. However, clouds will also form under these conditions, and the effects of clouds on radiation balance are not well understood. The feedback effects of water vapor in the tropics are complex. Held and Soden (2000) discussed aspects of this uncertainty but did not seem to reach any quantitative conclusions.

In most global climate models, an initial warming caused by additional CO_2 and other greenhouse gases leads to enhanced evaporation at the surface and a general moistening of the atmosphere. Since water vapor is a strong infrared absorber, the added moisture causes further warming. The amplifying effect of water vapor can be quite large, with GCMs typically predicting an increase in the global average warming by 70%–90% compared with calculations that maintain fixed water vapor. Minschwaner and Dessler (2004) wrote:

> "Observational studies have attempted to verify the positive water vapor feedback by examining the response of atmospheric humidity to changes in surface temperature caused by inter-annual variability, the annual cycle, volcanic eruptions, and the El Niño–Southern Oscillation; however results have been inconclusive, with some studies yielding a positive feedback and others indicating a negative response. There are several plausible mechanisms for creating a negative water vapor feedback in the upper troposphere. One oft-cited mechanism invokes the drying effects of deep cumulus convection, arguing that the mean detrainment altitude of deep convection will be both higher and cooler in a warmer climate compared to the present. Because the water vapor content of air pumped into the upper troposphere by convection is governed by the saturation vapor pressure at the temperature of cloud detrainment, this would imply a reduced supply of water at warmer surface temperatures, leading to drying and a negative feedback on climate."

Minschwaner and Dessler (2004) attempted to test the convective drying mechanism using a model specifically designed to examine the moisture content of the upper troposphere in the Tropics. Implications for water vapor feedback were also examined using measurements of relative and specific humidities in the tropical upper troposphere (UT) from microwave and infrared limb-viewing instruments in space. As the surface temperature rises, the saturation water vapor pressure increases as required by the Clausius–Clapeyron equation, which implies that air can hold more water before it becomes saturated (i.e., the maximum possible absolute humidity increases). The relative humidity (ratio of absolute humidity to maximum possible absolute humidity) may vary in ways that are difficult to predict. In the absence of any better knowledge, some investigators assumed that as the temperature changes, the relative humidity remains roughly constant, which then leads to an increase in absolute humidity because the maximum humidity increases with temperature. According to Minschwaner, Dessler, and Sawaengphokhai (2006), this assumption leads to roughly a doubling of the effect of CO_2 (i.e., the change in global average temperature goes from 0.8°C with no increase in absolute humidity to 1.6°C with constant relative humidity). Minschwaner and Dessler (2004) found that the drying mechanism (mentioned previously) occurs weakly so that the relative humidity decreases slowly with increasing temperature. Nevertheless, the absolute humidity does increase somewhat with increasing surface temperature. At the bottom line, Minschwaner and Dessler (2004) found that with no water vapor feedback, a doubling of CO_2 would produce a tropical surface warming of 0.8°C, and when water vapor feedback is included, the increase in temperature is 1.2°C. Note the huge discrepancy with Hall and Manabe (1999) who concluded that with constant relative humidity, the change in temperature would be 3.4°C.

Minschwaner, Dessler, and Sawaengphokhai (2006), in an update to Minschwaner and Dessler (2004), presented an analysis of the water vapor feedback in the tropical upper troposphere as simulated by 17 coupled ocean–atmosphere climate models. The strength of the water vapor feedback in the IPCC models was inferred using methods described by Minschwaner and Dessler (2004). The models indicated less drying than was found by Minschwaner and Dessler (2004). This would seem to imply a change in temperature, including the effect of water vapor, between 1.2°C and 1.6°C.

According to a NASA press release (Anon. A):

> "A NASA-funded study found some climate models might be overestimating the amount of water vapor entering the atmosphere as the Earth warms. Since water vapor is the most important heat-trapping greenhouse gas in our atmosphere, some climate forecasts may be overestimating future temperature increases. In response to human emissions of greenhouse gases, like carbon dioxide, the Earth warms, more water evaporates from the ocean, and the amount of water vapor in the atmosphere increases. Since water vapor is also a greenhouse gas, this leads to a further increase in the surface temperature. This effect is known as 'positive water vapor feedback.' Its existence and size have been contentiously argued for several years.
>
> The size of the positive water vapor feedback is a key debate within climate science circles. Some climate scientists have claimed atmospheric water vapor will not increase in response to global warming, and may even decrease. General circulation models, the primary tool scientists use to predict the future of our climate, forecast the atmosphere will experience a significant increase in water vapor.
>
> Using UARS data to actually quantify both specific humidity and relative humidity, the researchers found, while water vapor does increase with temperature in the upper troposphere, the feedback effect is not as strong as climate models have predicted. The increases in water vapor with warmer temperatures are not large enough to maintain a constant relative humidity."

5.2.3 Albedo of the Earth

The effective albedo (reflection coefficient) of the Earth for incident solar irradiance is an important factor in the global heat balance. With a solar irradiance of 342 W/m^2 spread uniformly over the area of the Earth, a 1% difference in albedo would produce a sizable forcing of 3.4 W/m^2. For lower latitudes where the solar irradiance is higher than the average, the effect of albedo is even greater. Human-induced changes in aerosols and clouds can cause an enhanced albedo and hence cooling ("negative forcing"). Changes in land use/land clearing (LULC) also have a significant effect on albedo.

> "Many methods have been used to estimate albedo, which cannot be measured directly. These methods differ in their scattering geometries, calibration accuracy, and in spectral, space, and time coverage. The different modes of observation include measurements of earthshine reflected from the Moon, broadband radiometer data from low orbits around Earth, geostationary cloud-cover observations, deep space radiometry, and surface radiometry. All of these methods require a theoretical model for relating the measured parameters to albedo, and

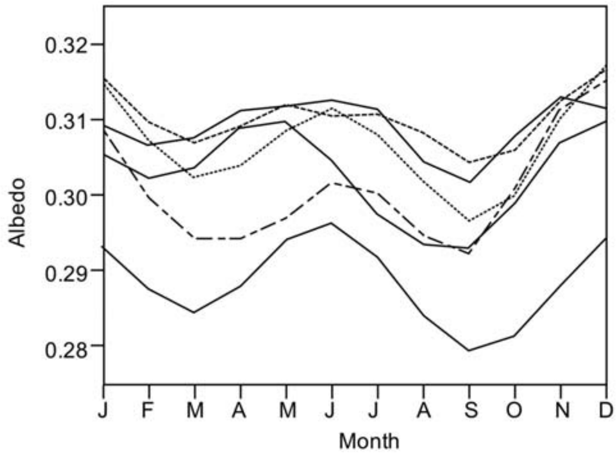

Figure 5.6. Comparison of various models for albedo of the Earth. Adapted from Charlson *et al.* (2005).

they all rely on different assumptions ... To date, the results from different measurement and modeling approaches are inconsistent among themselves and with each other. The magnitudes of the inconsistencies exhibited by both measurements and models of albedo changes and effects are as large as, or larger than, the entire enhanced greenhouse gas effect when compared in terms of the albedo change equivalent of climate forcing" (Charlson *et al.*, 2005).

Figure 5.6 shows a comparison of several estimates of Earth albedo. The differences between various estimates amount to over 3%, which translates into a difference in radiative forcing of over 10 W/m^2. Hence the uncertain overall average albedo of the Earth is a major factor in our lack of understanding of heat flows in the Earth's climate.

A vital parameter for global climate analysis is the albedo at the top of the atmosphere (TOA) which determines the heat input to the Earth. High latitudes are typically very cloudy, especially in maritime areas, and it is expected that cloud cover would increase the TOA albedo over the open ocean, while making little difference over sea ice or snow. A distinction is therefore drawn between surface albedo and TOA albedo. The radiative effectiveness (RE) of snow or ice is defined as the change in TOA albedo for an ice/snow concentration change between 0% and 100%. It is diminished by the presence of clouds and altered by ice/snow properties. Based on data, Gorodetskaya *et al.* (2006) found RE values of about 0.2 for sea ice or land snow cover. This implies, for example, that if a 400 W/m^2 solar flux impinges on a polar area above the atmosphere, the flux reflected back to space at the top of the atmosphere from that area would increase by roughly 80 W/m^2 as the Earth's surface in an area changed from 0% to 100% ice/snow cover. Thus, even at RE $\sim$ 20%, snow/ice cover provides a powerful feedback mechanism for climate change.

Large-scale changes in land use have undoubtedly had an effect on the Earth's climate through changes in the average albedo of the Earth. The effects of conversion of forest to farmland are described in Section 2.1.2.1. The impact of land clearing on albedo is discussed in Section 5.2.6.

The effect of land clearing and land use for agriculture on a large scale has contributed a net cooling to the areas most affected (mainly in the Northern Hemisphere). However, in areas that were irrigated, the increased moisture likely produced more cloudiness, which would have increased temperatures at night. As Figure 2.2 shows, the bulk of the deforestation took place in two steps: (i) from 1000 to 1700, and (ii) from 1700 to 1940. As Figure 2.4 shows, land use made a moderate contribution to the cooling in the Little Ice Age (1400 to 1850). Although the cooling effect of deforestation continued through the 20th century, the strong increase in urbanization and industrialization led to urban heat islands that spread out from urban centers. Thus, it appears that as we progressed through the 20th century, urban heating overtook the effects of land clearing and human intervention eventually produced a net heating at ground level.

5.2.4 Ocean emissivity

Volz (2006) discussed the role of the emissivity of seawater in the Earth's energy balance. It was mentioned that the word emissivity does not appear once in IPCC (2001). Yet emissivity is a multiplicative factor in the equation for radiant flux emitted by a body. The average emissivity of the Earth is believed to be in the range 0.92 to 0.965. The thermal radiant flux emitted by the oceans ($\sim$70% of the Earth's surface) depends on its emissivity. Volz (2006) estimated that the emissivity of seawater is about 0.93 with no wind and about 0.96 with a 15 m/s wind. Thus, wind increases the capability of the oceans to radiate thermal energy. The difference in radiant flux emitted at the top of the atmosphere was estimated to be about 7 W/m^2 across the extremes of no wind vs. a 15 m/s wind. Any incipient climate change that produces a change in wind velocities can trigger changes in ocean emissivity, which can then act to add to or subtract from the ongoing trend. A change in ocean emissivity of 1% would produce a significant forcing of the climate.

5.2.5 Heat islands of the Earth

5.2.5.1 Differences between surface temperatures and tropospheric temperatures

It is difficult to separate the anthropogenic influences on climate due to forcing by greenhouse gases and changes in land use, such as urbanization, industrialization, and agriculture. Surface temperature measurements have been modified to correct for urbanization by comparing temperature measurements in cities with those in surrounding rural areas (see Sections 3.1 and 3.2), but the results differ significantly depending on whether population data or satellite measurements of night light are used to classify urban and rural areas (Kalnay and Cai, 2003).

Kalnay and Cai (2003) compared the trends in observed surface temperatures at 1,982 sites in the continental U.S. over 50 years with the corresponding trends in satellite observations of tropospheric temperatures over a 2.5° square grid, to estimate the impact of land use changes on surface warming. First, they carried out an in-depth study of Baltimore, MD. The two temperatures (surface and troposphere) track one another quite closely in shape over the 50-year period with almost all of the "ups and downs" in both data sets showing nearly the same time variance. However, it was found that whereas the two sets of temperatures were nearly identical in the 1950s, with the passage of time, the surface temperatures increasingly diverged above the tropospheric temperatures. By the late 1980s and into the 1990s, the surface temperatures exceeded the tropospheric temperatures by a significant amount. They then extended this analysis to the continental U.S. Here, the data are much noisier, but, nevertheless, the surface temperature trend again exceeded the tropospheric temperature trend at the rate of 0.03°C per decade, or 0.3°C per century. Kalnay and Cai (2003) attributed this difference to land use changes, mainly industrialization:

> "Although it is not possible definitively to attribute the differences between the observation and the [tropospheric] temperature trends solely to land use, including urbanization, agriculture and irrigation, our results are compatible with such an interpretation. The well-known 'urban heat island' effect actually takes place at night, when buildings and streets release the solar heating absorbed during the day. At the time of the maximum temperature the urban effect is one of slight cooling, owing to shading, aerosols, and to thermal inertia differences between city and country that are not currently well understood. The effect of agricultural development, increasing evaporation during the day, would also tend to decrease the maximum temperature: irrigation would increase the heat capacity of the soil, thus increasing the minimum temperature. Therefore, both urbanization and agriculture effects could be consistent with the general increase in the minimum temperature and slight decrease in the maximum temperature, and contribute to the reduction in the diurnal temperature range shown in our estimates east of the Rockies. This implies that the comparison of urban and rural stations without including agricultural effects would underestimate the total impact of land-use changes."

Trenberth (2003) raised several objections to the procedure used by Kalnay and Cai (2003), arguing that changes in cloudiness and surface moisture are likely the main sources of the discrepancies along with deficiencies in the tropospheric measurements. Vose *et al*. (2004) raised the objection that systematic effects due to changes in observing time at many sites, changes in instrumentation at stations, and station moves or relocations, could "overwhelm" the bias caused by station urbanization. In addition, Vose *et al*. (2004) claimed that the trend difference between tropospheric and surface temperatures has been decreasing (rather than increasing) with the passage of time. They believe that the tropospheric measurements "are not accurate". Kalnay and Cai (2003) responded to the two criticisms in the same issue of *Nature*, saying (among other things) that they deliberately used raw (unadjusted) surface data because the multiple non-climatic adjustments are uniformly positive, so their estimate of the difference should be considered to be a lower limit.

It is not clear how recent revisions of tropospheric temperature data (Mears, Schabel, and Wentz, 2003) would affect the results of Kalnay and Cai (2003).

5.2.5.2 Correlation of surface temperatures with CO_2 sources

As we pointed out in Sections 3.2.6 and 5.2.5.1, there appear to be significant differences between temperature measurements near the surface and in the troposphere. de Laat and Maurellis (2004) analyzed temperature measurements at the surface and in the troposphere, and correlated them with surface CO_2 emissions. Tropospheric temperatures have not displayed temperature rises as high as those indicated by surface sources. Therefore, de Laat and Maurellis (2004) raised the question of whether the higher surface heating could be, at least partially, due to surface heat production, rather than global greenhouse gas forcing:

> "The differences between troposphere and surface temperatures could arise if the heating were to occur only in the atmospheric boundary layer (ABL), i.e., the observed surface temperature changes were to arise primarily from surface- or ABL-related processes. In addition, if industrial processes were to drive surface temperature changes, then the most important expected observable should be that these changes occur primarily in regions with the largest industrial surface CO_2 emissions."

Thus, de Laat and Maurellis (2004) sought a connection between enhanced surface temperatures and CO_2 production—not from the greenhouse perspective—but rather using CO_2 production as an indicator of localized or regional industrial activity. Global temperature data (actually temperature anomalies from the mean) at various sites were divided into two groups according to whether the CO_2 emissions were higher or lower than a selected threshold value at each site. The average temperature anomaly in each group was then plotted as a function of the CO_2 threshold value. In each case (at the surface or in the troposphere) the temperature anomalies were significantly greater (more positive) for the group of sites where surface CO_2 emissions exceeded the CO_2 threshold. In addition, the temperature anomalies near the surface were much greater than those in the troposphere (de Laat and Maurellis, 2004).

The majority of the industrial CO_2 emissions occur at northern mid-latitudes. Therefore, if these industries are responsible for regional heating, the effect should be greater in the NH than the SH. So the hemispheres should show different temperature trends. In fact, the rate of surface temperature rise from 1976 to 2000 was about 2.4 times greater in the NH than the SH. The differences over the sea were smaller. This concurs with the rapid increase in industrialization that has occurred in the Northern Hemisphere during the latter part of the 20th century.

Regardless of the exact warming mechanism, one does not necessarily expect that the same degree of warming will occur simultaneously in the troposphere and at the surface since the ocean's heat capacity will introduce significant delay in the sea surface temperature response. However, the higher temperature trends at the surface than in the troposphere (as well as a lack of agreement with climate models) suggest a hitherto-overlooked driver of regional surface temperature increases, linked to the degree of industrialization. This lends strong support to other indications that surface processes (possibly changes in land use or the urban heat effect) are crucial players in observed surface temperature changes. Although the exact mechanisms have yet to be determined, the findings of de Laat and Maurellis (2004) suggest that a significant part of the observed surface warming may be related to processes other than enhanced greenhouse warming (Kalnay and Cai, 2003).

de Laat and Maurellis (2006) was a follow-on to de Laat and Maurellis (2004) in which additional analysis was used to confirm the previously discovered correlation between temperature change and industrialization. Near-surface temperature trends are found to be higher on average for regions with higher industrial CO_2 emissions. But GCMs show no such increase in trends for regions with higher emissions. It was not claimed that a physical causality exists between the CO_2 emissions themselves and the temperature trends, but rather that some underlying process (urban heating?), for which CO_2 emissions functioned as a proxy, was at work.

5.2.5.3 Urban heat islands

As we pointed out in Sections 3.1.2 and 3.2.5, the effect of urbanization on temperature measurements is significant. Figure 5.7 shows a photo taken from space of the U.S. at night showing the concentration of light in urban regions.

This is particularly important in China due to rapid industrialization in the past few decades. Zhou *et al.* (2004) attempted to estimate the effects of urbanization and other land use changes on climate in China using the method of Kalnay and Cai (2003) based on the difference between measured surface temperatures and tropospheric temperatures, but taking into account the comments of Trenberth (2003) and Vose *et al.* (2004) by using a modified data set of tropospheric temperatures.

Using the nomenclature

$$\Delta T = \text{surface temperature} - \text{tropospheric temperature},$$

Zhou *et al.* (2004) found that that $\Delta T(\max)$ decreased by 0.016°C/decade while $\Delta T(\min)$ increased by 0.116°C/decade where max and min refer to daily high and low temperatures. Based on this result, Zhou *et al.* (2004) concluded that the diurnal temperature range (DTR) decreased by 0.132°C/decade over the past few decades in China (on average). Most Chinese stations are located in or near cities. The spatial pattern and magnitude of changes in the rate of change of DTR generally are consistent with several indicators for urbanization. Cities tend to store up solar energy absorbed in structures and roads during the day, and release this heat at night, thus reducing the DTR compared with rural areas surrounding the city. Water also plays an important role. Consequently, they attributed most of the ΔT as due to urbanization. Areas with the greatest increase in urban growth had the largest reductions in DTR.

Figure 5.7. The United States at night.

Degaetano and Allen (2002) found significant effects of urbanization on U.S. temperatures in the 20th century, particularly in regard to unusually warm nights.

Parker (2004) presented a contrary view. He studied warming trends in the second half of the 20th century at 264 stations worldwide, and found no significant difference in warming on windy nights vs. warming on calm nights. Since it was expected that the effect of urban release of heat at night is diffused by wind, the lack of difference between windy and calm nights suggests that the observed warming trend from 1950 to 2000 may not be due to urban heating. Parker (2004) drew a firm conclusion:

> "Here we show that, globally, temperatures over land have risen as much on windy nights as on calm nights, indicating that the observed overall warming is not a consequence of urban development."

But Parker (2004) went further:

> "So, urbanization has not systematically exaggerated the observed global warming trends in T_{min}. The same can be said for poor instrumental exposure

> and microclimatic effects, which are also reduced when instruments are well ventilated.''

While this analysis is certainly a point in favor of the argument that urban heating may not be a major factor in global warming, it is far from iron-clad. While wind might be expected to reduce the urban heating effect in a small urban locality, it might not have much effect in a heavily urbanized region. Furthermore, the extent and quality of the station data appear to be limited. The emphatic conclusions reached by Parker (2004) appear to be part of the Hadley Center party line: ''The reality and magnitude of global-scale warming . . .'

5.2.5.4 Heat generation by urbanization

The heat generated by human activities has traditionally been small compared with the massive heat flows involved in the Earth's climate. However, with the expansion of world population and higher energy usage in the 20th century, human activity is no longer negligible. Hoyt (2006) indicated that the total primary energy consumption in the U.S. in 2002 was 97.7 quadrillion Btu. This is equivalent to

$$97.7 \times 10^{15}\ \text{Btu} = 1.03 \times 10^{20}\ \text{joules}.$$

On a yearly average, this amounts to a continuous power generation of 3.27×10^{12} watts.

The area of the U.S. is 9,640,000 km^2. If we divide the total power by the total area, we obtain about 0.34 W/m^2. However, most of the power generated is localized into urban areas. The power density is probably higher than $\sim$1 W/m^2 in urban regions, and much higher than that in cities. These power densities are approaching those indicated by GCMs for greenhouse gas forcing in the 20th century.

Hoyt (2006), quoting a 1973 paper by Oke, suggested that the temperature increase of an urban center compared with its surroundings is approximated as 0.73 log(population):

> ''In 1900, the world population was 1 billion and in 2000, it was 6 billion for an increase of a factor of six. If the surface measuring stations are randomly distributed and respond to this population increase, it would equal 2.2 log(6) or 1.7°C, a number already greater than the observed warming of 0.6°C. However urban heat islands occur only on land or 29% of the Earth's surface, so that the net global warming would be $0.29 \times 1.7 = 0.5$°C which is close to the observed warming. It is not out of the realm of possibility that most of the twentieth century warming was [due to] urban heat islands.''
>
> ''Since satellite measurements began in 1979, the world's population has approximately doubled leading to an UHI signal of 0.67°C over land and 0.19°C globally. The observed surface warming is about 0.36°C over the same time period, so a substantial portion may be just uncorrected UHI effects. Other effects include land use changes, increased darkness of vegetation, direct heat from fossil fuel burning, a brighter sun, changes in cosmic ray intensity, soot on

snow, more soot in the atmosphere, and greenhouse gases (and this list is not exhaustive). There are many competing theories for the recent warming and some of them do a better job at explaining the observations than do greenhouse gases.

The land surface stations were designed to provide local climatology. They were not designed to detect climate change. Quality control of the surface network is inadequate'' (Hoyt, 2006).

5.2.6 Effects of land use/land clearing changes

Annual world land clearing amounts to over 100,000 km^2. A comparison of global maps showing land use (crop land, grazing land, evergreen forest, savannah, grassland, steppe, open shrub land, deciduous forest, and hot desert) reveals major changes worldwide from 1700 to 1900, and further changes from 1900 to 1990 (Pielke *et al.*, 2007b). Global cropland area increased from 2.6 million km^2 in 1700 to 15 million km^2 in 1980. Over the same period, the global extent of forest and woodland decreased by 17%, from 61 million km^2 to 51 million km^2 (see Section 2.1.2.1). A significant portion of the natural vegetation of the world has been cleared to grow crops. In much of India, eastern China, the forests and shrub lands of Europe, the steppes of Asia, and the Great Plains of North America, over 75% of the land is now cropland. Bonan (2002) wrote:

> ``Changes in land cover alter net radiation at the surface, the partitioning of this available energy between sensible and latent heat, and the partitioning of precipitation into runoff and evapo-transpiration. This arises from differences among vegetation in albedo, roughness, leaf area index, root distribution, and stomatal conductance and changes in soil texture. For example, vegetation generally has a lower albedo than bare soil, and forests have a lower albedo than pastures or croplands. As a result, overgrazing grasslands and clearing forests for croplands increases surface albedo ... Clearing forests for cropland or pastureland also reduces surface roughness. This reduces mechanical turbulence and sensible and latent heat fluxes. The partitioning of net radiation into sensible and latent heat is influenced by leaf area, stomatal conductance, root distribution, and soil texture. It is also affected by the overall hydrologic cycle. Evapo-transpiration is an important regulator of global climate.''
>
> ``The impact of historical land cover changes on climate is noticeable on a global scale, is comparable in magnitude to other climate forcings, and is important to reconstructing historical climate change. In particular, land cover changes in Europe and North America have likely cooled the climate of the Northern Hemisphere. If so, this land use change would have dampened the warming from increasing CO_2 and other greenhouse gases. Cooling from deforestation of Europe and North America may have contributed to the anomalously cold temperatures during the Little Ice Age from 1550 to 1850'' (Bonan, 2002).

A number of studies have been conducted in which a land surface model is used to define the properties of the surface for various forms and distributions of vegetation on the surface. The properties relevant to climate modeling include albedo, solar absorptance, roughness, sensible heat/latent heat ratio, and heat capacity of the soil. Typically, these properties are derived from sophisticated vegetation models. The results of these surface models can be used as boundary conditions for GCMs, and the temperature at the surface can thereby be estimated for varying types of vegetation. By comparing the estimated temperature for the period prior to human intervention (land clearing, deforestation, establishment of croplands, etc.) with that after such activities, one can estimate the change in climate for any region that was induced by such human intervention.

Bounoua *et al.* (2000) used a coupled biosphere–GCM model to examine the sensitivity of global and regional climates to variations in the "normalized difference vegetation index" (NDVI) over a 9-year period. Their results indicated a significant net cooling effect from increased vegetation.

Bonan (1997) combined a land model with a GCM to examine the effects of land use on the climate of the U.S. through three 5-year model integrations using natural vegetation, modern vegetation, and maximum agricultural (i.e., maximum deforestation) scenarios. Land use practices have replaced much of the natural needle-leaf evergreen, broadleaf deciduous, and mixed forests of the eastern United States with crops. The climate of the U.S. with modern vegetation is different from that with natural vegetation. The results of Bonan (1997) provide three important climate signals caused by modern vegetation:

(1) a 1°C cooling over the eastern United States and a 1°C warming over the western United States in spring;
(2) summer cooling of up to 2°C over a wide region of the central United States; and
(3) moistening of the near-surface atmosphere by 0.5 g/kg to 1.5 g/kg over much of the U.S. in spring and summer.

These changes in surface temperature and low-level moisture extend well into the atmosphere, and affect other aspects of the simulation. There are large changes in zonal wind. Regions with higher atmospheric moisture in spring and summer also have increased cloudiness, decreased boundary layer height, decreased net radiation, decreased sensible heat flux, increased latent heat flux, increased rates of infiltration, and increased soil water. Maximum agriculture reinforces these signals. Other studies have also found that the climate of the U.S. is sensitive to the specification of vegetation types.

Hale *et al.* (2006) used several GCMs in conjunction with land models over the period 1983–1992. They ran the models for the NH and the whole globe, considering (1) land effects only, (2) CO_2 greenhouse effects only, and (3) combined land effects and CO_2 greenhouse. Their results are summarized in Table 5.3.

According to these models, deforestation offset a significant fraction of putative CO_2-induced greenhouse warming, although there is some diversity in the results. As always, the effect of clouds remains an issue.

Table 5.3. Calculated temperature change (°C) from 1983 to 1992 due to deforestation and CO_2 greenhouse effect according to various GCMs. From Hale *et al.* (2006).

Model	*Deforestation only*		*CO_2 only*		*Deforestation and CO_2*	
	Global	*NH*	*Global*	*NH*	*Global*	*NH*
1	−0.24	−0.31	0.52	0.58	0.29	0.25
2	−0.13	−0.23	0.27	0.36	0.17	0.14
3	−0.14	−0.19	0.42	0.51	0.37	0.35
4	−0.25	−0.36	0.34	0.40	0.10	0.05
5	−0.17	−0.23	0.62	0.68	0.46	0.47

Hale *et al.* (2006) studied temperature trends over the past 30 years at 183 sites in the U.S. prior to, during and after significant periods of land use/land clearing (LULC) activity in these localities.

Station minimum temperatures. Prior to LULC activity, 22 stations showed a significant warming trend and 27 showed a significant cooling trend. After LULC, 78 had significant warming trends and only 2 had significant cooling trends. The most common type of dominant LULC conversion was from forest to urban. The post-change trend was ~1.4°C/decade.

Station maximum temperatures. Prior to LULC activity, only 7 stations showed a significant warming trend and 5 stations showed a significant cooling trend. After LULC, 76 had significant warming trends and only 4 had significant cooling trends. The post-change trend was ~2.1°C/decade.

Although these observations do not necessarily establish a cause–effect relationship between LULC and temperature, they are highly suggestive.

Lim *et al.* (2005) investigated the sensitivity of surface climate change to land types in the NH by subtracting tropospheric temperatures from the observed surface temperatures under the belief that tropospheric temperatures represent large-scale climate changes due to greenhouse gases and atmospheric circulation, and are less sensitive to regional surface processes associated with land types. These temperature differences then provide suggestive evidence of local or regional surface warming from non-greenhouse processes. The results suggest that urban heating contributes to observed warming trends.

5.2.7 Effect of clouds

A NASA website points out that:

> "As we all know from days at the beach, clouds block much of the solar energy and reflect it back to space before it can be absorbed by the Earth, the atmosphere, or the sunbather! The more plentiful and thicker the clouds are, the cooler the Earth. At the same time, clouds also act like greenhouse gases—they block the emission of heat to space and inhibit the ability of the planet to release its absorbed solar energy [to space]. [We all know that clear, cloudless winter nights produce the deepest freezes.] To complicate matters further, the altitude of clouds changes the amount of thermal infrared blocking. This effect is the result of the decrease in temperature with altitude—high clouds are colder and more effective at absorbing the surface-emitted heat in the atmosphere, while they emit very little to space because of their cold temperatures! So it turns out that clouds can either act to cool or warm the planet depending on how much of the Earth they cover, how thick they are, and how high they are. Low clouds made of spherical water droplets reflect much of the sunlight that falls on them, but have little effect on the emitted energy. Thus, low clouds act to cool the current climate. High clouds made up of ice crystals reflect less energy, but trap more of the energy emitted by the surface, and thus act to warm the current climate."

Ramanathan (1988) said that as surface warming occurs, the increased moisture from the warmer oceans should alter cloud distributions and characteristics but the nature of these cloud changes and the ways they affect radiative heating is unclear.

> "As a result, cloud feedback is one of the largest sources of uncertainty in the theory of climate change."

Ramanathan (1988) claimed that the albedo of the Earth would be about 10% if there were no clouds, but clouds bring it up to about 30%. An increase in the planetary albedo of $\sim$1% would zero out the estimated temperature rise from GCMs for a doubling of CO_2.

Leathers *et al.* (1998) emphasized that clouds will decrease daytime temperatures and increase nighttime temperatures, thus decreasing the diurnal temperature range.

Clouds play an important role in the heat balance of the Earth. Climate models have included the effects of clouds in various ways. However, most climate modelers agree that uncertainties in regard to the effects of clouds is a principal cause of disagreement between models. According to Bony *et al.* (2006):

> "Clouds strongly modulate the earth's radiation budget, and a change in their radiative effect in response to a global temperature change may produce a substantial feedback on the earth's temperature. But the sign and the magnitude of the global mean cloud feedback depends on so many factors that it remains very uncertain. Cloud feedbacks have long been identified as the largest internal

source of uncertainty in climate change predictions, even without considering the interaction between clouds and aerosols."

Bony *et al.* (2006) said that climate models exhibit "systematic biases" in simulating clouds that "restrict their ability to predict the magnitude of cloud feedbacks." They therefore concluded:

"Defining strategies for evaluation of cloud feedback processes in climate models is thus of primary importance to better understand the range of model sensitivity estimates and to make climate predictions from models more reliable."

Although they adopted the upbeat view that "progress has been made during the last few years in our understanding of processes involved in these feedbacks," there still remain many uncertainties in modeling clouds.

Held and Soden (2000) said that considerable controversy exists regarding the radiative treatment of clouds in climate models, and that the "treatment of clouds in climate models presents greater obstacles to quantitative analysis of climate sensitivity than does the treatment of water vapor."

Kiehl and Trenberth (1997) assumed that clouds exist in three layers and these layers are assumed to randomly overlap. In developing their model for the Earth's heat balance, they concluded that the cloudy-sky top-of-atmosphere outgoing radiative flux was 235 W/m^2, as shown in Figure 5.3. They adjusted the parameterization of clouds in a climate model to achieve this flux. Three cloud levels were introduced into their model: (i) a low cloud layer between 1 km and 2 km with fractional area of 49%, (ii) a mid-level cloud cover of fractional amount of 6% between 5 km and 6 km, and (iii) a high cloud cover of 20% between 10 km and 11 km. They assumed that random overlap led to a previous estimate of 62% total cloud cover. The emissivity of the low and mid-level clouds was assumed to be 1, while the emissivity of high-level clouds was set to 0.6. This led to the aforementioned outgoing flux of 235 W/m^2. In their model, the total long-wave radiative forcing for clear conditions was 125 W/m^2, and when clouds were included, this added 30 W/m^2, bringing the total to 155 W/m^2. Clouds not only absorb outgoing thermal radiation, but also contribute to cooling by reflecting more incoming sunlight than they absorb. It was estimated that short-wave forcing by clouds amounts to -50 W/m^2, a cooling effect. Thus, the net effect of clouds is $30 - 50 = -20$ W/m^2, a net cooling effect.

Marsh (2002) provided slightly different figures (clear-sky forcing = 146 W/m^2 and cloud effect = 33 W/m^2). Marsh (2002) quoted the IPCC Report as estimating the net effect of clouds as 31 W/m^2 for long-wave, and -44 W/m^2 for short-wave, with a net of -14 W/m^2. This is considerably lower than the estimate by Kiehl and Trenberth (1997). Other modelers have estimated a wide range of values.

Finally, we mention briefly that Gorodetskaya *et al.* (2006) discussed the effects of clouds in polar areas and oceans.

Rising global air traffic and its associated contrails have the potential for affecting climate via radiative forcing. Minnis *et al.* (2004) estimated increases in cirrus clouds due to jet contrails over heavily traveled air routes and used a global climate model to infer the resultant temperature change of air near the surface. It was concluded that the increasing cirrus over the past few decades led to a U.S. temperature increase of about 0.3°C per decade from 1975 to 1995. However, a note to the *Journal of Climate* claimed that this estimate was high by an order of magnitude because it extended local effects to a wide region. The lead author of Minnis *et al.* (2004) answered by suggesting that the estimate in Minnis *et al.* (2004) was probably an upper limit, while the smaller estimate provides a lower limit (Shine, 2005). The magnitude of the effect of aircraft contrails remains very uncertain.

5.2.8 Heat capacity, time constant, and sensitivity of Earth's climate system

The following estimate of the Earth's heat capacity is excerpted from Schwartz (2007).

The Earth's climate system involves a radiative balance between absorbed shortwave (solar) radiation Q and long-wave (thermal infrared) radiation emitted at the top of the atmosphere E.

$$Q \approx E. \tag{5.1}$$

The global annual mean absorbed shortwave irradiance is:

$$Q = \gamma J, \tag{5.2}$$

where γ is the mean planetary co-albedo (1 − albedo) and J is the mean solar irradiance at the top of the atmosphere ≈343 W/m^2.

Satellite measurements indicate $Q \approx 237$ W/m^2, corresponding to $\gamma \approx 0.69$ (albedo ≈ 0.31). The global annual mean emitted long-wave irradiance is

$$E = \varepsilon \sigma T^4, \tag{5.3}$$

where ε is the effective planetary long-wave emissivity, σ is the Stefan–Boltzmann constant, and T is the global mean surface temperature.

An energy imbalance $Q - E$ arising from a secular perturbation in Q or E results in a rate of change of the global heat content given by

$$\frac{dH}{dt} = Q - E, \tag{5.4}$$

where dH/dt is the change in heat content of the climate system. But the definition of the heat capacity of the Earth is given by the equation

$$\frac{dH}{dt} = C\frac{dT}{dt},$$

where C is an effective heat capacity that reflects only that portion of the global heat capacity that is coupled to the perturbation on the timescale of the perturbation. In the present context of global climate change induced by changes in atmospheric composition on the decade to century timescale, the pertinent heat capacity is that which is subject to a change in heat content on such timescales. Measurements of ocean heat content over the past 50 years indicate that this heat capacity is dominated by the heat capacity of the upper layers of the world's oceans.

Combining Equations (5.2)–(5.4), we have

$$C\frac{dT}{dt} = \gamma J - \varepsilon\sigma T^4. \tag{5.5}$$

Equation (5.5) can be solved for a few simple special cases. For the case of a step function forcing in which $F = (Q - E)$ makes a step change from one constant level to another constant level, the forcing F is defined as the difference between these two levels. In this case, the change in temperature (from the original temperature prior to the step-change) at a time (t) after the step-change is

$$\Delta T(t) = \frac{\tau}{C} F[1 - \exp(-t/\tau)], \tag{5.6}$$

where τ is a constant of integration that characterizes the e-folding time over which the system readjusts to a new temperature.

For large t, the exponential becomes negligible, and

$$\Delta T(t) = \frac{\tau}{C} F. \tag{5.7}$$

But this is just the climate sensitivity relation we had in Section 4.2. Therefore, we can identify the climate sensitivity parameter as:

$$\lambda = \frac{\tau}{C} \tag{5.8}$$

$$\Delta T(t) = (\lambda)F \tag{5.9}$$

and λ represents the ultimate temperature rise produced by a step function forcing F. It turns out that:

$$\tau = C\frac{T_0}{4J\gamma,} \tag{5.10}$$

so that

$$\lambda = \frac{T_0}{(4J/\gamma)}, \tag{5.11}$$

where T_0 is the initial value of T.

As Schwartz (2007) showed, with $T_0 = 288$ K, $J = 343$ W/m^2, and $\gamma = 0.69$, the estimated value for $\lambda = 0.3$°C per W/m^2. If there is a forcing F that engenders additional forcing via feedback, we can multiply λ by a feedback parameter (f). A feedback parameter of 2 to 2.5 would lead to a climate sensitivity of 0.6°C to 0.8°C per W/m^2, which is predicted by climate models.

Schwartz (2007) also mentions that if the forcing is not a step function, but a continuous ramp-up, as in $F = \beta t$, the solution of Equation (5.5) becomes

$$\Delta T(t) = (\beta\lambda)[(t - \tau) + \tau \exp(-t/\tau)]. \tag{5.12}$$

For $t \gg \tau$ the exponential is negligible, and we obtain

$$\Delta T(t) = (\beta\lambda)t \tag{5.13}$$

showing that the temperature increases continuously in proportion to the forcing.

Equation (5.8)—or (5.10)—defines a relation between C, λ, and τ. If any two are known, we can calculate the third. Schwartz (2007) estimated τ by two methods. One was based on rates of decay of impacts of volcanic eruptions, and the other is an abstract technique based on the range of observed fluctuations of temperature over the past century, which is limited by the rate at which the system equilibrates to a perturbation. The result was $\tau \approx 5$ years. Both the values of τ and λ are lower than accepted values. Since λ is proportional to τ, if τ was actually 10 years—instead of 5—the value of λ would double to 0.6°C per W/m^2.

Based on $\tau \approx 5$ years and $\lambda \approx 0.3$°C per W/m^2, Schwartz (2007) estimated the heat capacity of the Earth to be ≈16 W-years/°C per m^2. About 85% of this is due to the oceans and about 15% to the land.

The rather short time constant of the climate system determined by this analysis implies that the climate system is in near equilibrium with applied forcings. Hence the total forcing of the climate system over a given time period F can be estimated empirically from knowledge of the change in global mean surface temperature (GMST) over that period ΔT as (λF) with little error resulting from lag of the temperature response to forcing.

Climate models have estimated that the forcing due to a doubling of CO_2 concentration is about 3.7 W/m^2. If the estimated value of $\lambda \approx 0.3$°C per W/m^2 is correct, the estimated temperature rise due to the greenhouse effect would be 1.1°C. However, this does not include feedback effects.

5.2.9 Heat content of the oceans

Levitus, Antonov, and Boyer (2005) presented estimates of the variability of ocean heat content based on hundreds of thousands of temperature profiles. Their results for changes in the overall heat content of the oceans are shown in Figure 5.8. Although the overall average is predominantly upward, the heat content of the oceans is not uniform and various regions experience very different changes in heat content, as discussed in Levitus, Antonov, and Boyer (2005). The decreases around 1965 and more emphatically around 1983 have not been explained.

Levitus, Antonov, and Boyer (2005) also provided estimates of the components of the Earth's heat balance as shown in Table 5.4.

Levitus, Antonov, and Boyer (2005) concluded:

> "The long-term trend as seen in these records is due to the increase of greenhouse gases in the Earth's atmosphere ... However, the large decrease in ocean heat content starting around 1980 suggests that internal variability of the Earth system significantly affects Earth's heat balance on decadal time-scales."

Levitus, Antonov, and Boyer (2005) discussed the issue:

"Since atmospheric greenhouse gases such as carbon dioxide, methane, etc. are well mixed in the atmosphere, why isn't the ocean responding uniformly?"

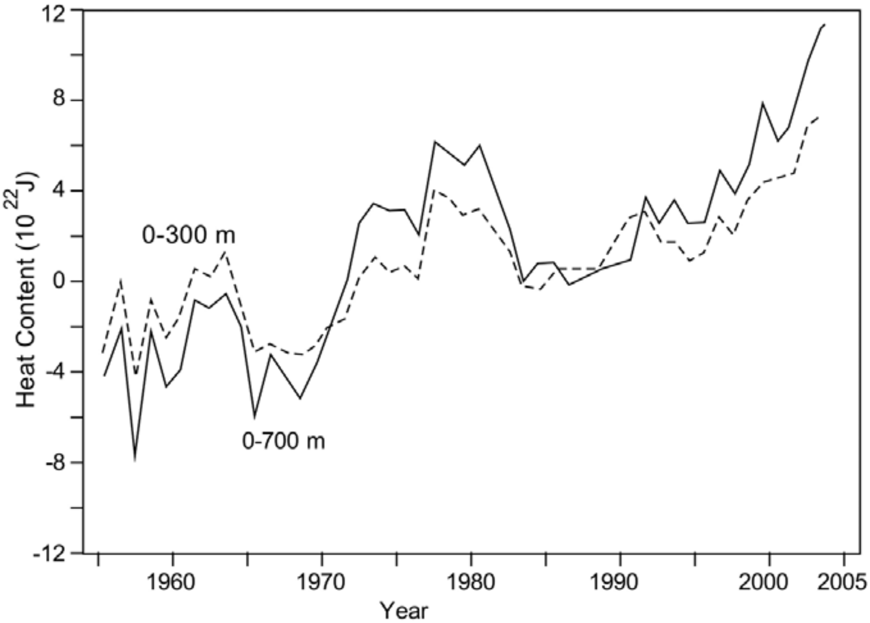

Figure 5.8. Changes in the overall heat content of the oceans. Adapted from Levitus, Antonov, and Boyer (2005).

Table 5.4. Estimated components of the Earth's heat balance. From Levitus, Antonov, and Boyer (2005).

Heat flow element	*Heat flow for period 1955–1998* (10^{22} J)
Heat absorbed by oceans	14.5
Heat absorbed by continents	0.9
Heat to melt continental glaciers	0.8
Heat absorbed by atmosphere	0.7
Heat to reduce Antarctic sea ice	0.3
Heat to melt mountain glaciers	0.1
Heat to melt Northern Hemisphere sea ice	0.005
Heat to melt Arctic sea ice	0.002

Their answer involves two parts:

(1) It is claimed that aerosols are not well mixed geographically and lead to significant variations in regional warming rates. However, this would suggest that a single global average temperature lacks utility in analyzing heat uptake by the oceans.
(2) Any change in the Earth's heat balance may induce global and regional changes in the circulation of the atmosphere and ocean that could in turn affect the net flux of heat across the air–sea interface on a regional basis. No mention was made of the possibility that ocean currents are unstable (see Sections 1.2.4 and 5.2.11) and can vary independently of the greenhouse effect.

A number of improvements have been made in the past decade in measurements to assess the changes in the global average ocean heat content anomaly (OHCA). The Argo global array of 3,000 free-drifting profiling floats 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. Argo deployments began in 2000 and by the end of 2006 the array was over 90% complete. However, this network requires continual servicing and replenishment. Expendable bathythermographs (XBTs) have been used by oceanographers for many years to obtain information on the temperature structure of the ocean to depths of up to 2,000 meters. The use of XBTs to measure the ocean's subsurface has significantly increased over the past decade. NOAA's XBT program (SEAS) currently supports about 80 voluntary observing ships. More than 14,000 XBT observations are made each year.

Lyman, Willis, and Johnson (2007) utilized these new data and found a significant cooling effect in the oceans for 2003–2005. This posed a significant problem for global-warming enthusiasts. However, it now appears that this cooling was "spurious" due to unforeseen instrument biases. A revision to the 2003–2005 data has not yet been published.

5.2.10 North Atlantic climate variability and ocean oscillations

Marshall *et al.* (2001) wrote an extensive review of variability in Atlantic Ocean circulation, and the effect of these on North Atlantic regional climate. The subject is lengthy and complex, and only the briefest of reports is given here. It was concluded that three major interconnected phenomena contribute to climate change in the North Atlantic region.

(i) Tropical Atlantic Variability (TAV): a fluctuation of tropical Atlantic sea surface temperature (SST) and trade winds.
(ii) North Atlantic Oscillation (NAO): a fluctuation in sea level pressure difference between the Icelandic Low and the Azores High.

(iii) Atlantic Meridional Overturning Circulation (MOC): fluctuations in the Atlantic's thermohaline circulation that may play a role in abrupt climate change.

Marshall *et al.* (2001) concluded:

> "The NAO exerts a dominant influence on the winter time temperatures of the Northern Hemisphere . . . Surface air temperature and sea surface temperatures in wide regions across the North Atlantic basin, in eastern North America, the Arctic, Eurasia and the Mediterranean, are significantly correlated with NAO variability."

They also concluded that changes in circulation patterns of the North Atlantic are directly tied to changes in regional winter time precipitation leading to increased precipitation in some regions, and drought in others. The NAO is also linked to changes in "storm tracks over the Northern Hemisphere from North America to Eurasia and the Mediterranean."

5.2.11 El Niños and climate

In the "normal" state, the sea surface temperature (and oceanic heat content) along the equator in the Pacific is warm in the west (near Asia) and cold in the east (near South America). The ocean surface waters are well mixed by wind stirring. Along the equator in the Pacific, this surface mixed layer is usually 150 m deep or deeper in the west, but it becomes shallower to the east until it essentially disappears near the South American coast. Sea level is also higher in the west. The trade winds, driving currents westward along the equator, feed and maintain the build-up of excess warm water on the western side (Cane, 1983).

It has been observed that quasi-periodic variations occur about this *normal* state every few years, in which the Pacific climate changes from the so-called El Niño conditions to the so-called La Niña conditions. NOAA has described these episodes as follows. El Niño episodes reflect periods of exceptionally warm sea surface temperatures across the eastern tropical Pacific. La Niña episodes represent periods of below-average sea surface temperatures across the eastern tropical Pacific. These episodes typically last approximately 9–12 months. During a strong El Niño, ocean temperatures can average 2°C–3.5°C above normal between the Date Line and the west coast of South America. These areas of exceptionally warm waters coincide with the regions of above-average tropical rainfall. During La Niña, temperatures average 1°C–3°C below normal between the Date Line and the west coast of South America. This large region of below-average temperatures coincides with the area of well below–average tropical rainfall. For both El Niño and La Niña the tropical rainfall, wind, and air pressure patterns over the equatorial Pacific Ocean are most strongly linked to the underlying sea surface temperatures, and *vice versa*, during December–April. During this period the El Niño and La Niña conditions are typically strongest, and have the strongest impacts on U.S. weather patterns. El Niño and La Niña episodes typically last approximately 9–12 months. They often begin to form during June–August, reach peak strength during December–April, and then decay during May–July of the next year. However, some prolonged episodes have lasted 2 years and even as long as 3–4 years. While their periodicity can be quite irregular, El Niño and La Niña typically occur every 3–5 years on average.

El Niños were originally recognized by fishermen off the coast of South America as the appearance of unusually warm water in the Pacific Ocean, occurring near Christmas and hence the name "El Niño" referring to the holy child. El Niño and La Niña are the warm and cold phases of an oscillation referred to as El Niño/Southern Oscillation, or ENSO, which has typically had a period of about 3–7 years. El Niño is thus one phase of a natural mode of oscillation that results from unstable interactions between the tropical Pacific Ocean and the atmosphere.

Although ENSO originates in the tropical Pacific ocean–atmosphere system, it affects weather patterns over the entire world. According to a NOAA website, there is evidence that ENSO has been occurring for at least 125,000 years. El Niños vary in intensity and duration. The 1982 and 1997–1998 El Niños were particularly strong. In such a strong El Niño, the accumulation of excess heat in the eastern Pacific is about 10^{16} kWh, a very large amount of energy. This affects the climate of a good part of the world, not merely the Pacific. For example, realclimate.org reports: "El Niños typically perturb the winter Northern Hemisphere jet stream in a way that favors anomalous warmth over much of the northern half of the U.S., the typical amplitude of the warming is about 1°C."

Cane (1983) describes a severe El Niño that occurred in 1982:

> "In July 1982 conditions in the eastern equatorial Pacific were unremarkable; by October the sea-surface temperature (SST) was almost 5°C above normal and sea level at the Galapagos Islands had risen by 22 cm. The anomalies at depth were even greater: a huge influx of warm water had increased the heat content of the upper ocean at a rate that exceeded the climatological surface heat flux by a factor of more than 3, and the thickness of the warm layer was now greater than all previously observed values. Temperatures at the South American coast were near normal, but within a month they too would rise sharply."

The Southern Oscillation refers to an oscillation in air pressure between the southeastern and southwestern Pacific waters. When the eastern Pacific waters increase in temperature (an El Niño event), atmospheric pressure rises in the western Pacific and drops in the east. This pressure drop is accompanied by a weakening of the easterly Trade Winds.

It is this combination of the Southern Oscillation and El Niño that constitutes the El Niño–Southern Oscillation (ENSO).

The atmospheric signature, the Southern Oscillation (SO), reflects the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin. The Southern Oscillation Index (SOI) is a measure of the large-scale fluctuations in air pressure occurring between the western and eastern tropical Pacific during El Niño and La Niña episodes. Traditionally, this index has been calculated based on the

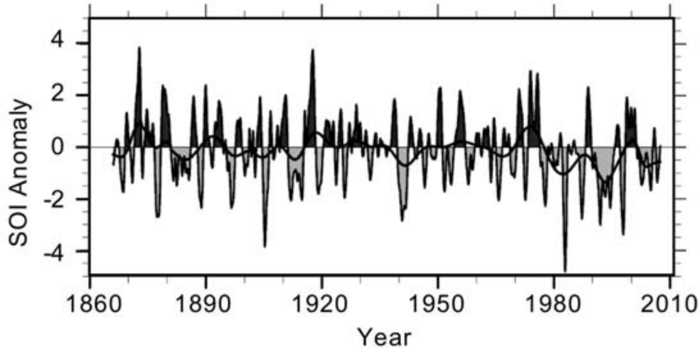

Figure 5.9. Long-term SOI index based on monthly values. Also shown are smoothed curves filtered to remove fluctuations of less than 8 months duration. Values prior to 1935 should be used with caution. Adapted from *http://www.cgd.ucar.edu/cas/catalog/climind/soi.html*

differences in air pressure anomaly between Tahiti and Darwin, Australia. In general, smoothed time series of the SOI correspond very well with changes in ocean temperatures across the eastern tropical Pacific. The negative phase of the SOI represents below-normal air pressure at Tahiti and above-normal air pressure at Darwin. Prolonged periods of negative SOI values coincide with abnormally warm ocean waters across the eastern tropical Pacific typical of El Niño episodes. Prolonged periods of positive SOI values coincide with abnormally cold ocean waters across the eastern tropical Pacific typical of La Niña episodes.

Estimates of the SOI have been made that date back to the mid-19th century.[5] These results show roughly equal positive and negative fluctuations for many years (see Figure 5.9). However, in the last ~25 years of the 20th century, the trend has been predominantly negative (McLean, 2007a, b). This is demonstrated in Figure 5.10.

This trend in the SOI has led to some controversy in connection with global warming. On the one hand, some climatologists have used computer simulations to infer that this trend in SOI is due to anthropogenic-induced global warming (Vecchi, 2006). Power and Smith (2007) also suggest human activity as a cause of negative SOI but they admit: "there is currently no consensus amongst climate models concerning change in the behavior of ENSO in response to global warming."

On the other hand, two notable naysayers (John McLean[6] and Bob Foster, see Section 3.2.8) have suggested that a rather sudden and decisive change in the circulation patterns and upwelling characteristics in the Pacific began around 1976 and has continued to this day. As can be seen from Figure 5.10, the Pacific has been predominantly under El Niño conditions for the past ~30 years. According to McLean and Foster, this predominance of warm surface waters in the Pacific has heated the Earth, particularly in the NH, and generated a rather abrupt upturn in global warming after 1976 (see Figures 3.4 to 3.7, the latter in color section). According to

[5] *http://www.cgd.ucar.edu/cas/catalog/climind/soi.html*
[6] *http://mclean.ch/climate/global_warming.htm*

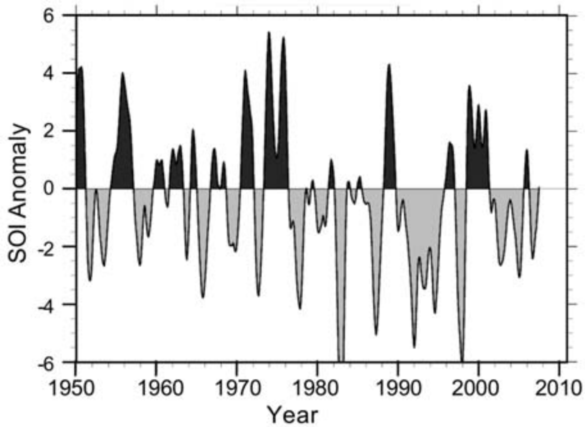

Figure 5.10. SOI index since 1950 showing predominantly negative values. Adapted from *http://www.cgd.ucar.edu/cas/catalog/climind/soi.html*

McLean:

> "The abruptness of this change in upwelling appears likely to be related to some cataclysmic event in the region. Scientists would surely have noticed any shift in winds that was strong enough to cause a semi-permanent 25% reduction in the upwelling of eastern Pacific cold water so the answer is probably hidden in the ocean itself. The only cataclysmic event in the general region at that time was the Guatemala earthquake of February 1976 in which 250,000 people were killed, but any link is purely speculative at the moment."

This is illustrated more dramatically in Figure 5.11. As is the case in most issues in climate change, there are diverse opinions. Has something changed in the Pacific

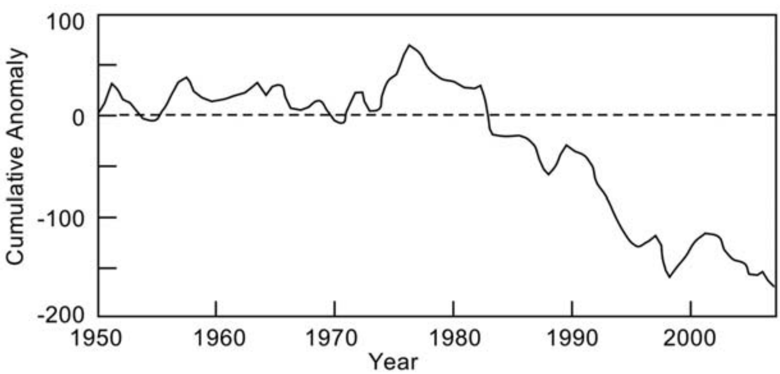

Figure 5.11. Integrated SOI anomaly since 1950. Adapted from McLean (2007a, b).

Ocean that is heating the Earth, independent of greenhouse gases? Or has the effect of greenhouse gases produced a change in the Pacific Ocean?

Further corroboration of the abrupt change in the El Niño–Southern Oscillation behavior around 1976/1977 was provided by other studies. For example, Meehl and Washington (1996) investigated possible causes for the effect:

> "Sea-surface temperatures in the tropical Pacific Ocean increased by several tenths of a degree during the 1980s and early 1990s, contributing to the observed global warming during this period."

Guilderson and Schrag (1998) said:

> "Several studies have noted that the pattern of El Niño–Southern Oscillation (ENSO) variability changed in 1976, with warm (El Niño) events becoming more frequent and more intense. This '1976 Pacific climate shift' has been characterized as a warming in SSTs through much of the eastern tropical Pacific."

Desler, Alexander, and Timlin (1996) said:

> "A prominent decade-long perturbation in climate occurred during the time period [1970–1991] in which surface waters cooled by $\sim 1^{\circ}$C in the central and western North Pacific and warmed by about the same amount along the west coast of North America from late 1976 to 1988."

DiLorenzo *et al.* (2007) said:

> "Particularly dramatic physical and biological excursions occurred during the 1976–77 change in the Pacific Decadal Oscillation."

Hare and Mantua (2000) said:

> "It is now widely accepted that a climatic regime shift transpired in the North Pacific Ocean in the winter of 1976–77. This regime shift has had far reaching consequences for the large marine ecosystems of the North Pacific. Despite the strength and scope of the changes initiated by the shift, it was 1015 years before it was fully recognized. Subsequent research has suggested that this event was not unique in the historical record but merely the latest in a succession of climatic regime shifts."

Wu, Lee, and Liu (2005) said:

> "The 1970s North Pacific climate regime shift is marked by a notable transition from the persistent warming (cooling) condition over the central (eastern) North Pacific since the late 1960s toward the opposite condition around the mid-1970s ... This large-scale decadal climatic regime shift has produced far-reaching

impacts on both the physical and biological environment over the North Pacific and downstream over North America."

According to NOAA:

"El Niños are not caused by global warming. Clear evidence exists from a variety of sources (including archaeological studies) that El Niños have been present for hundreds, and some indicators suggest maybe millions, of years. However, it has been hypothesized that warmer global sea surface temperatures can enhance the El Niño phenomenon, and it is also true that El Niños have been more frequent and intense in recent decades. Recent climate model results that simulate the 21st century with increased greenhouse gases suggest that El Niño-like sea surface temperature patterns in the tropical Pacific are likely to be more persistent."

"A rather abrupt change in the El Niño–Southern Oscillation behavior occurred around 1976/77 and the new regime has persisted ... However, it is unclear as to whether this apparent change in the ENSO cycle is caused by global warming."

5.3 VOLCANIC ERUPTIONS

Volcanic eruptions have had a significant—but not sustained—effect on climate (Robock, 2004; Prohom *et al.*, 2003). Volcanoes can be classified as to size by various indices. In regard to climate change induced by volcanic eruptions, the most important factor is the radiative forcing that is produced by injection of sulfurous material into the stratosphere. This is not always directly related to the explosiveness of the eruption. For example, the Mt. St. Helens eruption (1980) emitted from the side of the mountain and relatively little material was injected into the stratosphere, so it had only a minor effect on global climate. The *volcano explosivity index* (VEI) is measured from 1 to 8, with 8 being the most powerful. Each increase of 1 unit in the index results in an increase of about a factor of 10 in magma volume emitted, as shown in Table 5.5. The largest volcanoes in the past 250 years are listed in Table 5.6.

Volcanic eruptions inject finely comminuted magma as ash and gases into the atmosphere. Ash consists of frozen magma shards and fragments and pulverized rock fragments from the conduit of the volcano, and crystals. Volcanic gases are dominated by water vapor (~80%), and CO_2 (~10%), and the rest is made up of N_2, SO_2, H_2S, CO, H_2, HCl, and HBr. Volcanic aerosols, formed by sulfur species injected into the stratosphere—and not the ash—produces most of the resultant climate effects. These stratospheric aerosols affect global radiation by absorbing and back-scattering incoming solar radiation; the former leads to stratospheric heating, while the latter leads to surface cooling. The volcanic aerosols also catalyze a reduction of stratospheric ozone through heterogeneous chemical reactions. As ash, water vapor, SO_2, HCl, and other gases are injected into the atmosphere, the ash falls out of the atmosphere very rapidly, in a matter of minutes to weeks. Ash therefore has little global climate impact beyond local cooling and reduction of the diurnal cycle.

Table 5.5. The *volcano explosivity index* (VEI). From de Silva (2003).

VEI	*Description*	*Plume height*	*Magma volume*	*Example*
0	Non-explosive	<100 m	1,000 m^3	Kīlauea, Hawaii
1	Gentle	100 m–1,000 m	10,000 m^3	
2	Explosive	1 km–5 km	0.001 km^3	Galeras, Colombia, 1992
3	Severe	3 km–15 km	0.01 km^3	Ruiz, Colombia, 1985
4	Cataclysmic	10 km–25 km	0.1 km^3	Galunggung, 1982; Chile, 1993
5	Paroxysmal	>25 km	1 km^3	Mt. St. Helens, U.S., 1980
6	Colossal	>25 km	10 km^3	Krakatau, Indonesia, 1883 Millenia Huaynaputina, Peru, 1600 Pinatubo, Philippines, 1991
7	Super-colossal	>40 km	100 km^3	Tambora, Indonesia, 1815
8	Mega-colossal	>40 km	1,000 km^3	Toba, Indonesia, 71,000 YBP

Table 5.6. The largest volcanoes of the past 250 years. From Robock (2000).

Volcano	*Year of eruption*	*VEI*
Grimsvotn [Lakagigar], Iceland	1783	4
Tambora, Sumbawa, Indonesia	1815	7
Cosiguina, Nicaragua	1835	5
Askja, Iceland	1875	5
Krakatau, Indonesia	1883	6
Okataina [Tarawera], North Island, New Zealand	1886	5
Santa Maria, Guatemala	1902	6
Ksudach, Kamchatka, Russia	1907	5
Novarupta [Katmai], Alaska, U.S.	1912	6
Agung, Bali, Indonesia	1963	4
Mount St. Helens, Washington, U.S.	1980	5
El Chichón, Chiapas, Mexico	1982	5
Mount Pinatubo, Luzon, Philippines	1991	6

Moreover, water vapor and soluble gaseous components like HCl condense as temperatures drop in the upper troposphere and these components often rain out before they enter the stratosphere. Thus, tropospheric particles are removed from the atmosphere in several weeks by frequent precipitation (de Silva, 2003).

Volcanic eruptions can inject into the stratosphere tens of teragrams of chemically and micro-physically active gases and solid aerosol particles. Large volcanic eruptions inject sulfur gases into the stratosphere, which convert to sulfate aerosols. These gradually diminish, dropping by a factor of about $\frac{1}{3}$ each year. Large ash particles fall out much more quickly. The radiative and chemical effects of this aerosol cloud affect the climate system. By scattering some solar radiation back to space, the aerosols cool the surface, but by absorbing both solar and terrestrial radiation, the aerosol layer heats the stratosphere. Because the sulfate aerosol particles have an effective radius of about the wavelength of visible light, they interact more strongly with the short-wave incident solar radiation than the long-wave radiation emitted by the surface and atmosphere. Some incident sunlight that is back-scattered is reflected to space, cooling the planet. Some is forward-scattered, depleting the direct beam downward radiation, but increasing the downward diffuse radiation. Figure 5.12 shows the impact of two recent volcanic eruptions on direct and diffuse irradiance at a location (Mauna Loa, Hawaii) a considerable distance from the volcanoes. The major impact on solar irradiance occurs in the first year, extending somewhat through the second year. The increase in diffuse irradiance is roughly 70% of the decrease in direct irradiance, producing a maximum deficit in TSI of about 40 W/m^2 for both El Chichón and Pinatubo. This produces a global cooling. Although the Pinatubo eruption produced a larger stratospheric input, the center of the El Chichón cloud passed directly over Hawaii, while only the side of the Pinatubo cloud was observed at Hawaii (Robock, 2000).

Douglass and Knox (2005) provided the data for Figure 5.13 showing the rise and fall of the aerosol optical depth following the 1991 Pinatubo eruption.

They then attempted to estimate the time profile of temperature variation for several years after the eruption, based on Figure 5.13. The forcing produced by a change in optical depth was estimated by Hansen *et al.* (2002) to be about $-21\,W/m^2$ above the atmosphere per unit increase in aerosol optical depth. Thus, at the peak in Figure 5.13, the optical depth is 0.17 and the forcing is about $-3.6\,W/m^2$. As we showed in Section 4.6.2, the climate sensitivity parameter λ is estimated to be roughly $0.6°C/(W/m^2)$. Therefore, in a steady state with a continuous forcing of $-3.6\,W/m^2$, the temperature change would be $\sim 0.6 \times -3.6 = -2.2°C$. In the real transient case, following an eruption, some heat is taken up by the oceans, and there is a time lag for heating the lower atmosphere.

Douglass and Knox (2005) developed a model to determine the temperature change vs. time after the Pinatubo eruption. By fitting the model to the observed change in temperature after the eruption, atmospheric parameters could be fitted with the hope of providing an experimental test for global climate models. However, Douglass and Knox (2005) treated the forcing due to the increase in aerosol optical depth without allowing for heat uptake by the oceans. Hence the forcing led immediately to a temperature drop without a significant time lag. As a result, the parameters

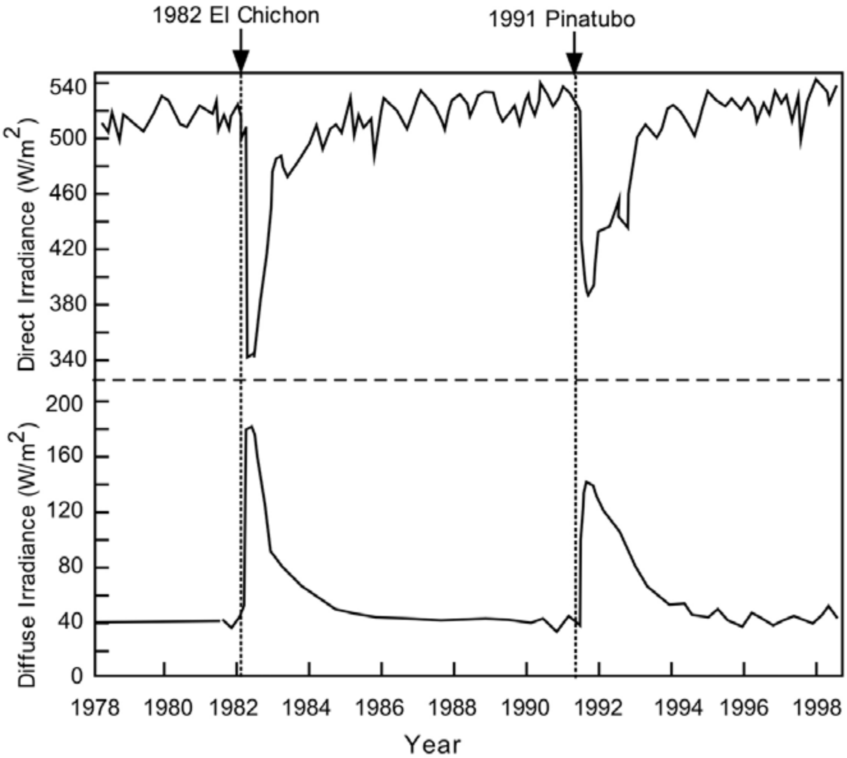

Figure 5.12. Direct and diffuse solar irradiance measured at Mauna Loa following volcanic eruptions at a solar zenith angle of 60° corresponding to the passage of sunlight through two Earth air masses. Adapted from Robock (2000).

derived by Douglass and Knox (2005) were not appropriate, as discussed by Robock (2005). The sharp temperature drop and subsequent slow rise after the eruption were modeled by Douglass and Knox (2005) in terms of a short time constant (about 0.5 year) and a very small value of λ (about $\frac{1}{4}$ of the generally accepted value of roughly 0.6°C/(W/m^2). Robock (2005) showed that a more proper description utilizes $\lambda \sim 0.6$°C/(W/m^2) with a much longer time constant (about 3 years).

The reductions of TSI produced by volcanic eruptions lead to sharp drops in global temperature for a year or two after each eruption, as shown in Figure 5.14.

The reduction in net TSI (and surface temperature) produced by a major eruption is huge and produces a very strong reduction in solar forcing. If the reduction in TSI (and surface temperature) observed during the first year after an eruption persisted for many years, the Earth would almost certainly enter an ice age. Fortunately, the heat capacity of the Earth is great enough that the reduction in global temperature produced by a Pinatubo eruption (VEI = 6) is only about 0.3°C. However, regional temperature reductions can be greater. The Tambora eruption of 1815 led to the "year without a summer" in 1816 in the Northern Hemisphere.

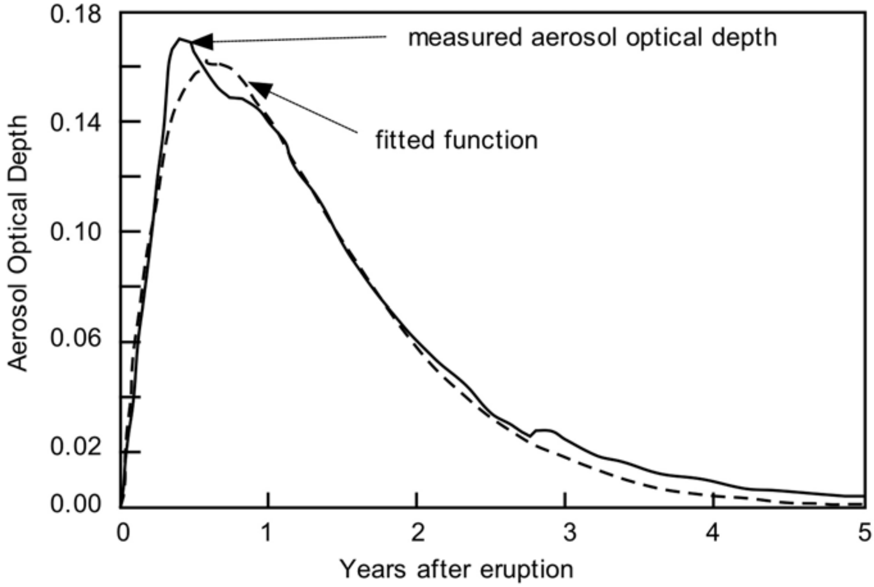

Figure 5.13. Aerosol optical depth following the 1991 Pinatubo eruption. The fitted function is $AOD = 0.697t \exp(-t/0.63)$ where t is the time after eruption in years. Adapted from Douglass and Knox (2005).

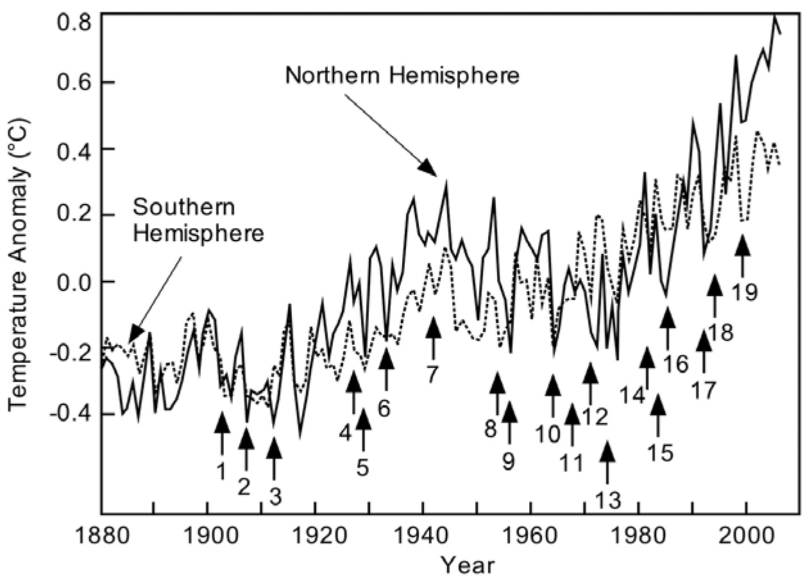

Figure 5.14. The relationship between major volcanic eruptions and hemispheric temperature variations. Volcanoes are identified by number in Table 5.7. This figure was inspired by a similar figure in Leroux (2005).

Table 5.7. List of volcanoes used in Figure 5.14.

Number	*VEI*	*Volcano(es)*
1	6	1902: Santa Maria (Guatemala), Mount Pelée (Martinique), Soufrière (Guadeloupe)
2	5	1907: Ksudach (Kamchatka)
3	6	1912: Katmai (Alaska)
4	3	1928: Paluweh (Indonesia)
5	3	1929: Reventador (Ecuador)
6	5+	1932: Cerro Azul (Argentina)
7	4	1942–1947: Hekla (Iceland)
8	4	1954: Mount Spurr (Alaska)
9	4+	1956: Bezymianny (Kamchatka)
10	4	1963: Gunung Agung (Indonesia)
11	4	1966: Awu (Indonesia)
12	4	1971: Hekla (Iceland)
13	4	1974: Fuego (Guatemala)
14	5	1980: Mount St. Helens (U.S.)
15	5	1982: El Chichón (Mexico)
16	3	1985: Nevada del Ruiz (Colombia)
17	6	1991: Pinatubo (Philippines)
18	4	1992: Mt. Spurr (Alaska)
19	3	2000: Mt. Usu

Tambora's eruption activity peaked April 10–11, 1815.

> "Tambora's eruptive force and atmospheric impact exceeded anything like it on Earth in the past 10,000 years. The catastrophic eruption was so powerful that it sheared Tambora nearly in half, from 4,300 to 2,850 meters. Tambora's dust funnel pumped 200 megatons of dust, rock, and aerosols into the stratosphere. In the immediate aftermath, violent winds blew throughout the area and pumice chunks 20 centimeters long rained down on the surrounding region. Floating ash

islands formed in the sea and a tsunami ravaged nearby shorelines ... All of this destruction occurred far from European and American eyes'' (Soon and Yaskell, 2007).

But the cold resulting from this eruption hit America with extreme effect in the next year and a half with destructive crop yields and winter weather in summer.

The greatest known eruption of the past 100,000 years was the Toba eruption of about 71,000 years ago. While the principal effects of Pinatubo lasted about two years, it is probable that the effects of Toba lasted for about six years. Individual large eruptions certainly produce global or hemispheric cooling for a few years.

As Figure 5.12 shows, the Earth typically returns to normal behavior about three years after a fairly major volcanic eruption. However, Robock (2000) raised the question whether longer term climate changes could be induced or enhanced by either (a) the impact of an extremely large volcano (e.g., Toba (VEI $\sim$ 8)), or (b) the cumulative effect of a series of large volcanoes (VEI + 5 to 6) over some time period.

In Section 1.2.2 it was indicated that 71,000 YBP to 75,000 YBP was a pivotal turning point where the climate turned from a ''mild phase'' to ''a full glacial world''. Could the eruption of Toba be implicated in this transition? It seems possible.

5.4 GLOBAL CLIMATE MODELS

5.4.1 Description of GCMs

Global climate models divide the atmosphere into many small three-dimensional cells with typically 10 to 20 vertical layers and 50,000 to 100,000 horizontal cells. Land areas are divided into surface cells, and oceans are also divided into multiple vertical layers combined with many horizontal cells. Within each atmospheric cell, the various parameters such as temperature, humidity, barometric pressure, and wind velocity are uniform, but are updated frequently, typically every 30 minutes. Each cell interacts with its neighbors according to physical laws that are expressed as mathematical equations. Solar energy impinges from above, and radiation is emitted outward. The rotation of the Earth is also taken into account.

The following four numbered paragraphs are excerpted from CCSP (2007).

1. Modern climate models are typically composed of four primary components: the atmosphere, the land surface, the ocean, and sea ice components.

2. Atmospheric models calculate the state variables of the atmosphere, such as temperature, pressure, humidity, kinetic energy, etc., as a function of space and time. The set of model equations is formulated by using geophysical fluid dynamics theory and physical laws governing the exchanges of the mass and energy. The atmosphere is divided into discrete vertical layers, which are then overlaid with a two-dimensional horizontal grid, producing a three-dimensional mesh of grid elements. A set of primitive equations is then solved as a function of space and time on this mesh. Models differ in spatial resolutions and configuration of model grids. Typical models

have spatial resolution of 200 kilometers in the horizontal direction, and 20 vertical levels below the altitude of 15 km.

3. The ocean component is a fully four-dimensional primitive equation model and is coupled to the atmosphere and ice models through the exchange of fluxes of heat, temperature, and momentum at the boundary between components. Like the atmosphere, the horizontal dimensions of the ocean are much larger than the vertical dimension, again resulting in separating the processes that occur in the vertical from those that occur in the horizontal. Unlike the atmosphere, which only has to deal with terrain differences at the lower boundary, the ocean has a much more complex, three-dimensional boundary, with continents and submarine basins and ridges. Further, the fluid behavior of seawater is very different from that of air.

4. Clouds reflect solar radiation to space, cooling the Earth–atmosphere system. Clouds also trap infrared radiation, keeping the Earth warm. The net effect depends on the height, location, microphysical and radiative properties of clouds, and their appearance in time with respect to the seasonal and diurnal cycles of incoming solar radiation. Cloud feedback refers to the changes in cloud amounts and properties that can either amplify or moderate a climate change. Uncertainties of cloud feedbacks in climate models have repeatedly been identified as the leading source of uncertainty in model-derived estimates of climate sensitivity. The fidelity of cloud feedbacks in climate models is therefore important to the reliability of their prediction of future climate change.

Global climate models have been used to extrapolate global temperatures backward in time as much as 1,000 years (e.g., Foukal *et al.*, 2006; Reid, 1997; Goosse *et al.*, 2005, 2006; Bauer, Claussen, and Brovkin, 2003; Brovkin *et al.*, 2006; Jones *et al.*, 1998). Global climate models have also been used extensively to try to explain the underlying physical reasons for the global climate changes that we have experienced over the past century or so. Global climate models have been used to analyze the climatic effects of volcanoes (Douglass and Knox, 2005; Robock, 2005) and ice ages (Charbit *et al.*, 2007; Dyke *et al.*, 2002). However, the main purpose of global climate models is typically to predict the future climate of the Earth and how it depends on future scenarios for greenhouse gas emissions. IPCC (2001) provides many references to various models.

Global climate models use physical laws to represent interactions between adjacent cells in the model, but they also require boundary conditions that specify how the TSI varies over the time duration of the model, the rate and spatial distribution of greenhouse gas and aerosol emissions, and the occurrence of special events such as major volcanic eruptions. Generally, the TSI is taken from some model. The model for historical TSI in Lean, Skumanich, and White (1992) has been used rather widely. However, as discussed in Section 4.4.4, this model is quite speculative. Bard *et al.* (2000) treated the TSI parametrically, dependent on how much lower the TSI was assumed to be during the MM. But as discussed in Section 4.7, we can only speculate about TSI in the past, and make wild guesses for the future. There exist reasonable models for greenhouse gas emissions (see Section 6.2) and aerosol production (see Section 3.2.4). However, when papers are published that utilize global climate models, it is not always clear which models are used for TSI, greenhouse gas emissions, and aerosol emissions, and these are the crucial factors that determine the outcome of the model.

5.4.2 The IPCC view of climate models

Chapter 8 (Climate Models and Their Evaluation) of the 2001 IPCC Report presented a rather positive view of GCMs:

> "Climate models are based on well-established physical principles and have been demonstrated to reproduce observed features of recent climate and past climate changes. There is considerable confidence that Atmosphere–Ocean General Circulation Models (AOGCMs) provide credible quantitative estimates of future climate change, particularly at continental and larger scales. Confidence in these estimates is higher for some climate variables (e.g., temperature) than for others (e.g., precipitation)" (IPCC, 2001).

The IPCC Report tended to emphasize the improvements that have been made in models, and provided a mostly upbeat evaluation.

- Expanded evaluation efforts makes it less likely that significant model errors are being overlooked.
- Climate models are being subjected to more comprehensive tests. This more diverse set of tests increases confidence in the fidelity with which models represent processes that affect climate projections.
- Substantial progress has been made in understanding the inter-model differences in equilibrium climate sensitivity. Cloud feedbacks have been confirmed as a primary source of these differences, with low clouds making the largest contribution ... The magnitude of cryospheric feedbacks remains uncertain, contributing to the range of model climate responses at mid to high latitudes.
- There have been ongoing improvements to resolution, computational methods, and additional processes (e.g., interactive aerosols) that have been included in more of the climate models.
- Most GCMs no longer use flux adjustments, which were previously required to maintain a stable climate. The uncertainty associated with the use of flux adjustments has therefore decreased, although biases and long-term trends remain in GCM control simulations.
- Progress in the simulation of important modes of climate variability has increased the overall confidence in the models' representation of important climate processes.
- The ability of GCMs to simulate extreme events, especially hot and cold spells, has improved. However, the frequency and amount of precipitation falling in intense events are underestimated.
- Simulation of extra-tropical cyclones has improved.
- Systematic biases have been found in most models' simulation of the Southern

Ocean. Since the Southern Ocean is important for ocean heat uptake, this results in some uncertainty in transient climate response.

- The possibility that metrics based on observations might be used to constrain model projections of climate change has been explored for the first time. Nevertheless, a proven set of model metrics that might be used to narrow the range of plausible climate projections has yet to be developed.
- To explore the potential importance of carbon cycle feedbacks in the climate system, explicit treatment of the carbon cycle has been introduced in a few climate AOGCMs.
- Earth System Models of Intermediate Complexity have been evaluated in greater depth than previously. Coordinated inter-comparisons have demonstrated that these models are useful in addressing questions involving long timescales or requiring a large number of ensemble simulations or sensitivity experiments.

The 2001 IPCC Report asked the question:

"How reliable are the models used to make projections of future climate change?"

Their response to this question is summarized below:

> "There is considerable confidence that climate models provide credible quantitative estimates of future climate change, particularly at continental scales and above. This confidence comes from the foundation of the models in accepted physical principles and from their ability to reproduce observed features of current climate and past climate changes. Confidence in model estimates is higher for some climate variables (e.g., temperature) than for others (e.g., precipitation). Over several decades of development, models have consistently provided a robust and unambiguous picture of significant climate warming in response to increasing greenhouse gases" (IPCC, 2001).

This is rather a strange statement for several reasons. One is that it is difficult to see how one can conclude that models "provide credible quantitative estimates of future climate change" because the future is yet to occur and at best, one would have to extrapolate from past success. But have the models been successful in the past? The IPCC seems to think so. The IPCC Report claims:

> "Models are routinely and extensively assessed by comparing their simulations with observations of the atmosphere, ocean, cryosphere and land surface."

The IPCC Report claims that models are able

> ". . . to reproduce features of past climates and climate changes, such as the warm mid-Holocene of 6,000 years ago or the last glacial maximum of 21,000 years ago. They can reproduce many features (allowing for uncertainties in reconstructing past climates) such as the magnitude and broad-scale pattern of oceanic cooling during the last ice age."

However, we must distinguish between use of models with adjustable parameters that can be tweaked to approximate trends discerned from proxies, as opposed to *a priori* predictions of trends without one eye on a known result. Thus, models tend to fall into the syndrome that they can *explain everything, predict nothing*. Broecker's famous "Angry Beast" article (Broecker, 1995) likened the Earth's climate to an angry beast. He said:

> "... No one understands what is required to cool Greenland by 16°C and the tropics by 4 ± 1°C, to lower the mountain snowlines by 900 m, to create an ice sheet covering much of North America, to reduce ... CO_2 by 30%, or to raise the dust rain ... by an order of magnitude. If these changes were not documented in the climate record, they would never have entered the minds of the climate dynamics community. Models that purportedly simulate glacial climates do so only because key boundary conditions are prescribed (the size and elevation of ice sheets, sea ice extent, sea surface temperature, CO_2 content, etc.). The current climate models do not explain and cannot reproduce the severe and abrupt climate changes in the proxy climatic record."

The point is that if we did not have geological evidence of past ice ages, it is likely that the modelers never would have imagined that ice ages were even possible!

The IPCC Report also claimed that

> "Models can simulate many observed aspects of climate change over the instrumental record. One example is that the global temperature trend over the past century can be modeled with high skill when both human and natural factors that influence climate are included."

This is a rather rose-tinted view of the situation. As in the case of modeling ice ages or the Holocene, modelers can adjust parameters to seek fits to known trends, although even that doesn't work out perfectly. Two related papers (Nagashima *et al*., 2006; Nozawa *et al*., 2005) carried out global climate models that included the impact of aerosols on 20th-century climate change. However, these papers appear to raise more questions than answers (see Section 3.2.4).

The fact that the models are based on "accepted physical principles" is a *necessary* requirement but not necessarily *sufficient* to assure that models deal adequately with the complexities of the Earth's climate.

Finally, the fact that models indicate significant warming due to greenhouse gases has nothing whatever to do with their reliability.

On the positive side, GCMs provide a basic framework for modeling the Earth's climate, and although these models are still rather primitive in many respects (clouds, aerosols, rain, inadequate spatial resolution, land use, etc.) these are all issues that are amenable to improvement in the future, and such improvements can be incorporated into the frameworks of models that have been developed.

5.4.3 Uncertainties and limitations of GCMs

> "The climate models developed in the U.S. and around the world show many consistent features in their simulations and projections for the future. However, they have not fully converged, since different groups approach uncertain aspects of the models in distinctive ways. This absence of convergence is one useful measure of the state of the science of climate simulation; convergence is to be expected once all climate-relevant processes are simulated in a convincing physically-based manner" (CCSP, 2007).

However, even after the various models converge, will they converge to the right answer?

The majority of studies with climate models have addressed the question of how much the future global temperature will rise as a result of a putative future doubling of carbon dioxide concentration in the atmosphere (doubling compared with the pre-industrial level of ~275 ppm). The equilibrium response, the response expected if one waits long enough (several hundred years) for the system to re-equilibrate, is the most commonly quoted measure. The range of equilibrium climate sensitivity predicted by various models is 1.5°C to 4.5°C. The difficulty in simulating the Earth's clouds and their response to climate change are given as the fundamental reason it has proven difficult to reduce the range of uncertainty in model-generated climate sensitivity. Uncertainty still remains considerable and is not decreasing rapidly, due in part to the difficulty of cloud simulation but also to uncertainty in the rate of heat uptake by the oceans (CCSP, 2007).

One major problem with GCMs is that it is difficult to test them against actual data. CCSP (2007) claimed that models are able to simulate the 20th-century global mean temperature record in a plausible way. However, variations in TSI are speculative, and uncertainties in effects of clouds remain as issues. Explanations for the temperature dip from 1940 to 1978 are not fully satisfactory, as we discussed in Section 3.2.4. While some models claim to reproduce measured temperatures in the 20th century, these seem to be contrived after the fact, with forcings chosen to obtain agreement. Such methods explain everything and predict nothing. Hoyt (2006) pointed out that the global temperature rise of ~0.6°C during the 20th century was lower than would be predicted by GCMs based on the known increase in CO_2 concentration. However, other factors (aerosols, land use, etc.) may have affected 20th-century temperatures significantly.

> "Uncertainties in the climatic effects of man-made aerosols (liquid and solid particles suspended in the atmosphere) are a major stumbling block in quantitative attribution studies and in attempts to use the observational record to constrain climate sensitivity. We do not know how much warming due to greenhouse gases has been cancelled by cooling due to aerosols. Uncertainties related to clouds increase the difficulty in simulating the climatic effects of aerosols, since these aerosols are known to interact with clouds and potentially change cloud radiative properties and cloud cover" (CCSP, 2007).

Atmospheric carbon dioxide has increased ~30% over the industrial period. Radiative forcing of climate change by increased concentrations of CO_2 and other long-lived greenhouse gases has been estimated to be $2.4 \pm 0.2\,W/m^2$ relative to the pre-industrial era. However, some models predict that a doubling of CO_2 would result in a forcing of about $4\,W/m^2$. The most recent IPCC Report estimated that this would produce a temperature rise of 1.5°C to 4.5°C, based on a temperature sensitivity factor in the range $0.38°C/(W/m^2)$ to $1.13°C/(W/m^2)$. The factor-of-3 uncertainty in present estimates is certainly unacceptably large for planning for mitigation or adaptation (Schwartz, 2003).

The increase in global mean temperature to date, relative to the pre-industrial era has been estimated to be $0.6 \pm 0.2°C$, suggesting a sensitivity of $0.25 \pm 0.09°C/(W/m^2)$, well below the low end of the IPCC range. But such an empirical estimate assumes that climate response is near equilibrium and that forcing is due entirely to long-lived greenhouse gases. The equilibrium assumption is claimed to be valid. However, forcings other than by greenhouse gases, particularly the cooling influence of anthropogenic aerosols due to their scattering of solar radiation, are thought to offset much of the greenhouse gas forcing on a global basis, resulting in a much lower total forcing and consequently much greater sensitivity. Present uncertainty in total forcing is so great as to preclude a meaningful empirical estimate of climate sensitivity from the temperature record and forcing over the industrial period (Schwartz, 2003).

Schwartz (2004) concluded

(1) A consistent finding of such studies is that the change in global mean temperature per forcing (i.e., climate sensitivity), is, to a good approximation, independent of the nature of the forcing (e.g., forcing because of changes in CO_2 mixing ratios, mixing ratios of other GHGs, aerosol direct forcing, or the solar constant), and independent as well of the geographical distribution of the forcing.
(2) An immediate consequence of the forcing–response paradigm is that forcings are additive. This hypothesis provides a path forward to calculating radiative forcing over the industrial period by adding the forcings.

However, feedback effects can significantly alter the additivity.

In discussing climate models, Schwartz (2004) said:

> "In practice, these models embody numerous assumptions, parameterizations, and approximations of the variables and phenomena being represented—water vapor, clouds, precipitation, snow and ice, radiation, transport of heat and water on all scales—the list goes on. The resolution of models is limited, typically, at present to 300 km ..."

Schwartz (2004) went on to say:

> "Considerations such as the foregoing would seem to call into question confidence that can be placed in statements such as the following from the IPCC 2001 assessment of climate change:

- Simulations that include estimates of natural and anthropogenic forcing reproduce the observed large scale changes in surface temperature over the 20th century.
- Most model estimates that take into account both greenhouse gases and sulphate aerosols are consistent with observations over this period.
- The large-scale consistency between models and observations can be used to provide an independent check on projected warming rates over the next few decades under a given emissions scenario.
- Detection and attribution studies comparing model simulated changes with the observed record can now take into account uncertainty in the magnitude of modeled response to external forcing, in particular that are due to uncertainty in climate sensitivity."

Schwartz (2004) concluded:

> "The sensitivity of global mean temperature change to an increase in atmospheric carbon dioxide (CO_2) is not well established. The complexity of the climate system precludes calculation of the response of Earth's climate to a change in a radiative flux component (forcing) from well-established physical laws. Consequently, determination of global climate sensitivity is a subject of intense research. This work is reviewed from time to time by pertinent national and international bodies. One such landmark review was that of a 1979 National Research Council panel, which concluded: 'We estimate the most probable global warming for a doubling of CO_2 to be near 3°C, with a probable error of 1.5°.' More recently, the IPCC concluded that 'Climate sensitivity [to CO_2 doubling] is likely to be in the range 1.5–4.5°C.' These estimates must be considered somewhat subjective. They are based mainly on calculations with climate models constrained, especially for the IPCC estimate, by observation of the extent of warming over the industrial period and concurrence of modeled and observed warming. Neither the Charney panel nor the IPCC quantitatively specified the meaning of their uncertainty bounds, but in the case of the Charney estimate, a National Research Council panel three years later expressed its understanding that 'the Charney group meant to imply a 50% probability that the true value would lie within the stated range.' Remarkably, despite some two decades of intervening work, neither the central value nor the uncertainty range has changed. The large uncertainty range, a factor of 3, in present estimates of climate sensitivity renders such estimates not particularly useful from the perspective of developing policy regarding either reduction of greenhouse gas (GHG) emissions or adaptation to a new, increasingly warm climate."

Leroux (2005) discussed the limitations and problems associated with global climate models in a 21-page diatribe. The "imperialism" of models is described. It was concluded that the virtues of "models are greatly overestimated."

Schwartz, Charlson, and Rodhe (2007) reviewed the latest (2007) IPCC assessments of climate change based on results from "an ensemble of 58 runs with 14 climate models" and concluded:

> "[IPCC] estimates [of] total anthropogenic forcing [were] 0.6 to 2.4 W/m^2 (595% confidence range). This factor of four range greatly limits the ability to evaluate the 'skill' of climate models in reproducing past temperature changes and to infer climate sensitivity from observed change because a given temperature increase might result from a large forcing and low climate sensitivity or alternatively from a small forcing and high climate sensitivity."

By comparison, the range of predicted temperature rise (0.4°C to 0.8°C) from 1910 to 2000 was only a factor of 2. Schwartz, Charlson, and Rodhe (2007) raised questions whether the temperature estimates spanned the full range of potential forcing, and concluded:

> "The narrow range of modeled temperatures gives a false sense of the certainty that has been achieved."

Schwartz, Charlson, and Rodhe (2007) never raised the question as to whether the purveyors of GCMs "fudged" their models with one eye on the known (or at least the believed) 0.6°C temperature rise from 1910 to 2000. However, this seems to be a likely possibility.

Ghan and Schwartz (2007) pointed out:

> "The practice of climate modeling has become tied to the production schedules for periodic international assessments of the science of climate change by the IPCC."

Each successive generation of IPCC Reports at roughly six-year intervals relies on simulations that are about 3 years old, which in turn, are based on climate models from the prior year (4 years before the IPCC Report). Inevitably, there is a lag from gaining understanding of processes to representing that understanding in climate models. Thus, there is a lag from understanding processes, to representing this understanding in models; and there is a further lag in representing these models in GCMs that are used in IPCC assessments, which can be as long as a full IPCC cycle or more (6 years). There is a further, similar lag of a full IPCC cycle between the representation of various processes in GCMs and the use of the results of that generation of models in scenario assessments (paraphrased from Ghan and Schwartz, 2007).

5.5 INSTABILITY OF THE CLIMATE

The conventional view of the person in the street seems to be that there is a "normal" climate that is stable, describable, and moderate. Any changes that occur must be due to some influence of humankind. Someone must be held accountable.[7]

However, the concept of a normal, steady quiescent climate is a fiction. While models portray the Earth as changing slowly and incrementally in a series of equilibrium steps, history reveals that the equilibrium of the Earth is not like a conventional marble in a bowl that readily returns to the bottom when displaced, but rather can sometimes act like a marble on an inverted bowl and move off to extremes when displaced from an unstable equilibrium. In Sections 1.2 and 5.4.1 we quoted from Broecker's "Angry Beast" article in which he asserted that the historical variations and gyrations of the Earth's climate have been so severe that had they "not [been] documented in the climate record, they would never have entered the minds of the climate dynamics community."

The behavior of water, which can exist in solid, liquid, and gaseous states on Earth, and which has significant heats of vaporization and melting, adds great complexity to the Earth's climate. The random fluctuations that continually occur about the unstable equilibrium in the Earth's climate can act as initiators for large excursions from equilibrium via a variety of feedback mechanisms. While climate models typically contend with forcings of about a watt per square meter, a change of 3% in the albedo of the Earth leads to a change in energy absorption by the Earth of about $10\,W/m^2$. Changes in albedo due to ice sheet expansion and contraction, changes in cloudiness, changes in land use, and emissions of atmospheric dust and aerosols can initiate feedback processes that can overwhelm the equilibrium climate models. Bielefeld (1997) estimated that at the height of the last ice age ($\sim$18,000 YBP) global radiation absorption was lower by 7%–10% than it is today. That would indicate a negative forcing of $24\,W/m^2$ to $34\,W/m^2$, which is far beyond anything typically contemplated with climate models, although a few models have considered climate extremes (e.g., Nisancioglu, 2004).

If the Earth was in a state of equilibrium, and reacted to change by adjusting to a new equilibrium state, a climate change could occur due to

1. Changes in the Earth's orbit about the Sun
2. Changes in innate solar irradiance
3. Changes in atmospheric composition due to emission of greenhouse gases
4. Eruption of volcanoes
5. Changes in ocean current flow patterns.

However, the Earth is not really in a stable equilibrium, and is subject to occasional large deviations in climate that may be too intense and too rapid to be accounted for

[7] This is a rather narrow manifestation of a more general attitude that prevails in our society: that a perpetrator must be identified for every bad thing that happens, and that person must be punished or sued. Thus, if you trip on the sidewalk, you sue the city for an uneven pavement.

by the above list of potential causes. It thus appears that internal fluctuations in the Earth's climate can trigger positive feedback mechanisms that can drive the climate far off "normal". For example, a simplistic concept is that due to a cold fluctuation, the polar ice will spread, reflect more sunlight causing expansion of the ice, etc. If that were the case, ice ages would occur even more frequently than they do. Thus, the mere positive feedback effect of spreading ice does not seem to be sufficient to cause major climate changes. Instead, it appears likely that some external factor is needed to reduce the heat flow to polar areas, which then, aided and abetted by the positive feedback of polar ice, leads to severe climate change. While some have argued for changes in the Earth's orbit as the cause, this seems less likely than a change in ocean current flows.

Sudden climate changes are discussed in Section 1.2.4.

6

CO_2 production and climate change

6.1 CO_2 CONCENTRATION: PAST AND PRESENT

6.1.1 Measurements and proxies

The atmospheric CO_2 measurements at Mauna Loa in Hawaii constitute the longest continuous record of atmospheric CO_2 concentrations available in the world. The Mauna Loa site is considered one of the most favorable locations for measuring undisturbed air because possible local influences of vegetation or human activities on atmospheric CO_2 concentrations are minimal and any influences from volcanic vents may be excluded from the records. The methods and equipment used to obtain these measurements have remained essentially unchanged during the 47-year monitoring program.

Because of the favorable site location, continuous monitoring, and careful selection and scrutiny of the data, the Mauna Loa record is considered to be a precise record and a reliable indicator of the regional trend in the concentrations of atmospheric CO_2 in the middle layers of the troposphere. Air samples at Mauna Loa are collected continuously from air intakes at the top of four 7 m towers and one 27 m tower. Four air samples are collected each hour for the purpose of determining the CO_2 concentration. Peaks occur every May and minima occur in September.

The Mauna Loa record shows a 19.4% increase in the mean annual concentration, from 316 parts per million by volume (ppmv) of dry air in 1959 to 377.4 ppmv in 2004. The 1997–1998 increase in the annual growth rate of 2.9 ppmv represents the largest single yearly jump since the Mauna Loa record began in 1958. This represents an average annual increase of 1.4 ppmv per year. This is smaller than the average annual increase at the other stations because of the longer record and inclusion of earlier (smaller) annual increases (see Figure 6.1).

Carbon dioxide measurements prior to the late 1950s derive primarily from ice cores. The conventional view is that the transition from snow to firn to ice occurs as

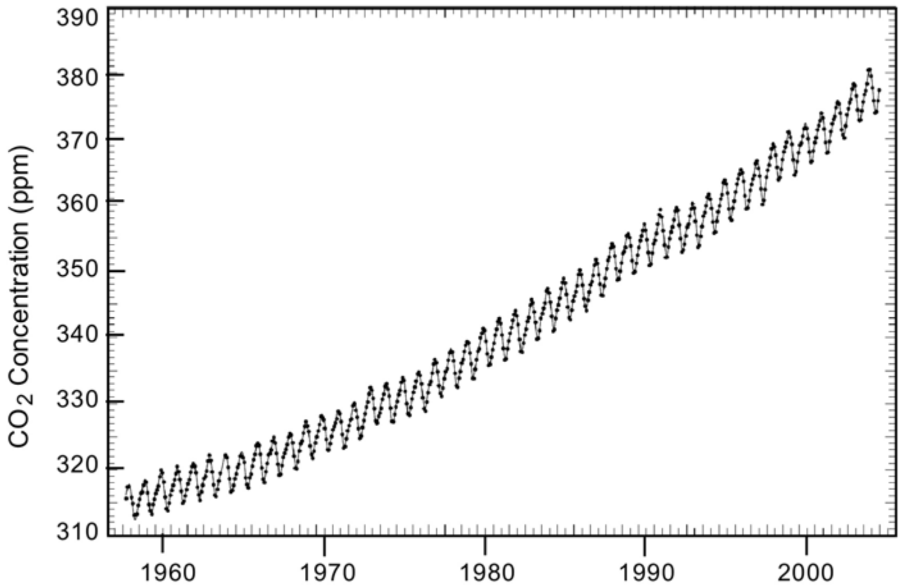

Figure 6.1. Measured CO_2 concentration at Mauna Loa.

the weight of overlying material causes the snow crystals to compress, deform, and recrystallize in more compact form. When firn is buried beneath subsequent snowfalls, the density is increased as air spaces are compressed due to mechanical packing as well as plastic deformation. Interconnected air passages may then be sealed and appear as individual air bubbles. This process is believed to take perhaps 100–200 years, so the air entrapped within the ice is believed to be younger than the ice by a century or more. It seems likely that the trapped air within the ice represents a broad distribution of ages younger than the ice. Friedli *et al.* (1986) and Etheridge *et al.* (1996) provided ice core data from Antarctica. The data from Etheridge *et al.* (1996) are shown in Figure 6.2.

During the Holocene, the reported CO_2 concentration was as shown in Figure 6.3.

The reported CO_2 concentration during the past 650,000 years is shown in Figure 6.3. The CO_2 concentration peaked around 280 ppm–290 ppm at the height of interglacial eras, and decreased to under 200 ppm during ice ages.

From a long-term point of view, the variation of CO_2 concentration in the atmosphere has varied widely across historical glacial cycles. Figure 6.4 shows the historical variation of CO_2 concentration during the past four glacial cycles. The peak CO_2 concentration in past interglacial periods was less than 300 ppm. The recent rise in CO_2 concentration from the pre-industrial level of $\sim$275 ppm to the present value of 375 ppm appears to be primarily due to anthropogenic release of CO_2 and other greenhouse gases as well as the strong warming trend in the second half of the 20th century that releases CO_2 from the oceans. However, it is not clear what geological

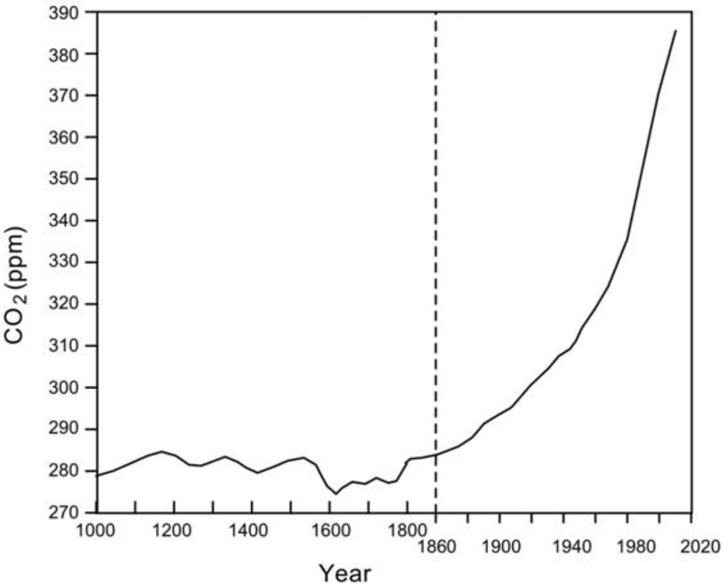

Figure 6.2. Atmospheric CO_2 concentration over the past 1,000 years. Adapted from Etheridge *et al.* (1996).

processes produce the changes in CO_2 concentration shown in Figure 6.4. Low CO_2 concentrations during periods of glaciation might be due, at least partially, to reduced deep-water ventilation associated with either year-round Antarctic sea ice coverage.

Jaworowski (2006) claimed that discrepancies between different ice core data cast doubt on their veracity. The process by which air is encapsulated in ice is described by Jaworowski as being very complex with many phase change processes occurring over longer time periods than the 100–200 years usually considered. Furthermore, some of these processes are claimed to produce discrimination between different chemical

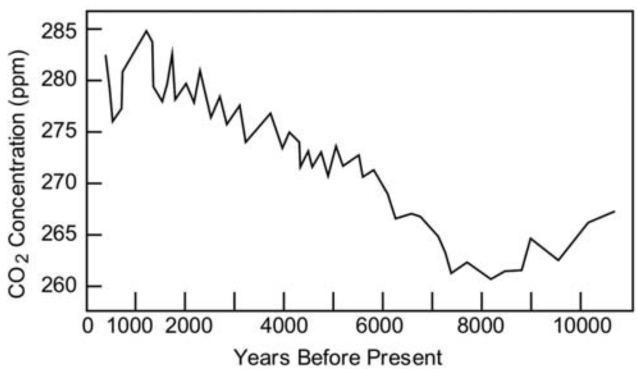

Figure 6.3. CO_2 concentration during the Holocene from ice cores. Adapted from Fliueckiger *et al.* (2002).

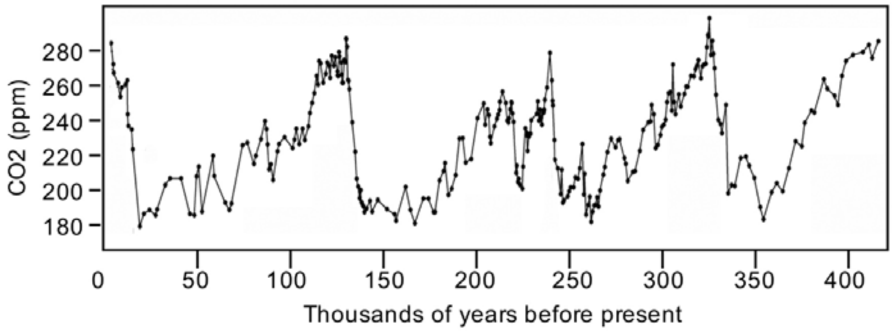

Figure 6.4. Historical variation of CO_2 concentration during the past four glacial cycles. Adapted from Petit *et al.* (1999).

species, resulting in inaccuracy in measured CO_2 concentration. According to Jaworowski, actual measurements of CO_2 in ice cores have varied over wide ranges. The conventional view is that these were spurious results and were discarded. But Jaworowski claims that the data were "fudged" to fit the anthropogenic climatic-warming theory. The claim is that data were selected to support global-warming alarmist beliefs. However, as realclimate.com points out:

> "It took a lot of long and painful lessons for scientists to come to [an] understanding of the natural carbon cycle and its anthropogenic contributions. Difficulties arose mainly from two problems: First, sampling of air masses and subsequent measuring of CO_2 concentrations was in itself a difficult problem. Measuring techniques … needed a significant amount of technical skill and patience for a proper measurement. The regular use of a CO_2 standard to permanently check the measurement quality was something of an exception. Secondly, nearly all early sampling facilities were tested in continental environments often under the sporadic influence of heavily polluted air masses."

As a result, some of the early measurements led to anomalous results that were seized on by Jaworowski (2006, 2007) that claim that the CO_2 concentration has oscillated wildly in the 20th century. But realclimate.com pointed out that this would require rapid heating and cooling that never occurred.

6.1.2 Carbon cycle: CO_2 fluxes

Knowledge of carbon exchange between the atmosphere, land, and the oceans is important in understanding the rate of build-up of CO_2 in the atmosphere due to human intervention in the Earth environment. However, the Earth's carbon cycle is complex. The oceans, the biosphere, and land exchange very large amounts of CO_2 each year, and the contributions from fossil fuel and cement production are relatively

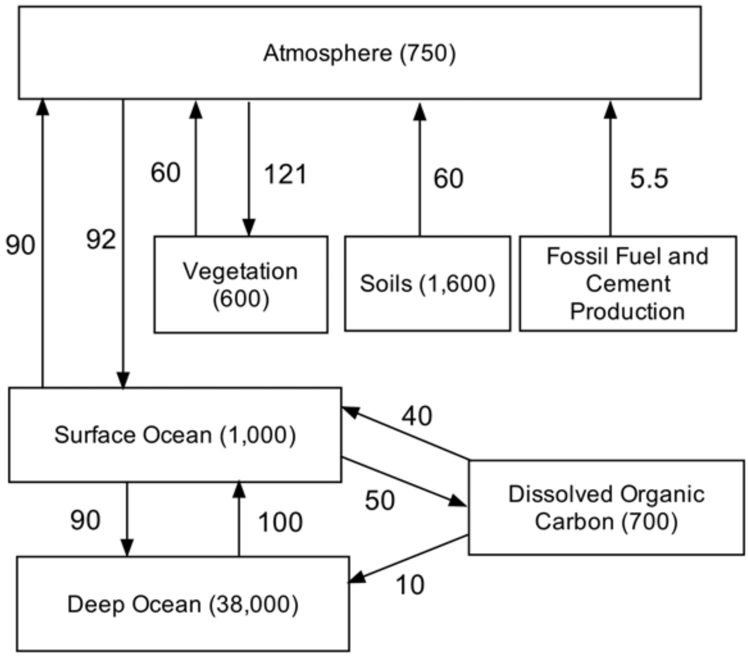

Figure 6.5. Rough estimates of carbon storage and annual carbon fluxes. Storage is in gigatons (Gt) of carbon and fluxes are in Gt/year of carbon. Ocean sediments are not shown, nor are many smaller contributors. Adapted from Northrup (2004).

small. Figure 6.5 provides a very rough simplified version of the carbon content and annual carbon fluxes in the Earth's ecosystem.

Sabine *et al.* (2004) estimated the long-term (1800–1994) and recent (1980–1999) transfers of CO_2 between the biosphere, the atmosphere, and the oceans (measured as Pg of carbon).[1] Their results are summarized in Table 6.1.

Emissions from fossil fuel burning and cement production were estimated from historical records. Storage in the atmosphere was estimated by converting measured ppm of CO_2 to Pg carbon, assuming 1 ppm CO_2 is equivalent to 2.11 Pg carbon. The uptake and storage in the oceans was estimated from ocean measurements described by Sabine *et al.* (2004). The net terrestrial balance is net amount of carbon generated by the biosphere. As can be seen from Table 6.1, this quantity is >0, indicating that the biosphere has been a net contributor of CO_2 to the environment. This net contribution is the difference between two larger numbers (emissions from land use – the terrestrial biosphere sink). Although the biosphere absorbs a great deal of CO_2, it emits even more.

Of the historical net emissions from 1800 to 1994 ($244 + 39 = 283$ Pg carbon), about 58% ended in the atmosphere and 42% ended in the oceans. For the past two

[1] 1 petagram (Pg) = 10^{15} grams.

Table 6.1. Exchange of CO_2 (Pg carbon) between biosphere, atmosphere, and oceans.

	1800 to 1994	*1980 to 1999*
(1) Emissions from fossil fuels and cement production	244 ± 20	117 ± 5
(2) Storage in the atmosphere	165 ± 4	65 ± 1
(3) Uptake and storage in the ocean	118 ± 19	37 ± 8
(4) Net terrestrial balance = (2) + (3) − (1)	39 ± 28	15
(5) Emissions from land use	100 to 180	24 ± 12
(6) Terrestrial biosphere sink = (4)—(5)	−61 to −141	-39 ± 18

decades, about half of net emissions remained in the atmosphere and half was taken up by the oceans.

Keeling (2005) suggested that the Sabine *et al.* (2004) estimates of ocean uptake of CO_2 should be slightly modified by including potential feedbacks due to ocean warming and increased stratification. For 1800 to 1994, Keeling estimated these to be −13 Pg carbon and +6 Pg carbon, for a net addition to the Sabine estimate of −7 Pg carbon. However, in a response to Keeling's comment, Sabine and Gruber claimed that such estimates are highly uncertain, and being small compared with the estimated error given in Table 6.1, need not be included until they can be resolved more accurately.

In contrast, a number of references concluded that the biosphere is (and has been) a net sink for CO_2. For example, Schimel *et al.* (2001) provided an overview of the current state of knowledge of global and regional patterns of carbon exchange by terrestrial ecosystems somewhat different from that of Sabine *et al.* (2004). Schimel *et al.* (2001) concluded that the annual emissions from fossil fuel burning and cement manufacture were roughly 6.3 Gt of carbon per year in the 1990s (in rough agreement with Table 6.1). According to Schimel *et al.* (2001) about half of this ended up in the atmosphere, about 27% ended in the oceans, and about 22% ended in plants and soil. The increase of ~3.2 Gt of carbon per year in the atmosphere during the 1990s was the culmination of a growth of about 170 Gt of carbon above the pre-industrial figure of 580 Gt of carbon in the atmosphere. This 170/580 = 29% increase in atmospheric carbon increased the atmospheric CO_2 concentration from the pre-industrial level of ~280 ppm to about 360 ppm by 1999.

The description given above is the conventional one that is widely accepted. However, this picture is not without its difficulties. In this picture the transport of huge amounts of CO_2 between the atmosphere, the oceans, and the land is so delicately balanced that the addition of a comparatively small annual CO_2 flux throws this system out of balance, resulting in growth of the CO_2 concentration in the atmosphere. As we have seen there is still uncertainty as to whether biosphere systems absorb some of the additional CO_2 or whether the biosphere is a net emitter of CO_2.

Schuster and Watson (2007) utilized a time series of observations from merchant ships between the U.K. and the Caribbean to establish the variability of sea surface $p(CO_2)$ and air-to-sea CO_2 flux from the mid-1990s to early 2000s. Two series of measurements were made, one for 15 months in 1994–1995 and one for three years in 2002–2005. However, the instrumentation was different in the two time periods. In the more recent data, they began with 180,000 data points, but because of the long lines connecting the equilibrator in the engine room to the detector some considerable distance away, they selected only 9,000 points for analysis chosen to be at the end of a line flushing period. They measured $p(CO_2)$ in the ocean (near-surface) and utilized other data for $p(CO_2)$ in the atmosphere. They found that whereas $p(CO_2)$ in the ocean changed from ~328 μatm in 1994–1995 to ~365 μatm in 2002–2005, the atmospheric $p(CO_2)$ changed from ~354 μatm in 1994–1995 to ~370 μatm in 2002–2005.[2] If these data are correct, it would suggest that the driving force for absorption of CO_2 by the ocean (the difference between $p(CO_2)$ in the atmosphere and the ocean) decreased from 26 μatm to 5 μatm in 10 years, which hardly seems likely. Other investigators (see Schuster and Watson, 2007) have found less extreme diminution of the capability of the oceans to uptake CO_2.

Falkowski *et al.* (2000) emphasized that the current high concentrations of CO_2 in the atmosphere represent "unchartered waters" that have not been seen in the past four glaciation–interglaciation cycles. However, this paper was perhaps unduly pessimistic, implying that "ample fossil fuel reserves" would lead to excessive growth of CO_2 in the 21st century (see Section 6.5 for a contrary view on fossil fuel reserves). The total of dissolved inorganic carbon (DIC) in the oceans is 50 times that of the atmosphere, and atmospheric CO_2 continuously exchanges with oceanic CO_2 at the surface at the rate of ~90 Gt of carbon per year in each direction, leading to rapid equilibration of the atmosphere with the surface water (see Figure 6.5). On dissolution in water, CO_2 forms a weak acid that reacts with carbonate anions and water to form bicarbonate. The capacity of the oceanic carbonate system to buffer changes in CO_2 concentration depends on the addition of cations from the relatively slow weathering of rocks. Because the rate of anthropogenic CO_2 emissions is several orders of magnitude greater than the supply of mineral cations, the ability of the surface oceans to absorb CO_2 will inevitably decrease as the atmospheric concentration of the gas increases over timescales of millennia. The concentration of total dissolved inorganic carbon in the ocean increases markedly below about the upper 300 m, where it remains significantly above the surface ocean–atmosphere equilibrium value in all ocean basins, as illustrated in Figure 6.5. The higher concentration of inorganic carbon in the ocean interior results from two processes.

> "Since CO_2 is more soluble in cold, saline waters, sequestration of atmospheric CO_2 in the ocean interior is controlled by the formation of cold, dense water masses at high latitudes. As these water masses sink into the ocean interior and are transported laterally, CO_2 is effectively prevented from re-equilibrating with the

[2] Here, we work with $p(CO_2)$ in units of μatm because we are considering dissolved CO_2. For atmospheric CO_2, 1 μatm is the same as 1 ppm.

atmosphere by a cap of lighter overlying waters. Re-equilibration occurs only when waters from the ocean interior are brought back to the surface, decades to several hundreds of years later. Coupled climate–ocean simulations suggest that CO_2-induced global warming will lead to increased stratification of the water column. If this occurs, the transport of carbon from the upper ocean to the deep ocean will be reduced, with a resulting decrease in the rate of sequestration of anthropogenic carbon in the ocean. The combined effects of progressive saturation of the buffering capacity and increased stratification will weaken two important negative feedbacks in the carbon–climate system.''

> ''Biological processes also contribute to the absorption of atmospheric CO_2 in the ocean. Phytoplankton photosynthesis lowers the partial pressure of CO_2 in the upper ocean and thereby promotes the absorption of CO_2 from the atmosphere. Approximately 25% of the carbon fixed in the upper ocean sinks into the interior, where it is oxidized through heterotrophic respiration, raising the concentration of dissolved inorganic carbon (DIC)'' (Falkowski *et al.*, 2000).

Thus, on timescales of centuries, decreased solubility of CO_2 with increasing ocean temperature is counteracted by biological processes. According to Falkowski *et al.* (2000):

> ''There are significant gaps in our knowledge that limit our ability to predict the magnitude of changes in oceanic uptake, but the likely changes in the biological pump are too small to counteract the projected CO_2 emissions in the coming century.''

However, the ''projected CO_2 emissions in the coming century'' may be greater than fossil fuel resources can supply (see Section 6.5). Nevertheless, Falkowski *et al.* (2000) concludes:

> ''If our current understanding of the ocean carbon cycle is borne out, the sink strength of the oceans will weaken, leaving a larger fraction of anthropogenically produced CO_2 in the atmosphere or to be absorbed by terrestrial ecosystems.''

Terrestrial ecosystems remove CO_2 from the atmosphere through photosynthesis and organic matter storage. It is returned to the atmosphere via a number of respiratory pathways as well as fire, in which large amounts of organic matter are oxidized in very short periods of time. Terrestrial carbon storage primarily occurs in forests. The turnover time of terrestrial carbon is on the order of decades. The activity of plants to remove CO_2 increases with the CO_2 concentration, but is believed to saturate between 800 ppmv and 1,000 ppmv CO_2. Falkowski *et al.* (2000) suggest that this ''concentration will probably be reached early in the next century at the present emissions rate. Because the saturation function decreases as CO_2 increases, terrestrial plants will become less of a sink for CO_2 in coming decades.'' However, as Section 6.5 indicates, it is unlikely that such high levels of CO_2 will be reached.

"The combined effects of higher CO_2 concentrations, higher temperatures, and changes in disturbance and soil moisture regimes lead to considerable uncertainty about the ability of terrestrial ecosystems to mitigate against rising CO_2 in the coming decades. However, recent results from long-term soil warming experiments in a boreal forest contradict the idea that the projected rise in temperature is likely to lead to forests that are now carbon sinks becoming carbon sources in the foreseeable future. Again, as in the case of marine ecosystems, we can predict that the negative feedback afforded by terrestrial ecosystems in removing anthropogenic CO_2 from atmosphere will continue; however, the sink strength will almost certainly weaken. The exact magnitude of the change in sink strength remains unclear" (Falkowski *et al.*, 2000).

6.1.3 CO_2 variations in glacial–interglacial cycles

Ice core records of CO_2 reach back as far as 420,000 years. These records have been used to examine the changes in atmospheric CO_2 concentration as the Earth evolved through the past four ice ages interspersed with interglacial periods.

Ice core records have low time resolution. The gas occlusion process takes a considerable time, resulting in smearing of the time periods over which gases are trapped in the ice. According to Ehrelinger, Cerling, and Dearing (2005), "There are still open questions about the reliability of the CO_2 record." The difference in age between the trapped CO_2 and the ice in which it is trapped can be several hundred to several thousand years. The CO_2 in Greenland ice cores are consistently higher than those from Antarctica, and since atmospheric CO_2 is well mixed, at least one of these must be in error. Apparently spurious variations in the Greenland data suggest that the Antarctic records provide the most reliable data (Ehrelinger, Cerling, and Dearing, 2005).

A number of studies of ice cores from Antarctica have shown that the CO_2 concentration rise (or fall) lags the temperature rise (or fall) that occurs during periods of increased glaciation or warming. The time lag was estimated to be $\sim$500 years by Roper (2006), 800 ± 200 years by Caillon *et al.* (2003), 1,300–5,000 years by Mudelsee (2001), "several thousand years" by Petit *et al.* (1999), 800 years by Monnin *et al.* (2001), and 400–1,000 years by Fischer *et al.* (1999). That would seem to imply that increased CO_2 is an effect—not a cause—of temperature change in this region. Siegenthaler *et al.* (2005) reported on two deep ice cores from East Antarctica. One of the cores was the only ice core covering at least eight glacial cycles, four cycles longer than previously available from ice cores. This allowed them to reconstruct the record of the concentration of atmospheric CO_2 much further back in time than was possible before, over the interval between 390,000 and 650,000 YBP. Analyzing the air extracted from ice cores is the only way to directly determine atmospheric greenhouse gas concentrations for times before routine atmospheric measurements were begun. Antarctic ice cores are claimed to be very suitable for CO_2 measurements because of their low temperatures and low concentrations of impurities, which minimize the risk of artifacts, and it is asserted that Antarctic ice cores are reliable recorders of atmospheric CO_2. In addition, the concentration of deuterium was interpreted as a proxy for temperature. By shifting the timescales of the entire CO_2 and deuterium records between 390,000 and 650,000 YBP relative to each other, they obtained the best correlation for a lag of CO_2 of 1,900 years.

A number of naysayers seized on these observations with enthusiasm to argue against rising CO_2 concentration as a cause of global warming; instead, they claim that rising temperatures (from some other cause) produce increasing CO_2 concentrations. It is well known that the capacity of the oceans to hold CO_2 diminishes as the temperature increases. However, the rise (or fall) of CO_2 actually preceded temperature changes in the far north, so the situation is more complicated than the naysayers seem to realize.

Caillon *et al.* (2003) discussed the use of ice cores to provide detailed records of local temperature and atmospheric concentrations of greenhouse gases in the past. Analyses of the Vostok ice core in Antarctica show that concentrations of carbon dioxide correlate well with Antarctic temperature throughout the last four climatic cycles, with glacial–interglacial CO_2 increases of 80 ppmv to 100 ppmv. Determining the mechanisms that cause these variations is important for understanding climate change, but the explanation for the strong link between atmospheric CO_2 and Antarctic air temperature is still unclear. One reason for this uncertainty is that the relative timing of temperature and CO_2 changes is not easily obtained and thus obscures the phasing of gas variations with climate signals borne by the ice. An approach to circumvent this difficulty proposed by Caillon *et al.* (2003) used records of atmospheric CO_2 content and temperature (based on ^{40}Ar content) contained only in the trapped gases. Although they believed their procedure is valid, they admitted that they "don't clearly understand the underlying mechanisms." Nevertheless, their result was that CO_2 increases and peaks at a shallower depth in the ice core than ^{40}Ar. They concluded that in a post-glacial warming period, the atmospheric CO_2 lags Antarctic warming by 800 ± 200 years.

Caillon *et al.* (2003) concluded that CO_2 is not the forcing that initially drives the climatic system during a deglaciation. Rather, deglaciation is probably initiated by some as-yet unclear forcing (possibly solar?) with positive feedback that influences first the temperature change in Antarctica (and possibly in part of the Southern Hemisphere), and then the increase in CO_2 in the Southern Hemisphere. According to Caillon *et al.* (2003) this sequence of events is still in full agreement with the idea that CO_2 plays, through its greenhouse effect, a key role in amplifying the initial orbital forcing that they suggest is solar-generated. First, the 800-year time lag is short in comparison with the total duration of the increases in temperature and CO_2 ($\sim$5,000 years) in a post-glacial warming. Second, it is shown that the CO_2 increase clearly precedes the Northern Hemisphere deglaciation. However, the initiation of the deglaciation step may require a random occurrence of climate factors amplified by a positive feedback mechanism. The putative role of the Sun in this is speculative. It appears that CO_2 may be controlled in large part by the climate of the Southern Ocean. Although there is not yet clear support for this assertion, a delay of about 800 years is claimed to be a reasonable time period to transform an initial Antarctic temperature increase into a CO_2 atmospheric increase through oceanic processes.

Ahn and Brook (2007) estimated a time lag for CO_2 to follow temperature changes of 720 ± 370 years.

In contrast to the previous discussion, a recent paper (Loulergue *et al.*, 2007) claimed that:

> "The phase relationship between CO_2 and ice core temperature inferred at the start of the last deglaciation (lag of CO_2 by 800 ± 600 yr) is overestimated and that the CO_2 increase could well have been in phase or slightly leading the temperature increase at the EPICA Dome C."

Soon (2007) provides an extensive review of what is known and theorized regarding the roles of carbon dioxide climate forcing and Earth orbit variations in past glacial–interglacial cycles. It was concluded that varying levels of minor greenhouse gases like CO_2 and CH_4 do not appear to have been a significant factor in glacial–interglacial temperature changes or large variations in global ice volume. He suggests that persistent orbitally moderated irradiance forcing and/or variations in innate solar irradiance exceed the global radiative forcings of CO_2 and CH_4 by several fold, and that regional responses to solar irradiance forcing are the principal drivers of water vapor cycling, together with cloud-and-ice insulator and albedo feedbacks. A host of other forcings and feedbacks, including dust and aerosol forcings, oceanic circulation, and vegetation cover feedbacks require further study. However, it was admitted that "there are still questions about how orbital forcings explain glaciation and deglaciation over the past few million years." Nevertheless, the conclusion was: "the popular notion of CO_2 and CH_4 radiative forcing as the predominant amplifier of glacial–interglacial phase transitions cannot be confirmed."

In a recent paper, Peacock, Lane, and Restrepo (2006) analyzed the variations of CO_2 concentration in glacial–interglacial cycles over the past 430,000 years. It was emphasized that there is no consensus on the underlying cause of the 80 ppm–100 ppm variation in the roughly 100 kyr glacial–interglacial cycles in CO_2 atmospheric pressure (pCO_2). The inability of any proposed single mechanism to explain the observed cycles in pCO_2 (which show considerable similarity over the past 430,000 years) led them to consider a combination of mechanisms. They pointed out that physical changes (ocean circulation, temperature, mixing) can only explain part of the observed atmospheric pCO_2 variability, so they invoked changes in ocean chemistry to explain the remainder. In their model, they distinguish three phases in the glacial–interglacial cycles: glacial, intermediate, and interglacial. Physical changes in the ocean (mixing, temperature) account for interglacial-to-intermediate transitions. The transition from intermediate to glacial involves a small increase in mean ocean nutrient levels and mean ocean alkalinity, accomplished by falling sea level and subsequent erosion of organic-rich shelf sediments.

> "The first part of the transition out of full glacial conditions is achieved through increased temperature and increased mixing in the Southern Ocean. The final part of the atmospheric pCO_2 rise up to full interglacial conditions is accomplished through rising sea level and the subsequent change in mean ocean alkalinity and

phosphate, and a rise in the Northern Hemisphere temperature and ocean mixing.''

They claimed that they were able to explain the full magnitude of the glacial–interglacial cycle in atmospheric pCO_2. However, their explanation is not unique and represents only one possible rather contrived explanation, yet to be substantiated. This is a very lengthy, complex paper that only a specialist can follow in detail. It demonstrates how complex the processes are for CO_2 exchange between the oceans and the atmosphere during glacial–interglacial conditions.

> Nevertheless, it is clear that varying CO_2 levels are a consequence of glacial–interglacial cycles and not a cause.

There is no consensus on the causes of glacial–interglacial CO_2 changes. There are at least 11 hypotheses, which may be grouped into three basic themes: (i) physical/chemical ''reorganization'' of the oceans, (ii) changes in the ocean carbonate system, and (iii) changes in ocean nutrient inventories. However, many of these hypotheses are not mutually exclusive. The interactions between marine and terrestrial ecosystems, changes in ocean circulation, radiative forcing, and greenhouse gases all probably interact in a specific sequence to give rise to the natural cyclic atmospheric and climatic oscillations. These interactions are not adequately represented in detailed models of glacial–interglacial transitions. The scientific community has generally approached glacial–interglacial transitions from a disciplinary perspective. This approach has not produced completely satisfactory explanations for what is clearly a large natural perturbation in the global carbon cycle. Clearly, a systems approach is needed (Falkowski *et al*., 2000).

Studies have also been made over the more recent Holocene period. Kouwenberg and Ria (2005) and Kouwenberg *et al.* (2005) pointed out that:

> ''An increasingly applied method to detect and quantify short-term fluctuations in Holocene CO_2 levels is the analysis of stomatal frequency of fossil leaves derived from peat and lake deposits. For a wide variety of tree species, there is observational and experimental evidence of an inverse relation between numbers of leaf stomata and ambient CO_2 concentration. Adjustment of stomatal frequency to changes in atmospheric CO_2 allows plants to retain the most profitable balance between carbon uptake for photosynthesis and loss of water through evaporation. Quantification of CO_2 responsiveness of individual tree species over the last century enables estimation of Holocene CO_2 levels by measuring stomatal frequency of fossil leaves. So far, stomata-based CO_2 reconstructions for the Holocene have mainly been derived from fossil leaves of broad-leaved trees and shrubs. However, because of the long-term dominance of conifers in temperate and boreal forest ecosystems, the use of fossil conifer needles could greatly improve the spatial and temporal coverage of such reconstructions.''

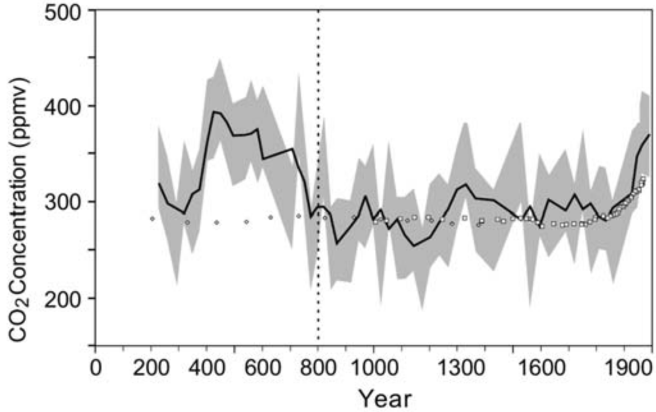

Figure 6.6. Reconstruction of paleo-atmospheric CO_2 levels based on stomatal frequency of fossil needles. Black line represents a three-point running average based on 35 needles per depth. Gray area indicates the uncertainty in the calibration. White diamonds and squares are measured data in ice cores. Adapted from Kouwenberg and Ria (2005) and Kouwenberg *et al.* (2005).

Kouwenberg and Ria (2005) and Kouwenberg *et al.* (2005) then went on to say that conifer needles were largely neglected after initial studies had suggested that stomatal frequency of conifers would not adjust to CO_2 mixing ratios above 280 ppmv. However, it was indicated that this observation was due to inadequate stomata quantification methods because conifers exhibit a different (more complex) mode of leaf development and subsequent epidermal morphology than the broad-leaved trees commonly used for stomatal frequency analysis. They developed an improved quantification strategy, to enable conifer needle stomata to act as a viable proxy for CO_2 concentration, and thereby obtain high-resolution CO_2 reconstructions for the Late Holocene. Their result is shown in Figure 6.6.

Kouwenberg and Ria (2005) and Kouwenberg *et al.* (2005) were concerned about the validity of their data on two counts: (a) disagreement with ice core data prior to 800, and (b) disagreement of their CO_2 data with *hockey stick* temperature profiles prior to 800. They argued that the ice core data tend to be smoother because they involve a much wider swath of times in each sample that tends to flatten out variations. However, they were unable to explain the significant differences prior to 800. They were also at a loss on how to relate their findings prior to 800 with *hockey stick* temperature profiles, and in the end, they said:

> "Since the reconstructed enhanced CO_2 levels between 300 and 750 AD are incongruent with global climate changes, the extremely low stomatal frequency of *T. heterophylla* in this period is unlikely to reflect pronounced changes in the global atmospheric CO_2 regime."

However, they were unaware of the inaccuracy of the *hockey stick* in this period, and perhaps should not have been so insecure about their results. The results shown in

Figure 7.6 indicate diametrically opposite viewpoints. On the one hand, the ice core data suggest an essentially flat profile for 2,000 years; on the other hand, the data on stomatal frequency of conifers suggest considerable variation in CO_2 levels during that period. Neither record shows a significant decrease during the LIA. It is not clear which, if any, should be believed.

6.1.4 CO_2 and global warming

As we saw in Section 5.4, global climate models estimate that global average temperatures are strongly affected by CO_2 concentration in the atmosphere, and models typically predict a temperature rise of about 3°C for an increase of CO_2 concentration from 280 ppm to 560 ppm, or in other terms, an increase of about 0.01°C for each ppm increase of CO_2. However, since the GCMs predict that the dependence of temperature rise on CO_2 concentration is logarithmic, it is not the difference in CO_2 concentration—but the ratio of concentrations—that matters. Thus, GCMs predict (on average) that when the CO_2 concentration doubles the temperature rise due to the greenhouse effect will be about 3°C. In other words

$$\Delta T = X \frac{\mathrm{CO_2\ final}}{\mathrm{CO_2\ initial}},$$

where the coefficient X is predicted by climate models to be roughly 1.5.

We also know (or more properly it is widely believed) that the global average temperature increased by ~0.6°C during a period when the CO_2 concentration in the atmosphere increased from 280 ppm to 380 ppm. This allows us to solve for the coefficient on the right side of the above equation

$$0.6 = X \frac{380}{280}$$

in order to fulfill the equality. Solving for X, we find $X = 0.44$. Thus, the observed change in temperature over the past century attributed to the rise in CO_2 by modelers is considerably less than what would be predicted by GCMs. However, modelers could well argue that the effects of aerosols and land use have mitigated the putative rise in temperature from greenhouse gases.

We saw in Figure 6.4 that the measured concentration (from ice cores) varied from about 190 ppm to 280 ppm between an ice age and an interglacial period. According to Leroux (2005), the difference in temperature between an ice age and an interglacial was about 10°C in the Antarctic and about 6°C globally. This corresponds to

$$7.0 = X \frac{280}{190}$$

$$X = 4.1.$$

Hence, the temperature change from ice age to interglacial was far greater than GCMs would predict based on the variation of CO_2 concentration.

Leroux made the important point that if an increase in CO_2 concentration was the cause of deglaciation from an ice age, and if GCMs are reasonably accurate, then one would expect (based on GCMs) that a change of 90 ppm in CO_2 concentration would have produced a change in global average temperature far smaller than 6°C. The predicted temperature increases from both the GCMs and the observations of the past century are far too low compared with the actual temperature changes that occurred between ice ages and interglacials. So, we have a major conflict. The ice age–deglaciation cycle and the last 100 years had similar changes in CO_2 concentration—but vastly different changes in temperature (Leroux, 2005).

There is a major conflict between the facts that, on the one hand, moderate changes in CO_2 concentration were associated with very large temperature changes during past ice age–interglacial cycles, while, on the other hand, there currently is a huge increase in CO_2 concentration compared with past interglacials, but not much difference in temperature. The putative relationship between CO_2 concentration and temperature is inconsistent.

In a similar vein, if the ice core measurements of CO_2 over the past millennium (Figure 6.2) are reasonably accurate, the changes in CO_2 concentration seem to be far too small compared with the suspected temperature changes during the MWP and the LIA. Perhaps the temperature changes during the MWP and LIA were small; alternatively, the data in Figure 6.2 may not be reliable (or at least they may be so smeared out in years that fluctuations are severely damped).

6.2 PROJECTIONS OF FUTURE CO_2 CONCENTRATION BY CLIMATOLOGISTS

A serious concern of global climate alarmists is that future fossil fuel usage may generate a great deal more CO_2 than the Earth can absorb, leading to higher CO_2 levels in the atmosphere, increasing the greenhouse effect, and raising world temperatures. The historical variation of CO_2 concentration in the atmosphere was shown in Figure 6.1. The CO_2 concentration has been advancing at the rate of roughly 1.8 ppm per year. Since the current CO_2 concentration is about 375 ppm, it would take about 100 years for the CO_2 concentration to double (from the pre-industrial level of $\sim$275 ppm) if the rate remained unchanged. On the other hand, the rate of CO_2 production might change in the future. If one assumes that future growth in CO_2 concentration will not remain constant at 1.8 ppm/year but will increase at its present percentage gain rate of 0.5% per year, then it would take about 70 years for the CO_2 concentration to double.

Various models to predict the future climate of the Earth have been based on widely different estimates of future CO_2 emissions in the 21st century, as shown in Figure 6.7.

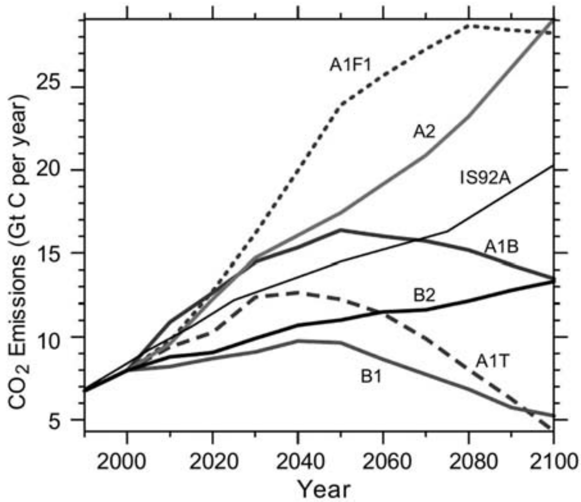

Figure 6.7. Range of projected future annual CO_2 emissions from various models (Gt/yr of carbon). Adapted from IPCC (2001).

The widely used IS92a projection (made by the IPCC in 1992 as a "business as usual" scenario) leads to annual carbon emissions that continue to increase through the 21st century from 6 gigatons per year in 1990 to 19 gigatons/year in 2100, even though the projection for carbon emitted per unit energy consumed included a significant decline over that period. This is due to the fact that the projection had a greater increase in total energy consumed (due to a burgeoning population using increasingly more mechanization) than the decline in carbon emission per unit energy consumed. It was not specified exactly how the world would go about producing ever more energy, while generating the decline in carbon emitted per unit energy consumed. A feature of IS92a worth noting is that the share of carbon-intensive coal, relative to less carbon-intensive natural gas and oil, rises after 2025, but the carbon emitted per unit energy consumed of the fuel mix declines overall, which implies a massive introduction of carbon-free energy sources.

The resultant CO_2 concentrations in the atmosphere from emissions from various models are shown in Figure 6.8. The heavier curves show future CO_2 concentration if the future CO_2 concentration grows at the compounded rate of 0.5%/year, or if future CO_2 grows at the fixed rate of 1.8 ppm/year. It can be seen that some of the models assume much greater future growth of the CO_2 concentration.

Hoffert *et al.* (1998) did not specify the ultimate rise in CO_2 concentration that results from the IS92a projection, but it appears to be at least 1,000 ppm by 2100. Hoffert *et al.* (1998) estimated the reductions in carbon emissions per year needed to stabilize the CO_2 concentration at various levels by 2100 as shown in Figure 6.9, based on the stabilization paths of Wigley, Richels, and Edmonds (1996). It is evident that IS92a leads to a CO_2 concentration greater than 1,000 ppm toward the end of the 21st century. To achieve lower CO_2 concentrations, emissions must be significantly lower.

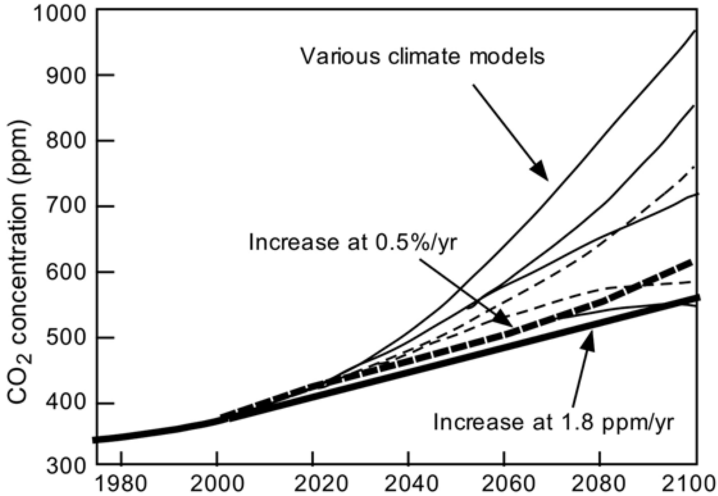

Figure 6.8. Various models for future CO_2 concentration in the 21st century. Adapted from IPCC (2001).

In order to stabilize the ultimate future CO_2 concentration in the atmosphere at some specific level, the annual emission rate must be controlled as shown in Figure 6.9. Clearly, the higher projections in Figure 6.7 are incompatible with controlling CO_2 concentration.

The increase in CO_2 concentration in the industrial era was shown in Figure 6.1. Comparing Figures 6.1 and 6.4, it may appear that the CO_2 concentration is headed ever upward in the 21st century. Climatologists tend to be extrapolators. Taking trends from the past, they project forward into the future, often without regard to the constraints of finite resources. Figure 6.7 shows the range of possible future CO_2

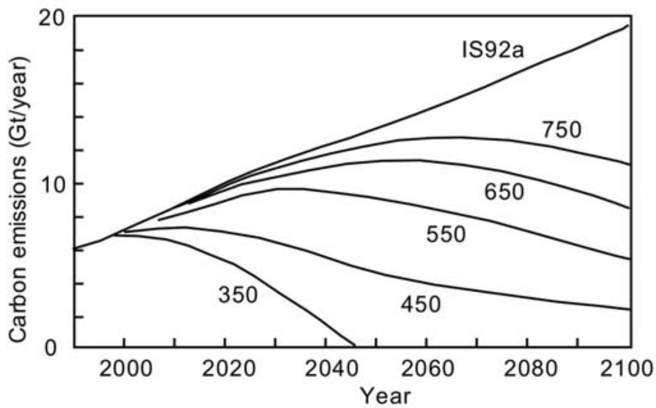

Figure 6.9. Carbon emissions per year needed to stabilize CO_2 concentration in the atmosphere at various levels of ppm. Adapted from Hoffert *et al.* (1998).

emissions that has been used by climatologists to predict future global warming. Many extrapolations involve huge future CO_2 emissions. Rutledge (2007) provides an even greater selection of 40 models, some of which yield carbon emissions rising as high as 36 Gt/yr, and 17 of which have higher emissions in 2100 than in 2005. It is not clear what assumptions (if any) were made regarding fossil fuel resources in making these extrapolations. However, the sources of CO_2 in the atmosphere are mainly oil, gas, and coal, and all three of these have already been heavily exploited, leaving constrained resources remaining for future development.

6.3 PROJECTIONS OF FUTURE GLOBAL TEMPERATURE RISE DUE TO CO_2

A common thread among papers that predict future climate change is estimation of the expected global temperature rise if the CO_2 concentration in the atmosphere doubles in the future. It is not always clear in these papers whether they mean doubling from the pre-industrial level (about 275 ppm) or doubling from the current level (375 ppm), but it seems likely that most papers deal with doubling from pre-industrial levels to a future level of about 550 ppm.

In addition, Chylek, Box, and Lesins (2004) estimated the sea level change due to doubling of CO_2 concentration in the atmosphere, and Adams, Maslin, and Thomas (1999) estimated the effect on polar ice of doubling of CO_2 concentration in the atmosphere. Hence, "doubling of CO_2 concentration in the atmosphere" has become a consistent and repetitive mantra for those predicting future climate change, and a widely accepted—but not necessarily credible—predicted increase in temperature from such a doubling appears to be roughly 3°C.

Global climate models are used to estimate the "forcing" of the atmosphere due to greenhouse gases. The forcing is an equivalent heat input (W/m^2) to the top of the atmosphere. The climate models then convert this forcing to a change in atmospheric temperature near the Earth's surface.

Hansen *et al.* (1998) described three scenarios for the forcing (see Figure 6.10) used by workers who predict future climate change:

> "Scenarios A, B, and C differ in assumed growth rates of greenhouse gases and in the presence or absence of large volcanic eruptions. Specifically, Scenario A assumed that CO_2 and other trace gases would continue to increase exponentially at rates characteristic of the preceding 25 years, and it was assumed that there would be no very large volcanic eruptions. Scenario A was designed to reach the equivalent of doubled CO_2 by about 2030 ... Scenario B had a slower, approximately linear, growth rate of greenhouse gases, reaching the equivalent of doubled CO_2 at about 2060. Scenario B also included occasional cooling from large volcanic eruptions, specifically with eruptions in 1995 and 2015. Scenario C had the same volcanoes as in scenario B but a still slower growth rate of greenhouse gases with a stabilization of greenhouse gas abundances after 2000."

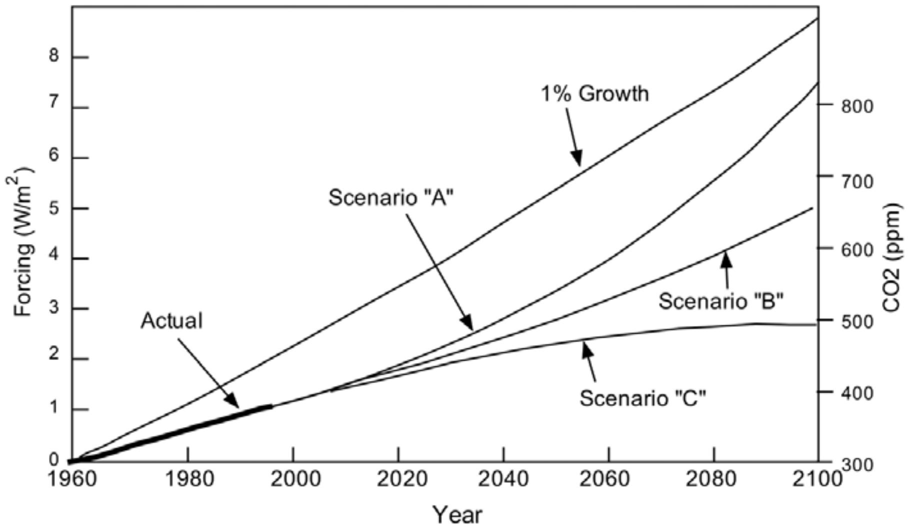

Figure 6.10. Scenarios for future atmospheric forcing by CO_2 build-up. Adapted from Hansen *et al.* (1998).

However, there seems to be a typo in the description of Scenario C since CO_2 is not fully stabilized until about 2080.

Hansen *et al.* (1998) said:

> "The CO_2 growth rate increased rapidly until the late 1970s, more than doubling in 15 years. But the growth rate has been flat in the past 20 years, despite moderate continued growth of fossil fuel use and a widespread perception, albeit unquantified, that the rate of deforestation has also increased. Apparently the rate of uptake by CO_2 sinks, either the ocean, or, more likely, forests and soils, has increased. Although flattening of the CO_2 growth rate may be in part a figment of inter-annual and inter-decadal variability, nevertheless, it emphasizes our ignorance of the factors controlling changes of the carbon cycle ... Climate forcing by greenhouse gases in the real world has been falling far short of the '1% CO_2' transient scenario, which is an idealized greenhouse gas scenario sometimes used for transient climate change studies. Indeed, the actual greenhouse forcing is only about half of that for '1% CO_2 [annual increases]'. The main conclusion we draw is an optimistic one. The slowdown of greenhouse climate forcing growth rates suggests that there is an opportunity to avoid the more rapid rates of climate change in the 21st century. Even the equivalent of doubled CO_2 climate forcing is not inevitable. Certainly it is conceivable for developing countries to maintain 3% annual growth of CO_2 emissions for a century, should they strap economic growth tightly to increased fossil fuel use, and for the developed world to maintain 1% annual growth for a century, should they mimic economic growth and fuel use trends of the United States in the 1990s. But common sense suggests that

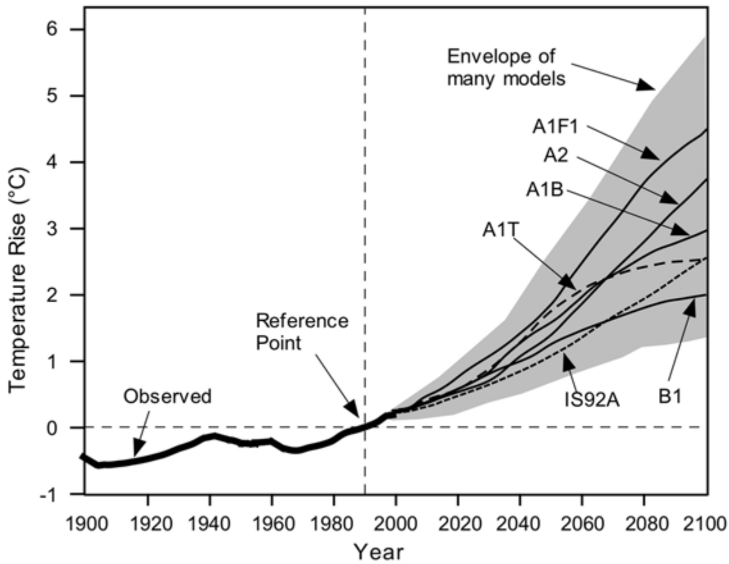

Figure 6.11. Range of projected future temperature increases. Adapted from IPCC (2001).

reasonable attention to climatic consequences, along with technological developments in energy efficiency and alternative energy sources, will render Scenario A undesirable and improbable. A more prudent and likely near-term course is in the range of Scenarios B and C, which yield an added greenhouse forcing of $1\,W/m^2$ in 30–40 years."

It is noteworthy that Hansen *et al.* (1998) are not skeptics—but leading activists—for climate control, and even they cautioned against unreasonable projections of future CO_2 forcing. In fact, even Scenario C is likely to be an overestimate of CO_2 forcing due to depletion of fossil fuels in the 21st century (see Section 6.5).

Using global climate models, scientists have projected future global temperature increases for various models of future CO_2 generation. Figure 6.11 shows a range of future projections. However, as we pointed out previously, even projection IS92a involves a higher production rate of CO_2 than is likely, and this is one of the lowest projections!

6.4 ENERGY AND CLIMATE IN THE 21ST CENTURY

Hoffert *et al.* (1998) analyzed the requirements to provide the world with needed energy while keeping a lid on ultimate CO_2 levels. In their formulation, the rate of emission of carbon to the atmosphere as CO_2 is the product of four terms.

(1) World population
(2) Gross domestic product (GDP) per person averaged for the world

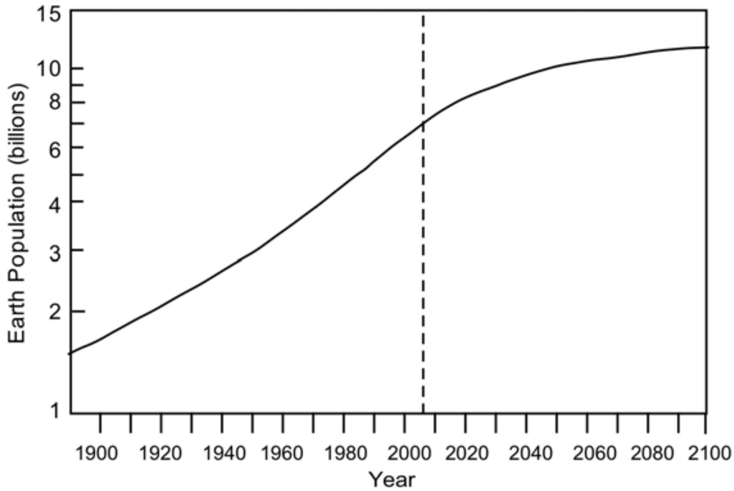

Figure 6.12. Projection of world population made by IS92a. Adapted from Hoffert *et al.* (1998).

(3) Energy required by the world per unit of GDP
(4) Mass of carbon emitted per unit energy consumed.

They utilized a baseline of the so-called "IS92a" projection made by the IPCC in 1992 as a "business as usual" scenario, and then departed from there to various constraints on CO_2 production.

The IS92a projection of world population is shown in Figure 6.12 with an estimated world population of 5.3 billion in 1990, a population of ~6.6 billion in 2006, and an eventual plateau of 11.4 billion at the end of the 21st century. The GDP per person was estimated by IS92a to be U.S.$4,100 in 1990 and was projected to increase at around 1.6% per year through the rest of the 21st century. The energy per unit GDP was estimated by IS92a to be 0.49 Watt-years per U.S.$ in 1990 and was (optimistically) projected to decrease at the rate of 1% per year through the remainder of the 21st century. The IS92a projection for mass of carbon emitted per unit energy consumed is shown in Figure 6.13. This model evidently builds in an implicit departure from fossil fuels, as well as increases in efficiency, leading to a steadily decreasing carbon factor with time.

Hoffert *et al.* (1998) did not specify the ultimate rise in CO_2 concentration that results from the IS92a projection. They estimated the reductions in carbon emissions per year needed to stabilize the CO_2 concentration at various levels by 2100 as was shown in Figure 6.9. It seems evident from Figure 6.7 that IS92a leads to a CO_2 concentration greater than 1,000 ppm. To achieve lower CO_2 concentrations, emissions must be reduced significantly.

> "Stabilizing atmospheric CO_2 at twice pre-industrial levels while meeting the economic assumptions of 'business as usual' implies a massive transition to carbon-free power, particularly in developing nations" (Hoffert *et al.*, 1998).

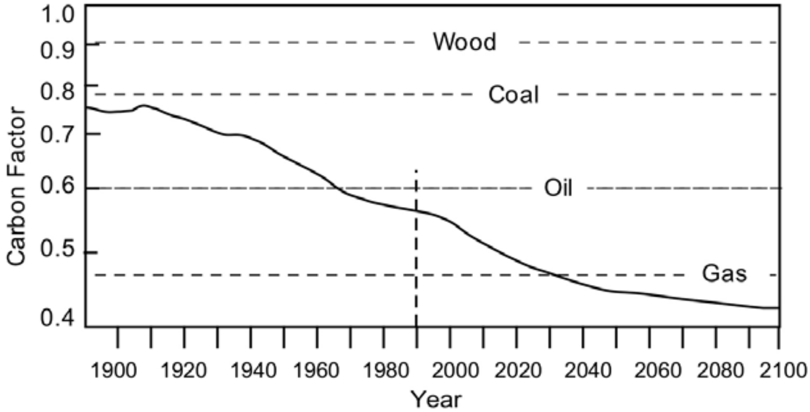

Figure 6.13. Projection by IS92a of "carbon factor" = kg of carbon emitted per Watt-year of energy generated in the 21st century. Adapted from Hoffert *et al.* (1998).

Lightfoot and Green (2002) estimated the required rate of world average annual energy intensity decline required to stabilize the level of CO_2 in the atmosphere at some level, such as 550 ppm in 2100 (about double the pre-industrial level). However, their projections of energy mix and energy efficiency for 2100 seem very optimistic.

The present world population of about 6.6 billion may grow to 11 billion by 2100. As prosperity expands, people will want to use more energy per capita. This burgeoning world population will seek a better life by consuming more energy per capita. Most of these people have a major goal in life to emulate the lifestyle of Americans, which entails using energy at a rate comparable with that of Americans. There is no way that they can be successful. The U.S. has about 5% of the world's population and uses about 20% of the world's energy. If the people of the world emulated Americans, world energy usage would increase by a factor of 4. Increasing population would drive energy usage still higher. World primary power consumption in 2006 was ~12 TW, of which ~85% was fossil-fueled. By 2050, world power demand may grow to as much as 30 TW. By 2100, it will likely be considerably higher. The main problem facing humankind in the 21st century is providing itself with these enormous energy requirements. If one were to assume that oil, gas, and coal resources are unlimited, and fossil fuels were produced in sufficient quantity to supply the impending demand during the 21st century with a mix typical of today, carbon emissions during the 21st century would be very high and the threat of global warming would likely be significant. If the role of coal increases in the 21st century, which will exacerbate the problem because coal has a higher carbon content than oil or gas per unit energy produced. However, the estimated fossil fuel resources remaining are limited. Hydrocarbon production will likely top out before 2025 and coal production will likely top out around 2030. Assuming that greenhouse gas emissions are limited in the 21st century by the available fossil fuel resources, emissions will peak by 2025–2030. The ultimate run-out to depletion of fossil resources would just be enough to double the CO_2 concentration, but it seems likely that this may never occur because energy

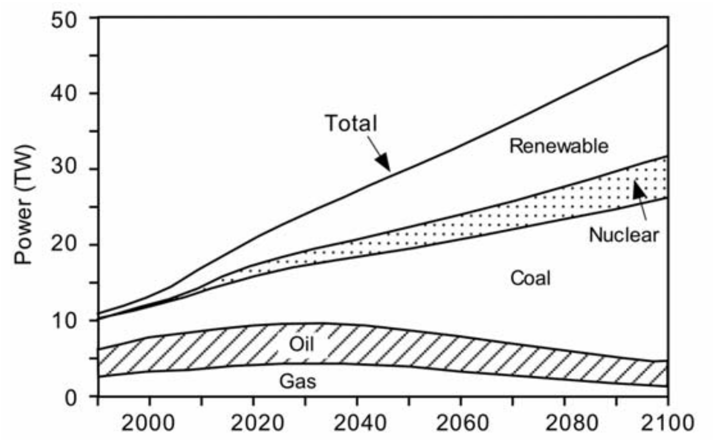

Figure 6.14. Energy mix for generation of electric power in the 21st century assumed by IS92a projection.

production in the second half of the 21st century will have to undergo significant changes as fossil fuel production (and consumption) inevitably pursues an increasingly downward trend.

The widely used IS92a projection is based on the energy mix for electric power generation shown in Figure 6.14. The heavy reliance on coal leads to very high carbon emissions as shown in Figure 6.13.

The world will face a crisis sometime around or after 2030. But that crisis will not be calamitous global warming. The crisis will be that with oil, gas, and coal production going at full bore, the world will not able to supply the energy that is demanded. This could lead to significantly higher energy costs, resulting in worldwide economic recession or depression. However, on the positive side, it provides the incentive to develop renewable energy to become more competitive. Whether renewable energy can be developed and expanded rapidly enough to stave off economic collapse remains to be seen. Alternatively, Idso and Idso (2007) has proposed a massive increase in the use of nuclear power, glossing over the problems inherent in such a strategy.

Hoffert *et al.* (2002) emphasized that the problem of stabilizing the CO_2 levels in the atmosphere relates to energy:

> "In the 20th century, the human population [of the Earth] quadrupled and primary power consumption increased 16-fold."

Creating a transition toward such stabilization will require reductions in energy use as well as development of primary energy sources that do not emit carbon dioxide to the atmosphere. Mid-century primary power requirements that are free of carbon dioxide emissions could be several times what we now derive from fossil fuels ($\sim 10^{13}$ watts), even with projected improvements in energy efficiency. Hoffert *et al.* (2002)

surveyed potential future energy sources with emphasis on their capability to supply massive amounts of carbon emission–free energy. These included terrestrial solar and wind energy, solar power satellites, biomass, nuclear fission, nuclear fusion, fission–fusion hybrids, and fossil fuels from which carbon has been sequestered. They also studied nonprimary power technologies that could contribute to climate stabilization include efficiency improvements, hydrogen production, storage and transport, superconducting global electric grids, and geo-engineering. They concluded that all of these approaches currently have severe deficiencies that limit their ability to stabilize the production of CO_2. Furthermore, they suggested that the IPCC (and many others) are overly optimistic regarding the potential for advanced energy technologies to quickly reduce CO_2 emissions significantly. Their conclusion was that we need a drastic expansion of research on renewable energy.

Anon. (J) provides a number of commentaries on Hoffert *et al.* (2002). Some of these came to the defense of their energy technologies (particularly solar-thermal and nuclear) but these appear to be self-serving to some degree. Several comments had to do with the role of energy conservation. Professor Albert Bartlett said:

> "Even without the greenhouse problems, the obvious impossibility of continuing these [past energy] growth rates would lead rational people to say that ... the world's first order of business should be to stop the growth of populations and the growth of per capita primary power consumption. Instead of advocating the obvious, the authors paint a picture of all manner of technological fixes that, at enormous expense, may provide some answers to the need to stop the growth in emissions of greenhouse gases that are associated with energy production. As is so often the case, technological fixes are offered without being reviewed in the light of Eric Sevareid's Law: 'The chief cause of problems is solutions.' One can be sure that each technological solution will create new problems that are not indicated by calculations, equations, and technical speculations."

The U.S. Government is currently placing major emphasis in their energy research on a hydrogen economy. Zubrin (2007) quotes a Secretary of Energy who said:

> "We envision a future economy in which hydrogen is America's clean energy choice—flexible, affordable, safe, domestically produced, used in all sectors of the economy, and in all regions of the country ... Environmental pollution will no longer be a concern. Every nation will have all the energy it needs available within its borders ... The sources of hydrogen are abundant. The more you have of something relative to demand for that, the cheaper it's going to be, the less expensive it'll be for the consumer ... One of the greatest results of using hydrogen power, of course, will be energy independence for this nation ... If we develop hydrogen power to its full potential, we can reduce our demand for oil by over 11 million barrels per day by the year 2040."

In the words of Robert Zubrin: "Its all bunk." Zubrin then goes on to describe alternative processes for producing, storing, and using hydrogen and shows clearly

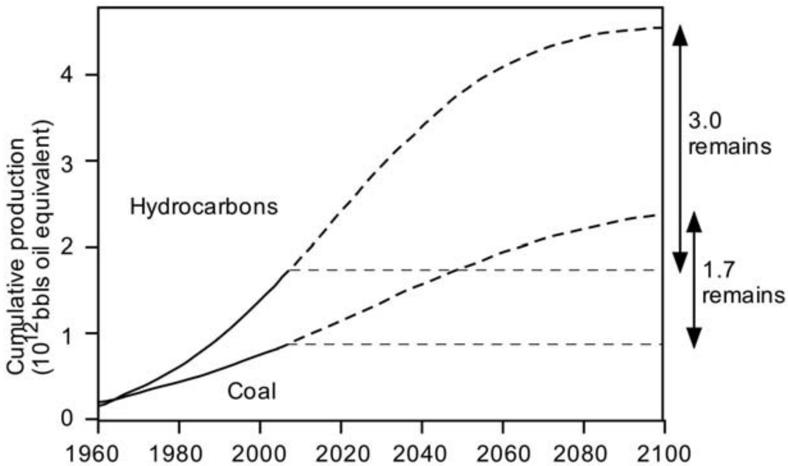

Figure 6.15. Estimated cumulative production of hydrocarbons (oil, natural gas, and natural gas liquids) and coal to date, and projected ultimate production by 2100. Adapted from Rutledge (2007).

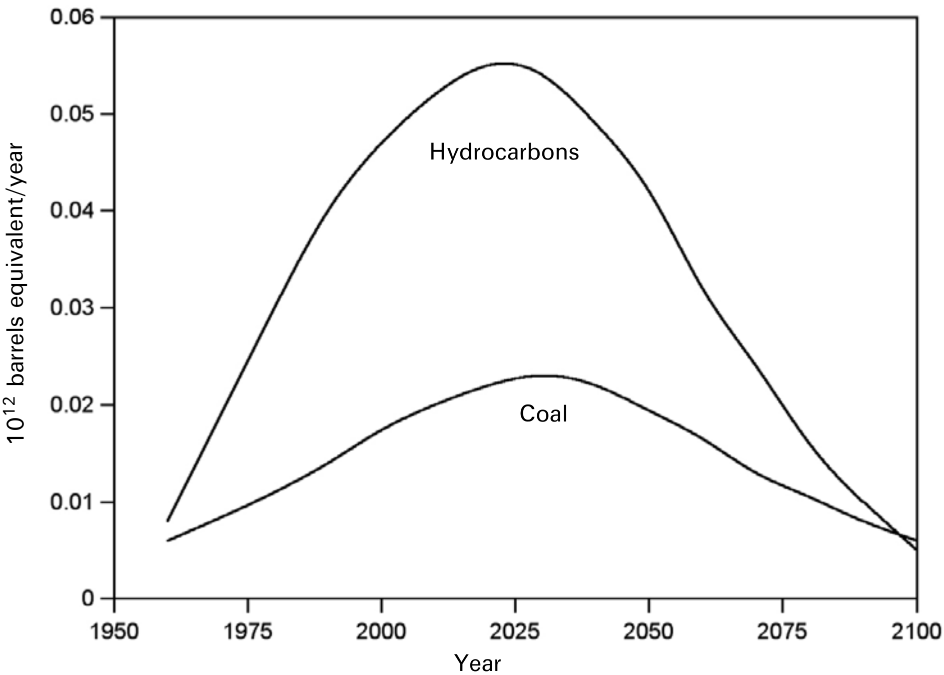

Figure 6.16. Estimated annual production of hydrocarbons (oil, natural gas, and natural gas liquids) and coal to date, and projected ultimate production by 2100. From Rutledge (2007).

that the whole concept of a hydrogen economy is impractical and costly (Zubrin, 2007).

6.5 CONSTRAINTS ON CO_2 PRODUCTION IMPOSED BY THE LIMITS OF FOSSIL FUELS

The increase in CO_2 concentration in the atmosphere from the pre-industrial estimate of ~275 ppm to the present value of ~375 ppm shows that there has been an increase of about 100 ppm. In this period, the world burned a great deal of fossil fuel. Now we must ask how much fossil fuel remains and what is the probable limit to future CO_2 concentration in the atmosphere from burning the available fossil fuels in the 20th century?

Deffeyes (2001) provided an analysis of probable U.S. and world oil reserves. The best estimate is that cumulative world oil production will eventually reach about 2.1×10^{12} barrels, and the world has already produced roughly half that amount. U.S. oil production was estimated at around 0.22×10^{12} barrels, and about 85% of that has already been consumed. Oil isn't the only fossil fuel; there are also natural gas, natural gas liquids, and coal. It was estimated that world production of total hydrocarbons (oil, gas, and gas liquids) may approach 4.5×10^{12} barrels of oil (equivalent), and the world has already produced roughly 38% of that amount. These resources are finite and significant fractions of their initial endowments in the Earth have already been exploited (Rutledge, 2007).

A simplistic analysis would suggest that since burning ~38% of the world's fossil fuels has increased the CO_2 concentration in the atmosphere by about 100 ppm,

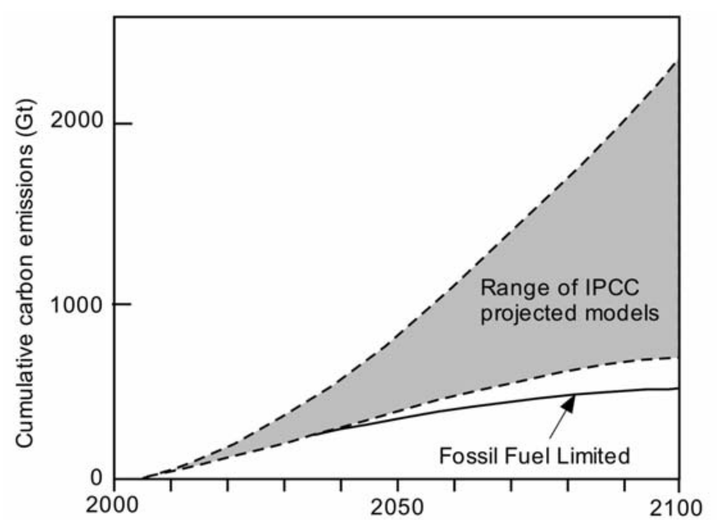

Figure 6.17. Comparison of cumulative CO_2 emissions based on fossil fuel constraints with the range of IPCC projections for future CO_2 emissions. From Rutledge (2007).

burning the remainder is likely to add another ~150 ppm, bringing the ultimate level to perhaps 525 ppm by the end of the 21st century, at which time the world will have only small amounts of recoverable fossil fuels remaining. This suggests that Scenario C in Figure 6.10 and Scenario B1 are more likely than the other scenarios in Figures 6.7 and 6.11 as fossil fuels become depleted. There may be barely enough fossil fuel to "double the CO_2 concentration in the atmosphere" (relative to pre-industrial levels), and all the climatologists who continue to deal with a quadrupling of CO_2 appear to be working in fantasy.

Estimation of future production of fossil fuels is a tricky business that requires extrapolation from past data. Rutledge (2007) has done a good job of analyzing the (admittedly sketchy) available information and projecting forward to the future. Figure 6.15 shows the expectation for future cumulative production of fossil fuels extrapolated from current levels. Figure 6.16 shows the annual production rates corresponding to the cumulative rates in Figure 6.15 (Figure 6.16 is just the slope of Figure 6.15).

Rutledge (2007) has estimated CO_2 emissions based on a production rate limited by the finite resources as indicated in Figures 6.15 and 6.16. This is compared with the range of projections made by the IPCC in Figure 6.17. It can be seen that most projections of future CO_2 emissions are overly generous in their implied estimate of remaining fossil fuel resources.

7

Impacts of global warming

7.1 GLOBAL-WARMING ALARMISTS

In Ionescu's play *Rhinoceros* written for the theater of the absurd, he explores the pressures on people to conform to trends and adopt expanding belief systems. As more and more people turn into rhinos, the pressure to conform by doing likewise becomes intense. Today, we witness just such a pressure on politicians, scientists, and the public to jump on the global-warming bandwagon. Even George W. Bush, who in his tenure as President of the United States has opposed every single effort to legislate even the most mild and moderate steps to improve or protect the environment, has begun to weaken on global warming in 2007. Former Vice-President Gore led a national campaign to raise consciousness about the dangers of global warming, based heavily on the *hockey stick* model. His efforts netted him the Nobel Peace Prize. The United Nations, through its Inter-governmental Panel on Climate Change (IPCC) has similarly taken an alarmist position, also dependent on the *hockey stick*. The Union of Concerned Scientists, and a number of U.S. governmental agencies have taken similar positions. In addition, quite a large number of scientists have also become very concerned regarding the potential impacts of global warming.

"Global warming" encompasses a range of viewpoints. Clearly, we are in the midst of an interglacial period characterized by a general warming trend, although temperatures today appear to be lower than the maximum reached in the Holocene about 6,000 years ago (see Section 1.3). In the last century, surface temperatures were rising (see Figure 3.6). Global warming is a fact, although there are regional variations (see Figure 3.9); the temperature increase in the U.S. has been minimal (see Figure 3.4), and see Section 3.2.3 on Arctic and Antarctic temperatures. What is not known is the degree and extent to which the current warming trend is a natural fluctuation in the Earth's climate, perhaps partly due to variations in solar irradiance, ocean currents, urban heat islands, and other non-greenhouse factors, vs. global warming being primarily due to greenhouse gas emissions. However, we do know that TSI variations have been small since about 1980.

One piece of circumstantial evidence in this regard is the question of whether such fluctuations in the Earth's climate have occurred before in the past millennium or two. If the current warming trend is extreme and unprecedented, that would suggest that the greenhouse gas influence may be significant. On the other hand, if significant temperature fluctuations occurred in the past, the present trend may be just another such fluctuation. This argument is not ironclad but it is suggestive. There is considerable evidence that there have been fluctuations during the entire Holocene period (see Figure 1.15) and that temperatures in the past have exceeded current temperatures in some periods. There is also evidence that there were indeed periods known as the LIA and the MWP during the last millennium, with temperatures during the MWP similar to those of today. Furthermore, it is known that the Sun exhibited rather different sunspot characteristics during the LIA compared with today. However, the alarmists, relying on the *hockey stick* model, would argue that the MWP never occurred and the LIA was merely a small fluctuation localized in Europe. The *hockey stick* temperature profile shows the temperature rise during the 20th century to be unique against a flat background of a thousand years of small fluctuations. Unfortunately, the *hockey stick* profile is clearly wrong (see Section 2.2.3).

IPCC (2001) presents an alarmist view of global warming, adopting the *hockey stick* picture, and ignoring all the evidence to the contrary. For example, the IPPC Report said:

> "The warming shown in the instrumental observations over the last 140 years is larger than that over a comparable period in any of the multi-century control simulations carried out to date. If the real world internal variability on this time-scale is no greater than that of the models, then the temperature change over the last 140 years has been unusual and therefore likely to be externally forced. This is supported by paleo-reconstructions of the last six centuries,[1] which show that the 20th century warming is highly unusual. Three of the five years (1995, 1996 and 1998) . . . are the warmest globally in the instrumental record, consistent with the expectation that increases in greenhouse gases will lead to sustained long-term warming. When anthropogenic factors are included, models provide a plausible explanation of the changes in global mean temperature over the last hundred years."

The 2001 IPCC Report also said:

> "The 1990s are likely to have been the warmest decade of the millennium in the Northern Hemisphere and 1998 is likely to have been the warmest year."

None of these claims hold up under scrutiny, as was shown in Section 2.4.

[1] Here, the IPCC refers to the various MBH publications that derived the *hockey stick*.

The alarmists depend on global climate models that predict the temperature rise that will result from future increases in greenhouse gas concentration. In particular, the common feature of these models has been the estimate of the expected temperature rise from a doubling of CO_2 concentration. Many such estimates have been made. A typical IPCC range of projections for future temperatures is shown in Figure 6.11. These projections ignore the limits on the availability of fossil fuels. The wide swath of resultant estimates attests to the uncertainties inherent in such models. But even if we accept some median estimate, the question arises as to whether there is enough fossil fuel remaining in the world to produce a doubling of CO_2, and based on Hubbert's peak analyses, such a doubling appears unlikely (Deffeyes, 2001).

The 2001 IPCC Report provides not merely 1—but 19—separate chapters on the impacts of global warming, comprising over 1,000 pages of descriptions of impacts. It is difficult to summarize this huge body of material. Table 7.1 lists a number of potential climate disasters in IPCC (2001). The other 999+ pages of the IPCC Report amplify this theme.

While many global-warming alarmists have based their arguments on *hockey stick* models, and projections of future CO_2 generation that are unsupportable by natural resources, leading to predictions of dire consequences, Dr. James E. Hansen stands out as a more credible alarmist. He acknowledges that projections of future warming are unduly pessimistic and suggests that future temperature increases will not be as great as many of the predictions indicate. But he claims that giant ice sheets can disintegrate by mechanical means and thus be seriously reduced by even moderate increases in temperature. These arguments must be taken seriously.

The Real Climate blog (*http://www.realclimate.org*) provides the alarmist view of global-warming impacts. This website is clearly maintained by technically capable people but their objectivity seems doubtful (see Section 2.3.2).

On April 26, 2007, James E. Hansen (perhaps the most well-known and well-respected global-warming alarmist) gave testimony on the dangers of global warming to the Select Committee of Energy Independence and Global Warming of the U.S. House of Representatives. Hansen provided the case for alarmists in considerable detail. Only a few quotations are given here.

According to Hansen, the greatest near-term danger is sea level rise. He said that "sea level is already rising at a rate of 3.5 cm per decade and the rate is accelerating" due primarily to "ice sheet disintegration." He said: "there is increasing realization that sea level rise this century may be measured in meters if we follow business-as-usual fossil fuel emissions," and that "adaptation to a continually rising sea level is not possible." According to Hansen, "increasingly rapid changes on West Antarctica and Greenland ... are truly alarming."

One of the major slow feedback processes that Hansen identifies is "the effect of warming on emissions of long-lived greenhouse gases," caused by the "melting of tundra in North America and Eurasia," which "is observed to be causing increased ebullition of methane from methane hydrates."

Hansen said: "continued business-as-usual greenhouse gas emissions threaten many ecosystems," and that "very little additional [climate] forcing is needed ... to cause the extermination of a large fraction of plant and animal species."

Table 7.1. Impacts of global warming according to IPCC (2001).

Projected changes during the 21st century in extreme climate phenomena and their likelihood	*Representative examples of projected impacts*
Higher maximum temperatures; more hot days and heat waves over nearly all land areas (very likely)	Increased incidence of death and serious illness in older age groups and urban poor Increased heat stress in livestock and wildlife Shift in tourist destinations Increased risk of damage to a number of crops Increased electric cooling demand and reduced energy supply reliability
Higher (increasing) minimum temperatures; fewer cold days, frost days, and cold waves over nearly all land areas (very likely)	Decreased cold-related human morbidity and mortality Decreased risk of damage to a number of crops, and increased risk to others Extended range and activity of some pest and disease vectors Reduced heating energy demand
More intense precipitation events (very likely over many areas)	Increased flood, landslide, avalanche, and mudslide damage Increased soil erosion Increased flood runoff could increase recharge of some floodplain aquifers Increased pressure on government and private flood insurance systems and disaster relief
Increased summer drying over most mid-latitude continental interiors and associated risk of drought (likely)	Decreased crop yields Increased damage to building foundations caused by ground shrinkage Decreased water resource quantity and quality Increased risk of forest fire
Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities (likely over some areas)	Increased risks to human life, risk of infectious disease epidemics, and many other risks Increased coastal erosion and damage to coastal buildings and infrastructure Increased damage to coastal ecosystems such as coral reefs and mangroves
Intensified droughts and floods associated with El Niño events in many different regions (likely)	Decreased agricultural and rangeland productivity in drought- and flood-prone regions Decreased hydro-power potential in drought-prone regions
Increased Asian summer monsoon precipitation variability (likely)	Increased flood and drought magnitude and damages in temperate and tropical Asia
Increased intensity of mid-latitude storms (little agreement between current models)	Increased risks to human life and health Increased property and infrastructure losses Increased damage to coastal ecosystems

He also said: "Earth's history shows that climate is remarkably sensitive to global forcings" and that "positive feedbacks predominate," causing "the entire planet to be whipsawed between climatic states."

Summarizing, Hansen said: "The dangerous level of CO_2 is at most 450 ppm, and it is probably less ... Ignoring the climate problem at this time, for even another decade, would serve to lock in future catastrophic climatic change and impacts that will unfold during the remainder of this century and beyond." The Earth "is close to dangerous climate change, to tipping points of the system with the potential for irreversible deleterious effects ... The planet is on the verge of dramatic climate change." We "are forced to find a way to limit atmospheric CO_2 more stringently than has generally been assumed ... We cannot shrink from our moral responsibilities ... to preserve the planet for future generations."

Idso and Idso (2007) reviewed this testimony and provided a commentary and critique (see end of Section 7.2).

7.2 GLOBAL-WARMING NAYSAYERS

Several groups and institutions have risen to challenge the claims of the global-warming alarmists. Singer and Avery (2007) and Monckton (2006) reached conclusions that appear to be based on incomplete data and models to support their view that climate warming is a fiction. Since very little in the field of global warming is ironclad, it is not difficult to find errors in and objections to the claims of alarmists. And just as a lawyer seeks to build a case by selecting out those elements of evidence that favor his client's interests, so have these naysayers prepared their cases with the evident intent of reaching a pre-ordained conclusion that global warming is a fiction. The National Center for Public Policy Research is just one of several organizations devoted to impugning global warming (see Marsh, 2001, for example).

It is unfortunate that the global climate alarmists have provided so much ammunition to the naysayers by (1) adopting the *hockey stick* that is clearly wrong, (2) issuing dire warnings of improbable future cataclysmic outcomes, and (3) setting up the poorly conceived Kyoto Protocol.

Singer and Avery (2007) is a typical naysayer document. The thesis of the book is that the Earth undergoes 1,500-year cycles and we are in the midst of the warming trend in this cycle, and it "appears likely that warming will continue for some time into the future, perhaps 200 years or more, regardless of human activity." Thus, in one fell swoop, all evidence to the contrary is swept aside, and it is argued that we are simply a cork bobbing on a cyclic ocean beyond our control (or influence). But this is not too surprising since Singer and Avery (2007) are associated with the National Center for Policy Analysis, a right-wing, reactionary, quasi-evangelist organization that puts belief ahead of data. While this entire book is based on the hypothesis that a 1,500-year cycle rules our climate, no evidence for the 1,500-year cycle is actually presented. Several quotations from articles purporting to find the 1,500-year cycle are given but no data are shown. Indeed, the National Center for Policy Analysis runs a website entitled: "The Physical Evidence of Earth's Unstoppable 1,500-Year Climate Cycle," but amazingly enough, no actual physical evidence is presented! Singer and

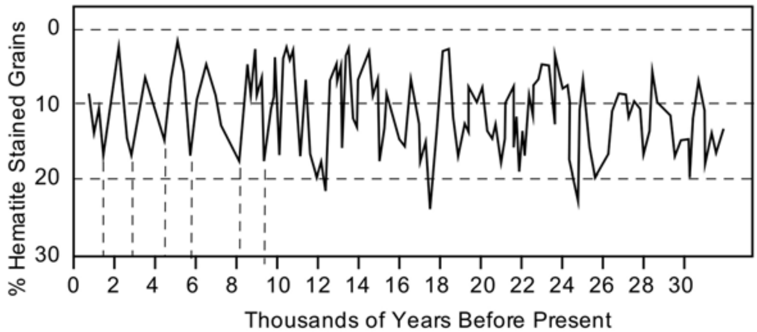

Figure 7.1a. Indication of 1,500-year cycle during the Holocene. Adapted from Bond *et al.* (1997).

Avery (2007) base their use of the putative 1,500-year cycle implicitly on Bond *et al.* (1997, 2001), Debret *et al.* (2007), and others. These references utilize evidence from northern deep-sea ice cores that contain *lithic grains* presumably transported by *ice-rafting* during warm periods as glaciers carry rubble to the sea embedded in icebergs that transport this material south where they are deposited. While the above references make some liberal claims that were seized on by Singer and Avery (2007) to support their pre-conceived thesis, when the data in Bond *et al.* (1997, 2001) are actually examined, the argument does not appear so ironclad to this writer. While Figure 7.1a is provocative, Figures 7.1b and 7.1c from a later publication by the same group are far less convincing. Other references that report data on the putative 1,500-year cycle include Bianchi and McCave (1999) and Rohling *et al.* (2002). And even if one adopts the 1,500-year cycle for ice-rafting, the actual implication for global climate remains vague.

The blog *http://www.climateaudit.org* presents considerable counter-evidence to the alarmist point of view (see Section 2.3.1).

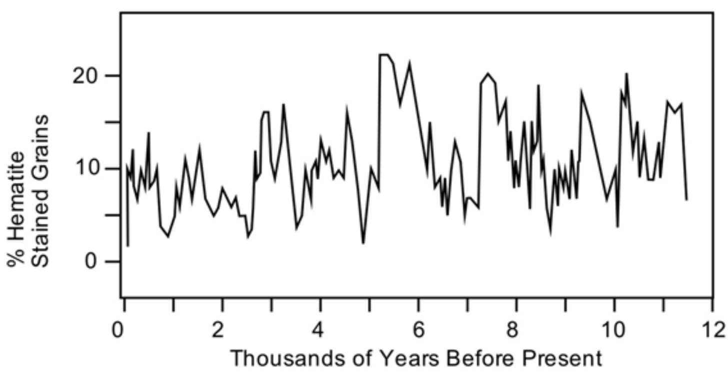

Figure 7.1b. Ice raft data during the Holocene. Adapted from Bond *et al.* (2001).

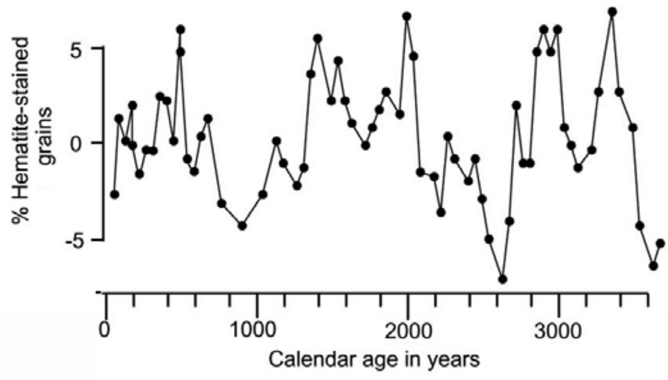

Figure 7.1c. Ice raft data during recent millennia. Adapted from Bond *et al.* (2001).

Leroux (2005) is a major work, comprising about 500 pages on global climate change. It disputes the alarmist view that greenhouse gases are causing the current warming, and by implication, minimizes predictions of future impacts. However, the objectivity of this book is uncertain.

The *http://www.co2science.org* blog provides a number of articles in the naysayer camp. Of greatest interest is the critique of James Hansen's congressional testimony given by Idso and Idso (2007). Some brief quotes from Hansen's testimony are given at the end of Section 7.1.

The main topics in Idso and Idso (2007) were the principal topics addressed by Hansen: (1) ice sheet disintegration, (2) sea level trends, (3) atmospheric methane concentrations, (4) climates of the past, (5) predicted warming-induced extinctions of terrestrial plants and animals, (6) the CO_2-induced preservation of terrestrial species, and (7) predicted CO_2-induced extinctions of calcifying marine organisms. In addition, they discussed a number of other topics that Hansen addressed in less detail, including (1) positive vs. negative climate feedbacks, (2) effects of drought on agriculture in a CO_2-enriched world, (3) sea level rise over the next hundred years, (4) the adaptability of living organisms to rising sea levels, (5) the "dangerous" level of atmospheric CO_2, (6) the magnitude of climate forcing due to a doubling of the air's CO_2 content, (7) empirical evaluations of Earth's climate sensitivity, (8) the ability of man to control global climate, (9) the need to act now to reduce CO_2 emissions, and (10) the role of morality in the debate over what to do—or not do—about anthropogenic CO_2 emissions.

Idso and Idso (2007) provided point-by-point arguments in rebuttal to most of Hansen's claims. In regard to sea level rise, the data in Section 7.3 suggest a slower rise than Hansen indicated, and the probability of disintegration of ice sheets in the 21st century appears to be exaggerated. While Idso and Idso (2007) dismiss Hansen's concerns out of hand, the consequences of such an eventuality are so profound that it must be considered seriously even if it is improbable.

While Hansen was concerned about release of methane from methane hydrates as polar areas warm up, Khalil, Butenhoff, and Rasmussen (2007) showed that the

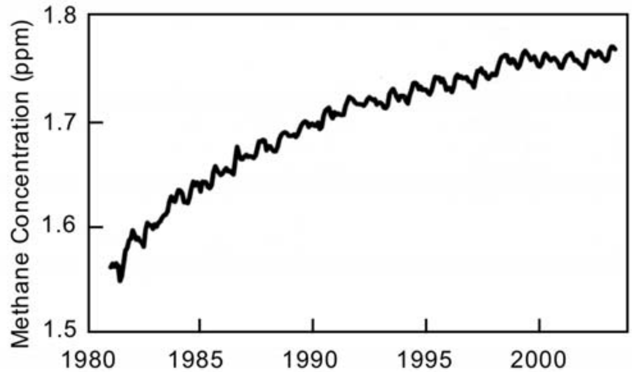

Figure 7.2. Variation of atmospheric methane concentration over the past ~25 years. Adapted from Khalil, Butenhoff, and Rasmussen (2007).

methane concentration in the atmosphere reached a plateau in the 1990s and is no longer increasing. Figure 7.2 suggests that the trend in atmospheric methane concentration, "has been decreasing for the last two decades until the present when it has reached near zero," and that "it is questionable whether human activities can cause methane concentrations to increase greatly in the future" (Khalil, Butenhoff, and Rasmussen, 2007). Idso and Idso (2007) capitalized on this short-term improvement to conclude that there is no long-term problem, but the long term remains uncertain.

Idso, Idso, and Idso (2003) and Idso and Idso (2007) provide rebuttals to Hansen on the claims of "extermination of a large fraction of plant and animal species." This material is beyond the scope of this book and the reader is referred to the Idso reports for details.

It is particularly noteworthy that Hansen was quoted as saying: "the dangerous level of CO_2 is at most 450 ppm, and it is probably less." If that were the case, humanity appears to be lost. With a current CO_2 concentration of ~383 ppm, and annual increases of about 2 ppm per year, we will likely reach 450 ppm in roughly the next 35 years, and it seems most unlikely that any action by the world community can prevent this without economic disaster.

7.3 SEA LEVEL RISE AND THE GREENLAND AND ANTARCTIC ICE SHEETS

Dr. James Hansen is widely regarded as a leading expert on global climate change. According to Dr. Hansen:

> "The dominant issue in global warming, in my opinion, is sea-level change and the question of how fast ice sheets can disintegrate" (Hansen, 2004).

The issues involved in contemplating the effect of global warming on sea level rise illustrate the complexity and uncertainty involved in predicting the future.

Douglas and Peltier (2002) discussed many aspects of measurements of sea level rise and fall. At the height of the last glacial maximum, ~21,000 years ago, so much of the Earth's water was tied up in great high-latitude ice sheets that the oceans were about 120 meters lower than they are today. Compared with those of previous millennia, the changes in global sea level (GSL) occurring today are tiny. The GSL increased by about 120 m as a result of the deglaciation that followed the last glacial maximum. By about 5,000–6,000 YBP (years before present), the melting of the great high-latitude ice masses was essentially completed. Thereafter, the GSL rise was small, and appears to have almost ceased by 3,000-4,000 YBP (Douglas and Peltier, 2002).

According to Singer and Avery (2007), when the great ice sheets began to melt at the end of the last period of glaciation, the initial rapid rise of sea level was about 200 cm per century. This gradually changed to a slower rate of rise (15 cm–20 cm per century) about 7,500 years ago, once the large ice masses covering North America and North Europe had melted away. But the slow melting of the West Antarctic Ice Sheet continued and will continue, barring another ice age, until it has melted away perhaps 6,000 years from now. This means that the world will continue to endure a sea level rise of about 18 cm per century (1.8 mm per year), just as it has been in previous centuries. And it is likely that there is nothing we can do about it. Thus, Singer and Avery (2007) attribute the continuing slow sea rise to the natural consequences of the post-glacial period but make no allowance for anthropogenic global heating adding to this rather bland picture. However, they seem to be predisposed to reject all arguments for anthropogenic-induced global warming.

Douglas and Peltier (2002) pointed out that the measurements of relative sea level (RSL) at any location have large annual and decadal fluctuations that tend to obfuscate the long-term trends with noise. Consequently, only very long–term records can accurately provide the underlying trend. A CNES analysis showed that use of only four decades of data at the tide gauge sites led to an overestimate of the GSL rise. Other studies showed that the extreme dependence of trend on record length is real, and not an artifact of the tide gauge. To remain accurate over periods of a century or more, tide gauges,which over time may be repaired, moved, upgraded, and so on, must be kept consistent. But tide gauges, no matter how accurate and consistent, make local measurements. And they measure only relative sea level with respect to the surface of the solid Earth. Without independent estimates of vertical land movement, tide gauges cannot determine whether the water level is rising, the land is sinking, or both. Even though most estimates of the GSL rise made in the past decade or so have used records that are as long as possible, the various estimates still differ significantly. The origin of the differences probably lies in the methods used to correct for vertical land movements at tide gauge sites. Hence, all data on sea level rise must be examined critically.

According to Hoffman (1984):

> "Future global sea level will depend primarily on three factors: (1) the total quantity of water filling the oceans' basins; (2) the temperature of the oceans' layers, which determines the density and volume of their waters; and (3) the

bathymetry (shape) of the ocean floor, which determines the water-holding capacity of the basins. A rise in global temperature can, by a variety of physical mechanisms, transfer snow and ice from land to the sea, increasing the quantity of water in the ocean basins, and can raise the oceans' temperatures, causing the thermal expansion of their volumes. Changes in the bathymetry of the oceans' floors occur independently of climate change. Because geological changes in the ocean floor could not raise or lower global sea level by more than a centimeter or two by 2100, this factor is not considered in constructing global scenarios. An evaluation of the impacts of sea level rise at specific coastal sites, however, will require consideration of local uplift or subsidence, which by 2100 could cause changes in land elevation that are large enough to be of significance to local planning. Projecting sea level rise requires the means to estimate future changes in atmospheric composition, to relate these changes to global warming, and then to determine how the warming can cause land-based snow and ice to enter the sea and the oceans to expand thermally."

Lombard *et al.* (2005) found large oscillations in decadal changes in sea level due to the El Niño–Southern Oscillation and the Pacific Decadal Oscillation, and cautioned against extrapolating short-term sea level data from satellite measurements.

Jevrejeva *et al.* (2006) also found significant oscillations in sea level with periodicities ranging up to 30 years. For the period 1993–2000, they found a sea level rise of 2.4 ± 1.0 mm/year, comparable with the value they estimated for 1920–1945. Since the period 1993–2000 was during an uptrend in the oscillatory pattern, the longer term value will presumably be lower.

Holgate and Woodworth (2004) estimated the sea level rise from 1952 to 1997 (55 years) based on 177 tide gauges divided into 13 regions with near global coverage, and using a Glacial Isostatic Adjustment model to correct for land movements. Sea level rise over these 55 years was estimated to have averaged 1.7 ± 0.2 mm/year, although the curve showed periodic oscillations. Furthermore, the curve of sea level vs. time seemed to be accelerating upward in the 1990s. In a more recent study, Holgate (2007) chose nine long and nearly continuous sea level records from around the world to explore rates of change in sea level for 1904–2003. The lack of high-quality, long-life gauge records was circumvented by finding representative gauges that matched the data for 1952 to 1997 when more data were available. These records were found to capture the variability found in a larger number of stations over the last half-century studied in their 2004 paper. The addition of new data not only extended the time period back to 1904, but it also extended the time period forward to 2003. The new results indicated that the apparent acceleration noted in the 1990s tailed off and now appears to have just been another oscillation, while the extended curve indicated that the rate of rise of sea level was slightly higher early in the century than it was later in the century. It should be noted that a number of papers have been bandied about regarding the TOPEX-POSEIDON result that the rise in sea level from 1993 to 2003 was 3.0 mm/year (e.g. Shepherd and Wingham, 2007), and Hansen claims it is 3.5 mm/year, but it now seems clear that this was just part of an upward cycle and cannot and must not be extrapolated. For the century as a whole, the

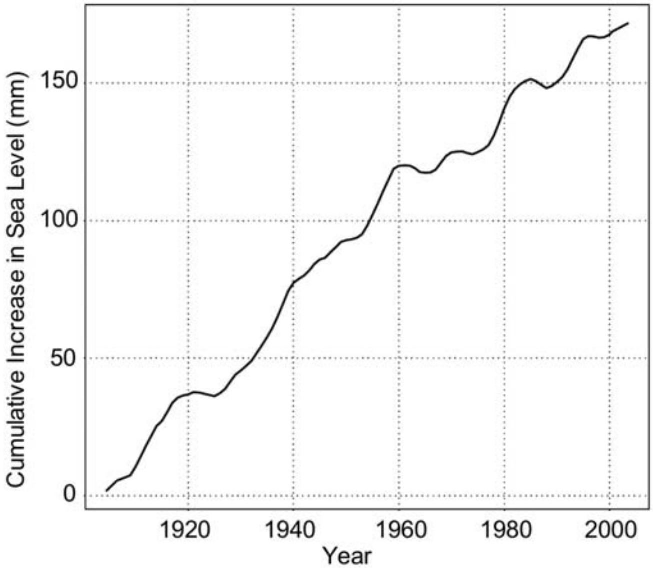

Figure 7.3. The mean sea level record from the nine tide gauges over the period 1904–2003 based on the decadal trend values for 1907–1999. Adapted from Holgate (2007).

average rate of rise was 1.7 mm/year, but for the first part of the century is was 2.0 mm/year and for the latter part of the century it was 1.45 mm/year. The cumulative curve is shown in Figure 7.3.

The contribution of melting ice sheets to sea level rise was estimated by Shepherd and Wingham (2007). They estimated that the East Antarctica Ice Sheet (EAIS) is gaining some 25 Gt/year, the West Antarctica Ice Sheet (WAIS) is losing about 50 Gt/year, and the Greenland Ice Sheet (GIS) is losing about 100 Gt/year. These trends provide a modest contribution to sea level rise of about 0.35 mm/year. However, these short-term results should not be extrapolated because of the oscillatory behavior of ice sheet loss.

While measurements of sea level appear to be problematic, estimates have been made of the amounts of ice contained in the great ice sheets on Greenland and Antarctica. If the volumes of ice at these sites diminish, and it is assumed that the lost ice appears in the oceans as liquid water, the sea rise resulting from any volume change in ice can be estimated (360 Gt of ice is equivalent to ~1 mm of sea level). Alley *et al.* (2005) estimated that for Greenland, between 1993/1994 and 1998/1999, the ice sheet lost 54 Gt per year of ice, equivalent to a sea level rise of ~0.15 mm/year (the excess of melt water runoff over surface accumulation was about 32 Gt/year, leaving ice flow acceleration responsible for a loss of ~22 Gt/year).

Rignot and Kanagaratnam (2006) used satellite radar interferometry observations of Greenland to detect widespread glacier acceleration below 66°N between 1996 and 2000, which rapidly expanded to 70°N in 2005. Accelerated ice discharge in the west and particularly in the east doubled the ice sheet mass deficit in the last decade from 90 km^3 to 220 km^3 per year. This provides a less optimistic outlook for Greenland.

Divine and Dick (2006) found evidence of persistent ice retreat in the Arctic since the second half of the 19th century. However, it was not clear whether this was a trend that will continue, or whether it was part of a cycle (“a similar shrinkage of ice cover was observed in the 1920s–1930s, during the previous warm phase of the LFO, when any anthropogenic influence is believed to have still been negligible”).

Koberle and Gerdes (2003) explored the time variability of Arctic sea ice properties in a coupled ocean–sea ice model of the Arctic and the northern North Atlantic driven by 50-year NCEP–NCAR reanalysis data No appreciable trend in sea ice volume was found for the period 1948–1998 although rather long sub-periods (e.g., 1965–1995) exhibited a large decline in sea ice volume. Their analysis concluded that wind forcing significantly contributes to the decadal variability in the Arctic ice volume. They concluded: “these results make connecting ‘global warming’ to Arctic ice thinning very difficult for two reasons.” The two reasons are (i) large decadal and longer term variability masks any trend, and (ii) there might be long-term trends in wind stress that tend to either increase or decrease ice volume that would mask the effects of temperature change.

Lindsay and Zhang (2005) pointed out that recent observations of summer Arctic sea ice over the satellite era show that record or near-record lows for the ice extent occurred in the years 2002–2005. It was hypothesized that:

> “The thinning since 1988 is due to preconditioning, a trigger, and positive feedbacks: 1) the fall, winter, and spring air temperatures over the Arctic Ocean have gradually increased over the last 50 years, leading to reduced thickness of first-year ice at the start of summer; 2) a temporary shift, starting in 1989, of two principal climate indexes (the Arctic Oscillation and Pacific Decadal Oscillation) caused a flushing of some of the older, thicker ice out of the basin and an increase in the summer open water extent; and 3) the increasing amounts of summer open water allow for increasing absorption of solar radiation, which melts the ice, warms the water, and promotes creation of thinner first-year ice, ice that often entirely melts by the end of the subsequent summer. Internal thermodynamic changes related to the positive ice–albedo feedback, not external forcing, dominate the thinning processes over the last 16 yr. This feedback continues to drive the thinning after the climate indexes return to near-normal conditions in the late 1990s. The late 1980s and early 1990s could be considered a tipping point during which the ice–ocean system began to enter a new era of thinning ice and increasing summer open water because of positive feedbacks. It remains to be seen if this era will persist or if a sustained cooling period can reverse the processes.”

Wingham *et al.* (2006), using radar altimetry, found that mass gains for East Antarctica slightly outweighed mass losses for West Antarctica, “exacerbating the difficulty of explaining twentieth century sea-level rise.” Chen *et al.* (2006) using the Gravity Recovery and Climate Experiment (GRACE) satellite mission during its first 3.5 years (April 2002–November 2005), found that mass gains for East Antarctica roughly balanced mass losses for West Antarctica. Velicogna and Wahr (2006) found similar results. Davis *et al.* (2005) also found growth in East Antarctica, but of lesser magnitude.

According to Anon. (D):

> "Over the past century, sea level has slowly been rising. This is in part due to the addition of water to the oceans through either the melting of or the 'calving' off of icebergs from the world's land ice. Many individual mountain glaciers and ice caps are known to have been retreating, contributing to the rising sea levels. It is uncertain, however, whether the world's two major ice sheets—Greenland and Antarctica—have been growing or diminishing. This is of particular importance because of the huge size of these ice sheets, with their great potential for changing sea level. Together, Greenland and Antarctica contain about 75% of the world's fresh water, enough to raise sea level by 70 m–75 m, if all the ice were returned to the oceans. Measurements of ice elevations are now being made by satellite radar altimeters for portions of the polar ice sheets, and in the future measurements will be made by a laser altimeter as part of NASA's Earth Observing System (EOS). The laser altimeter will provide more accurate measurements over a wider area. The Greenland ice sheet is warmer than the Antarctic ice sheet and as a result, global warming could produce serious melting on Greenland while having less effect in the Antarctic. In the Antarctic, temperatures are far enough below freezing that even with some global warming, temperatures could remain sufficiently cold to prevent extensive surface melting. Where ice sheets extend outward to the ocean, the ice tends to move out over the surrounding water, forming ice shelves. There is concern that, with global warming, the water under the ice shelves would be warmer and cause them to break up more readily, forming very large icebergs. If the ice shelves of West Antarctica were to break up, this would release more inland ice in an irreversible process, possibly leading to sea level rises of several meters."

Douglas and Peltier (2002) claimed that although the long-term average global sea level (GSL) rise for the past few millennia has been stable at a level near zero, the GSL abruptly began to rise around the mid-19th century. No studies, however, have detected any significant acceleration of GSL rise during the 20th century. In the last dozen years, published values of 20th-century GSL rise ranged from 1.0 mm/yr to 2.4 mm/yr, even though all investigators used essentially the same database of tide gauge measurements. Douglas and Peltier (2002) made a significant distinction between estimates of a GSL rise of 2 mm/yr and 1 mm/yr. If the correct value of GSL rise is near 1 mm/yr, then it is argued that global warming provides an explanation: 1 mm/yr of the GSL rise corresponds to that expected from the thermal expansion of the oceans and the melting of small ice sheets and mountain glaciers caused by the $\sim$0.6°C increase in global surface temperature during the last 100 years. This explanation would further imply that melting of the great Greenland and Antarctic ice sheets is not currently contributing significantly to the GSL rise. But if, as Douglas and Peltier (2002) argued, the true rate of contemporary GSL rise is probably closer to 2 mm/yr, it is then likely that these ice sheets are contributing.

Douglas and Peltier (2002) concluded that the GSL rise for the past century is closer to 2 mm/yr than 1 mm/yr, and it was suggested that this "must be seen as posing a definite geophysical puzzle." Current best estimates are that the thermal expansion of the oceans contributes 0.6 mm/yr to GSL rise and the melting of small ice sheets and glaciers also contributes about 0.3 mm/yr. Together, these two contributions amount to less than 1 mm/yr, leaving a deficit of the same order to be explained. Douglas and Peltier (2002) suggested three possible resolutions of this puzzle.

(1) The century-scale tide gauge records might be biased upward, perhaps as a consequence of a strong enhancement of the influence of thermal expansion at coastal locations.
(2) The true global rate of secular GSL rise might be closer to 2 mm/yr than to 1 mm/yr, implying that the great polar ice sheets on Antarctica and Greenland are losing mass at a net rate that contributes 1 mm/yr to the global value. However, Douglas and Peltier (2002) raised an objection to this possibility based on constraints on the present day rate of polar ice mass loss provided by Earth rotation observations. If the best currently available result derived from satellite laser ranging is correct, it would be impossible to solve the puzzle by invoking the required rate of mass loss from Greenland, Antarctica, or both. If, however, it could be demonstrated that the laser-ranging result was in significant error, this solution would become possible.
(3) A third possible solution of the puzzle is that the current best estimate of the influence of thermal expansion is significantly biased downward as a consequence of under-sampling the Southern Hemisphere ocean at all depths and the abyssal ocean in both hemispheres.

In the opinion of Douglas and Peltier (2002), none of these three individual possibilities can be entirely ruled out at present, nor can the possibility that the key may involve a mix of all three.

Alley *et al.* (2005) emphasized:

> "Future sea-level rise is an important issue related to the continuing buildup of atmospheric greenhouse gas concentrations. The Greenland and Antarctic ice sheets, with the potential to raise sea level ~70–75 meters if completely melted, dominate uncertainties in projected sea-level change. Freshwater fluxes from these ice sheets also may affect oceanic circulation, contributing to climate change. Observational and modeling advances have reduced many uncertainties related to ice-sheet behavior, but recently detected, rapid ice-marginal changes contributing to sea-level rise may indicate greater ice-sheet sensitivity to warming than previously considered. Over the last century, sea level rose ~1.0 to 2.0 mm/year, with water expansion from warming contributing 0.5 ± 0.2 mm (steric change) and the rest from the addition of water to the oceans (eustatic

Table 7.2. Historical dependence of sea level on CO_2 concentration.

Years before present	*CO_2* (ppmv)	*Eustatic sea level change* (m)
>35 million	1,250	+73
~32 million	500	+45
21,000	185	−132
50	280	0

change) due mostly to melting of land ice. By the end of the 21st century, sea level is projected to rise by 0.5 ± 0.4 m in response to additional global warming, with potential contributions from the Greenland and Antarctic ice sheets dominating the uncertainty of that estimate."

Alley *et al.* (2005) provided some historical data on the relation between estimated atmospheric CO_2 concentration and the ice contribution to eustatic sea level referenced to modern (pre-Industrial Era) conditions (i.e., $CO_2 \sim 280$ ppmv, eustatic sea level 0.0 m) as shown in Table 7.2.

Alley *et al.* (2005) suggested that the Greenland Ice Sheet may melt entirely from future global warming, whereas the East Antarctic Ice Sheet (EAIS) is likely to grow through increased accumulation (for warming less than ~5°C). The future of the West Antarctic Ice Sheet (WAIS) remains uncertain, with its marine-based configuration raising the possibility of important losses in the coming centuries. Alley *et al.* (2005) said:

> "Despite these uncertainties, the geologic record clearly indicates that past changes in atmospheric CO_2 were correlated with substantial changes in ice volume and global sea level. Recent observations of startling changes at the margins of the Greenland and Antarctic ice sheets indicate that dynamical responses to warming may play a much greater role in the future mass balance of ice sheets than previously considered. Models are just beginning to include these responses, but if they prove to be important, sea-level projections may need to be revised upward. Also, because sites of global deepwater formation occur immediately adjacent to the Greenland and Antarctic ice sheets, any notable increase in freshwater fluxes from these ice sheets may induce changes in ocean heat transport and thus climate."

However, as we pointed out in Sections 1.2.4.3 and 6.1.3, there is considerable evidence that the CO_2 concentration rise (or fall) lags the temperature rise (or fall) that occurs during periods of increased glaciation or warming in the Southern Hemisphere. The time lag was estimated to be of the order of 1,000 years. That would seem to imply that increased CO_2 is an effect—not a cause—of temperature change.

Table 7.3. Projected rise in sea level (cm). From Hoffman (1984).

Year	*Low* $\Delta T \sim 1.5°C$	*Medium* $\Delta T \sim 3°C$	*High* $\Delta T \sim 4.5°C$
1986	0	0	0
2000	5	11	17
2025	13	32	55
2050	24	66	117
2075	38	114	213
2100	56	180	345

Hoffman (1984) estimated the sea level rise expected from various degrees of global warming. Low, medium, and high scenarios were based on ultimate temperature rises of 1.5°C, 3°C, and 4.5°C by 2100, respectively, for a putative doubling of CO_2 concentration. The projected rise in sea level is summarized in Table 7.3.

According to Titus (1990):

> "Since 1979, there has been a general consensus that a doubling of carbon dioxide would raise global temperatures 1.5 to 4.5°C, and that such a doubling is likely to occur over the next century. More recent assessments have pointed out that emissions of methane, nitrous oxide, and numerous other gases that absorb infrared radiation could further increase this warming, and that warmer temperatures may increase the rate of natural emissions of these gases. Although national policy makers are beginning to formulate strategies to slow global warming, there is an emerging consensus that at least a one or two degree warming is inevitable, due to past emissions and the time it will take to change production practices and retire existing machinery. In the late 1970s, some scientists suggested that the projected global warming might cause a 5 to 7 meter rise in sea level over the next few decades, due to a disintegration of the West Antarctic Ice Sheet. However ... such a deglaciation would take at least 200–500 years. As a result, most recent assessments have focused on other contributors to future sea level rise: expansion of ocean water and the melting of mountain glaciers and parts of the ice sheet in Greenland."

Titus (1990) provided the estimates of future sea level rise shown in Table 7.4.

IPCC (2001) said:

> "Disintegration of the West Antarctic Ice Sheet or melting of the Greenland Ice Sheet could raise global sea level up to 3 m each, over the next 1,000 years, submerge many islands, and inundate extensive coastal areas ... The projected

Table 7.4. Predicted rise (cm) in sea level by 2100. From Titus (1990).

Source	*Year*	*Low estimate*	*Mid–Low*	*Mid–High*	*High*
World Meteorological Organization	2050	20			170
Environmental Protection Agency	2100	70	160	210	340
National Research Council	2100	50			190

sea-level rise of 5 mm/yr for the next 100 years would cause enhanced coastal erosion, loss of land and property, dislocation of people, increased risk from storm surges, reduced resilience of coastal ecosystems, saltwater intrusion into freshwater resources, and high resource costs to respond to and adapt to these changes (high confidence) . . . Many coastal areas will experience increased levels of flooding, accelerated erosion, loss of wetlands and mangroves, and seawater intrusion into freshwater sources as a result of climate change. The extent and severity of storm impacts, including storm-surge floods and shore erosion, will increase.''

The projection of 5 mm/yr is far higher than most other projections, and reflects the extreme alarmist views of the IPCC Report.

Conway *et al.* (1999) found:

''The history of deglaciation of the West Antarctic Ice Sheet (WAIS) gives clues about its future. Southward grounding-line migration was dated past three locations in the Ross Sea Embayment. Results indicate that most recession occurred during the middle to late Holocene in the absence of substantial sea level or climate forcing. Current grounding-line retreat may reflect ongoing ice recession that has been under way since the early Holocene. If so, the WAIS could continue to retreat even in the absence of further external forcing.''

This would seem to suggest that the process of disintegration of the WAIS has been under way for some time, independent of anthropogenic influences.

According to Dasgupta *et al.* (2007):

''Until recently, studies of sea level rise (SLR) typically predicted a 0–1 meter rise during the 21st century. The three primary contributing factors have been cited as: (i) ocean thermal expansion; (ii) glacial melt from Greenland and Antarctica (plus a smaller contribution from other ice sheets); and (iii) change in terrestrial storage. Among these, ocean thermal expansion was expected to be the dominating factor behind the rise in sea level. However, new data on rates of deglaciation in Greenland and Antarctica suggest greater significance for glacial melt, and a possible revision of the upper-bound estimate for SLR in this century. Since the

Greenland and Antarctic ice sheets contain enough water to raise the sea level by [7.2 m and 61.1 m, respectively] small changes in their volume would have a significant effect. Since the IPCC Report in 2001, there has been an increased effort to improve measures of mass loss for the Greenland ice sheet and its contribution to SLR."

Dasgupta *et al.* (2007) claimed that satellite interferometry observations led to an estimate that the contribution of the Greenland ice sheet to SLR is double the rate assumed in the IPCC Report. Dasgupta *et al.* (2007) also indicated that the rate of loss of the WAIS is several times greater than that assumed in the IPCC Report.

Mörner (1973, 2004) provided a contrary view:

"Sea level rose for glacial eustatic reasons up to about 5000 years before present (YBP). After that, global sea level has been dominated by the redistribution of ocean water masses (and by ocean-stored heat). This redistribution of water masses is driven by the interchange of angular momentum between the solid Earth and the hydrosphere (in feedback coupling) primarily expressed as changes in the oceanic surface current systems. In view of this, it has been very hard to define any global eustatic signal. This is where and why a dialectic between models and observations enter the sea level debate. According to the glacial loading models, global sea level is now rising by 1.8 to 2.4 mm/year. The IPCC models have hypothesized a very rapid rise in the near future ... Both the glacial loading models and the ICPP scenarios are strongly contradicted by observational data for the last 100–150 years that cannot have exceeded a mean rate of 1.0–1.1 mm/year. In the last 300 years, sea level has oscillated close to the present with peak rates in the period 1890–1930. Sea level fell between 1930 and 1950. The late 20th century lacks any sign of acceleration. Satellite altimetry indicates virtually no changes in the last decade. Therefore, observationally based predictions of future sea level in the year 2100 give a value of ±10 cm [in contradiction to] model outputs by IPCC as well as global loading models. In conclusion, there are firm observationally based reasons to free the world from the condemnation to become extensively flooded in the 21st century."

Mörner (1973, 2004) also concluded that sea level at the Maldive Islands had actually fallen between 1950 and 2001. However, Church, White, and Hunter (2006) contradicted this finding. Mörner (1973, 2004) has been widely quoted by the naysayers of global warming. It provides plenty of grist for any mill intent on showing that global warming is a fiction.

Perhaps the best analysis of sea level rise was provided by Church and White (2006). They reconstructed global sea level from a variety of data sources back to 1870. From 1870 to 2004 (135 years), the total GSL rise was 195 mm, an average of 1.44 mm per year. For the 20th century, the rise was about 160 mm (1.7 ± 0.3 mm per year) indicating a slight acceleration during the 20th century.

James E. Hansen claims that even this relatively benign scenario might nevertheless lead to destruction of the Greenland Ice Sheet. His arguments were based on a previous paper (Hansen, 2004) in which he pointed out that ice sheet growth is a slow, dry process, inherently limited by the snowfall rate, but disintegration is a wet process, driven by positive feedbacks, and once well under way it can be explosively rapid. Figure 7.4 (see color section) shows a moulin on the Greenland Ice Sheet. The moulin, a near-vertical shaft worn in the ice by surface water, carries water to the base of the ice sheet. There the water acts as a lubricating fluid that speeds motion and disintegration of the ice sheet. Hansen reviewed the situation during past ice sheet disintegrations. He claimed:

> "About 14,000 years ago, sea level rose about 20 m in approximately 400 years. That is an average of 1 m of sea level rise every 20 years. The nature of glacier disintegration required for delivery of that much water from the ice sheets to the ocean would be spectacular (5 cm of sea level, the mean annual change, is about 15,000 cubic kilometers of water)" (Hansen, 2005).

Hansen believes that the Earth is "now out of energy balance by close to $+1\ \mathrm{W/m^2}$, i.e., with that much more energy absorbed from sunlight than the energy emitted to space as thermal radiation" which is "due mainly to rapid growth of greenhouse gases, especially CO_2 and CH_4, and the thermal inertia of the ocean." The greenhouse gases produce a downward forcing while the thermal inertia of the oceans prevents a rapid temperature rise, thus limiting re-radiation from Earth to space. Hansen pointed out that: "CO_2 and CH_4 amounts today are far outside the ranges that existed for hundreds of thousands of years" (Figure 7.5). However, in more distantly past interglacials, CO_2 concentrations sometimes exceeded 1,000 ppm.

Most of this putative energy imbalance goes into warming the oceans. However, Hansen believes that mechanisms exist to transfer some of this energy to the ice sheets. He believes that a further 1°C temperature rise might be enough to do significant damage to the Greenland Ice Sheet. Such mechanisms are likely to have occurred during the rapid disintegration of the ice sheets after the last glaciation (14,000–11,000 years ago). According to Hansen (2005):

> "The net effect of these processes, which eventually will include a positive feedback from lowering of the ice surface altitude, is the potential for a highly nonlinear response, a process that could run out of control, possibly to the ultimate demise of the entire south dome (64°N) of the Greenland ice sheet, if the strong planetary forcing is maintained long enough. The question is: how long is long enough?"

Hansen (2005) suggested:

> "Three time constants play critical roles in creating a slippery slope for human society: T_1, the time required for climate, specifically ocean surface temperature, to respond to a forced change of planetary energy balance; T_2, the time it would take human society to change its energy systems enough to reverse the growth of greenhouse gases; T_3, the time required for ice sheets to respond substantially to a

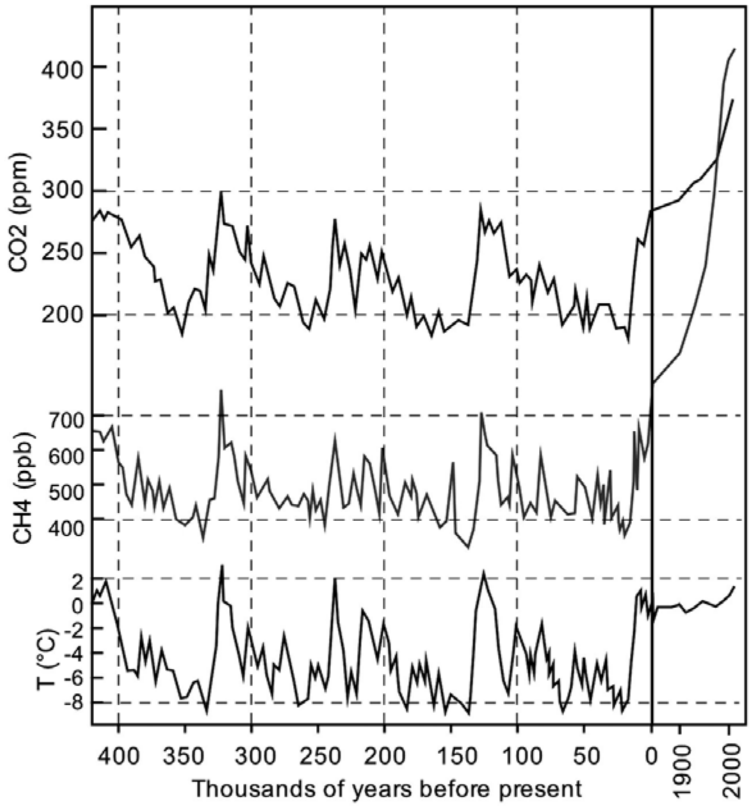

Figure 7.5. Record of atmospheric CO_2, CH_4, and temperature extracted from an Antarctic ice core. Adapted from Hansen (2005).

large relentless positive planetary energy imbalance ... T_1, the climate response time, is 50–100 years, as a result of the large thermal inertia of the ocean. T_2, the energy infrastructure time constant, also is perhaps 50–100 years ... T_3, the ice sheet response time, is the time constant of issue.''

''T_3 is of the order of centuries, not millennia, as commonly assumed. Growth of ice sheets requires millennia, as growth is a dry process limited by the snowfall rate. Ice sheet disintegration, on the other hand, is a wet process that can proceed more rapidly, as evidenced by the saw-toothed shape of glacial–interglacial temperature and sea level records.''

Hansen (2005) summarized:

''The likelihood that T_3 is comparable to $T_1 + T_2$ has a staggering practical implication. $T_3 \gg T_1 + T_2$ would permit a relatively complacent ''wait and see'' attitude toward ice sheet health. If, in the happy situation $T_3 \gg T_1 + T_2$, we should confirm that human forcings were large enough to eventually alter the ice sheets, we would have plenty of time to reverse human forcings before the ice sheets responded. Unfortunately, $T_3 \sim T_1 + T_2$ implies that once ice sheet changes pass a critical point, it will be impossible to avoid substantial ice sheet disintegration. If T_3 indeed is not very much larger than $T_1 + T_2$, it becomes of high priority to detect as early as possible beginnings of ice sheet disintegration. High precision measurements of ice motion and sea level change are needed for early detection of any acceleration in the global rates of ice movement and sea level rise."

Oppenheimer and Alley (2005) commented on Hansen (2005).

"If Hansen is right about ice sheet response to the global energy imbalance and if IPCC's projections of future greenhouse gas concentrations prove correct, [a 1°C rise might disintegrate the Greenland Ice Sheet] it would be too late to stem a catastrophic sea level rise, given the commitment to future warming already in the pipeline."

But Oppenheimer and Alley (2005) indicated that, based on evidence from the last interglacial, the ice sheets may be stable to a 3°C temperature increase.

Huybrechts (2002) modeled the Greenland and Antarctica ice sheets from the last interglacial (~120,000 YBP) through the last glacial maximum (~20,000 YBP) to the present.

"Together, their current volume contains enough ice to raise global sea level by almost 70 m, of which 61 m would derive from the Antarctic ice sheet and 7 m from the Greenland ice sheet. Major issues concern how much additional water was locked up in these ice sheets at the Last Glacial Maximum (LGM), when did this maximum occur, and over which period was the ice released back into the oceans? This problem bears directly on the amount of ice stored elsewhere on the globe, since the total eustatic sea-level depression is rather well constrained to have been between ~125 and 135 m. The majority of ice at the LGM was contained in the ice sheets of Laurentia and Fennoscandia, but their combined estimated volume falls far short of the required ~130 m [sea level equivalent] in many assessments ..."

Huybrechts (2002) found that the sea level depressions at 21,000 YBP were between 13 m and 21 m for the Antarctic Ice Sheet and between 1.9 m and 3.5 m for the Greenland Ice Sheet. It was concluded:

"It is hard to conceive that both ice sheets could have contributed more than ~25 m of equivalent sea level at the time of maximum sea-level depression. The implication is that the other northern hemisphere ice sheets [Laurentia and Fennoscandia] must have contained an equivalent sea-level volume of between minimum 100 m and perhaps as much as 120 m at the LGM, substantially more than often assumed" (Huybrechts, 2002).

Figures 7.6 and 7.7 (both in color section) show the modeled results for Greenland and Antarctica (1) during the last interglacial, (2) near glacial maximum, and (3) at the present. For Greenland, it was estimated that the rise in sea level due to melting during the interglacial was ~5.5 m, and the fall in sea level due to icing was ~2.7 m at the last glacial maximum, compared with the present. For Antarctica, it was estimated that the rise in sea level due to melting during the interglacial was ~1.4 m, and the fall in sea level due to icing was ~19.2 m at the last glacial maximum, compared with the present. These results suggest that a significant diminution of the Greenland Ice Sheet can occur during an interglacial. However, the calculations revealed that the Greenland minimum ice during the last interglacial is not very strongly constrained and is sensitive to assumptions. For plausible combinations of climatic conditions and only small shifts in the duration and magnitude of the peak warming, the ice sheet during the last interglacial could have varied from just a little smaller than today to only a small single dome covering only central–north Greenland. The major difference between the Greenland Ice Sheet during the last glacial maximum and today seems to be the much wider margins at the glacial maximum. If the model is correct, we might not yet have seen more than a small fraction of the ultimate disappearance of the Greenland Ice Sheet (Huybrechts, 2002).

The model suggests that there is not much difference between Antarctica today and Antarctica during the last interglacial. The main difference during the glacial maximum was a significant spread of the margins. The model provides some hope that Antarctica may be less sensitive to global warming than Greenland.

Of all the potential impacts of global warming, the potential rise of sea level would appear to be the most serious because of the possibility of much greater effects if the Greenland Ice Sheet is seriously impacted by modest temperature increases. However, it is not clear that much can be done about this.

7.4 FUTURE INCREASES IN GLOBAL TEMPERATURE

Nozawa *et al.* (2007) utilized three projections for future greenhouse gas concentrations in a coupled ocean–atmosphere general circulation model. One projection assumed 1% increases in CO_2 for the entire 21st century, leading to a concentration of over 800 ppm by 2100. The most moderate model had an asymptote of 540 ppm in 2100. The estimated temperature increases in the 21st century range from 4°C to 2.4°C.

Anon. (F) utilized several projections of future CO_2 concentrations that increase by 2100 over a range varying from 470 ppm to well over 1,000 ppm, leading to temperature increases by 2100 ranging from 1.4°C to 5.8°C. They presented an ultimate *hockey stick* temperature profile with almost no temperature variation over the past millennium as shown in Figure 7.8 (color section).

Anon. (H) projected temperature increases by 2100 ranging from 2°C to 6°C (comparable with Figure 7.8, color section).

At the heart of almost all alarmist beliefs are claims that we are already in an unprecedented, incredibly high–temperature cycle, and projections of significant future increases in global temperature will lead us still higher. For example, Mann, Bradley, and Hughes (1999) said:

> "... our results suggest that the latter 20th century is anomalous in the context of the last century. The 1990s was the warmest decade and 1998 the warmest year at moderately high levels of confidence."

Of course, this was the first MBH paper where the *hockey stick* was revealed, and these claims should be treated with caution.

Singer and Avery (2007) quote a number of alarmist claims from various sources:

> "Nineteen ninety-nine was the most violent year in the modern history of weather. So was 1998. So was 1997. And 1996 ... A nine-hundred-year-long cooling trend has been suddenly and decisively reversed in the past fifty years ... Scientists predicted that the Earth will shortly be warmer than it has been in millions of years. A climatological nightmare is upon us. It is almost certainly the most dangerous thing that has ever happened in our history."
>
> "Climate extremes would trigger meteorological chaos-raging hurricanes such as we have never seen, capable of killing millions of people; uncommonly long, record-breaking heat waves; and profound drought that could drive Africa and the entire Indian subcontinent over the edge into mass starvation."
>
> "From sweltering heat to rising sea levels, global warming's effects have already begun ... We know where most heat-trapping gases come from: power plants and vehicles. And we know how to limit their emissions."
>
> "No matter if the science of global warming is all phony ... climate change [provides] the greatest opportunity to bring about justice and equality in the world."

Fortunately, Hansen (2004), written by a leading alarmist, provided a more balanced and credible picture. He pointed out:

> "The IPCC scenarios may be unduly pessimistic, however. First, they ignore changes in emissions, some already under way, because of concerns about global warming. Second, they assume that true air pollution will continue to get worse, with ozone, methane and black carbon all greater in 2050 than in 2000. Third, they give short shrift to technology advances that can reduce emissions in the next 50 years."

Furthermore, limitations on the availability of fossil fuels will have a dramatic effect as the 21st century wears onward. Hansen (2004) went on to say:

> "Observed global carbon dioxide and methane trends for the past several years show that the real world is falling below all IPCC scenarios. It remains to be proved whether the smaller observed growth rates are a fluke, soon to return to IPCC rates, or are a meaningful difference."

Note that Khalil, Butenhoff, and Rasmussen (2007) found that increases in methane concentration have stagnated.

The projection made by Hansen (2004) was:

> "... at the low end of the IPCC range of two to four watts per square meter. The IPCC four watts per square meter scenario requires 4 percent a year exponential growth of carbon dioxide emissions maintained for 50 years and large growth of air pollution; it is implausible.'

One legitimate concern is that the Earth's climate appears to be precariously perched on the edge of a fence that can topple off one way or the other, once pushed by some "trigger" to get the process rolling. We are in a global-warming period, particularly at higher latitudes. As the ice and snow cover at higher latitudes diminishes, the heat input to the Earth increases and the warmth spreads. It is possible that we are entering such a positive feedback era in which global warming, regardless of greenhouse gases, has somehow gotten started and is likely to propagate by its own momentum. Severe reduction of burning fossil fuels will not reverse such a trend, and besides, the world will soon encounter fundamental limits to the rate at which it can produce fossil fuels.

7.5 CHANGES IN PRECIPITATION: FLOODS AND DROUGHT

Houghton (2004) pointed out that water needs and water availability pose a major problem for humankind in the future, independent of whether global warming occurs. Although Houghton (2004) admits that there are substantial uncertainties in predictions of precipitation by climate models, it is asserted that different areas will experience more or less precipitation and these can be predicted to some degree. For example, it is claimed: "northern high latitudes will experience higher precipitation in winter, and southern Europe, Central America, southern Africa and Australia can expect significantly drier summers." He describes a study of the effect of a putative 4°C temperature rise on the Sacramento Basin in California. And then an IPCC-like recounting of the disasters of global warming follows.

Leroux (2005) takes a diametrically opposite position. Leroux quotes studies that claim that "there is no discernible global trend in tropical cyclone numbers, intensity or location" and that "there is no evidence to suggest any major changes in the area or global location of tropical cyclone genesis in greenhouse conditions." Leroux disparages the IPCC belief that warmth begets evaporation that then begets rainfall. In regard to rainfall, Leroux writes many pages on the complexity of how rain forms and the difficulty in making such predictions. He describes the extreme rainfalls that occur occasionally in France. He explains these events as being independent of putative global warming.

The subjects of storm formation and precipitation patterns are complex and beyond the scope of this book. It is doubtful that anything definitive can be extracted from the literature. Certainly, the Earth's weather is not constant and we cannot expect it to remain quiescent. Change is inherent in the Earth system. The extent to which greenhouse gases will affect these natural changes remains in doubt.

8

Global climate change and public policy

8.1 THE KYOTO PROTOCOL

This section is based to a considerable extent on Anon. (I).

8.1.1 Description of the Kyoto Protocol

The Kyoto Protocol is an agreement made under the U.N. Framework Convention on Climate Change (UNFCCC). Countries that ratify this protocol commit to reduce their emissions of carbon dioxide and five other greenhouse gases, or engage in emissions trading if they maintain or increase emissions of these gases.

The Kyoto Protocol now covers more than 160 countries globally and over 55% of global greenhouse gas (GHG) emissions. At its heart, the Kyoto Protocol establishes the following principles:

1. Kyoto is underwritten by governments and is governed by global legislation enacted under the U.N.'s aegis.
2. Governments are separated into two general categories.
    - Developed countries, referred to as "Annex I countries" (who have accepted GHG emission reduction obligations and must submit an annual greenhouse gas inventory); and
    - Developing countries, referred to as "Non-Annex I countries" (who have no GHG emission reduction obligations but may sell emission rights if they do reduce emissions.

Between 2008 and 2012, Annex I countries have to reduce their GHG emissions by an average of ~5% below their 1990 levels (for many countries, such as the EU member states, this corresponds to some 15% below their expected GHG emissions in 2008). While the average emissions reduction is 5%, specific national limitations vary widely (e.g., 8% reductions for the EU and 10% emissions increase for Iceland), but since the EU intends to meet its target by distributing different rates among its member states, much larger increases (up to 27%) are allowed for some of the less developed EU countries. Reduction requirements expire in 2013.

Kyoto includes "flexible mechanisms" which allow Annex I economies to meet their GHG emission limitation by purchasing GHG emission reductions from elsewhere. What this means in practice is that Non–Annex I nations have no GHG emission restrictions so they can produce as much GHG emissions as they prefer, but if they do go about implementing GHG reductions, they can sell the rights to these reductions to Annex I nations, thus enabling them to generate the CO_2 instead.

The Kyoto linking mechanisms are in place for two main reasons:

1. The cost of complying with Kyoto is prohibitive for many Annex I countries (especially those countries, such as Japan or the Netherlands, with highly efficient, low GHG–polluting industries, and high prevailing environmental standards). Kyoto therefore allows these countries to purchase *Carbon Credits* instead of reducing GHG emissions domestically. Hence those countries that have already done a good job are punished for doing a good job but can bail themselves out by purchasing credits from others. Instead of exempting these countries for their good past performance, they are required to pay for it.
2. This is seen as a means of encouraging Non–Annex I developing economies to reduce GHG emissions since by doing so they can profit from the sale of *Carbon Credits*. It is not clear to this writer why developing economies are merely "encouraged" while responsible developed countries are punished with unfair requirements.

8.1.2 Status of the Kyoto Agreement

Signing

The treaty was negotiated in Kyoto, Japan in December 1997, and signed by most countries by March 15, 1999. The treaty could not take effect until it included enough Annex I countries to account for at least 55% of emissions from Annex I countries. The agreement came into force on February 16, 2005 following ratification by Russia on November 18, 2004 that drove the total over 55%. As of December 2006, a total of 169 countries and other governmental entities have ratified the agreement (representing over 61.6% of emissions from Annex I countries). Emissions from non–Annex I countries were not stated. Notable exceptions include the U.S. and Australia. Other countries, like India and China, being Annex II countries, have ratified the protocol but are not required to reduce carbon emissions under the present agreement.

Details of the agreement

The Kyoto Protocol is an agreement under which industrialized countries will reduce their collective emissions of greenhouse gases by 5.2% compared with the year 1990 (but this represents a 29% drop from what it would be in 2010 without Kyoto). The goal is to lower overall emissions of six greenhouse gases (carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, HFCs, and PFCs) calculated as an average over the five-year period of 2008–2012. National limitations range from 8% reductions for the E.U. and some others to 7% for the U.S., 6% for Japan, 0% for Russia, and permitted increases of 8% for Australia and 10% for Iceland. This agreement was negotiated as an amendment to the UNFCCC, which was adopted at the Earth Summit in Rio de Janeiro in 1992.

China, India, and other developing countries were exempt from the requirements of the Kyoto Protocol on the specious grounds that they were not the main contributors to the greenhouse gas emissions during the industrialization period that are believed by alarmists to be causing today's putative runaway climate change.

However, critics of Kyoto argue that China, India, and other developing countries will soon be the top emitters of greenhouse gases. More importantly, without Kyoto restrictions on these countries, industries in developed countries would be driven toward these non-restricted countries, and thus there would be no net reduction in carbon. Furthermore, if the effects of CO_2 are anywhere near what the U.N. thinks they are, most of the global warming still lies ahead of us and China will be the main contributor to it.

If the global climate models are correct, and if CO_2 emissions continue to rise in the 21st century, the global warming in the 21st century will far surpass that of the 20th century. The Kyoto agreement exempts the main contributor to this putative 21st-century warming: China. As more and more industrialization is shifted from the U.S. and Europe to China, China's output of greenhouse gases will swell, and there are no constraints on these emissions!

Financial commitments

The Protocol also reaffirms the principle that developed countries will have to pay billions of dollars, and supply technology to developing countries for climate-related studies and projects. This was originally agreed to in the UNFCCC.

Emissions trading

Kyoto is a "cap and trade" system that imposes national caps on the emissions of Annex I countries. On average, this cap requires countries to reduce their emissions 5.2% below their 1990 baseline over the 2008 to 2012 period. Although these caps are national-level commitments, in practice most countries will distribute their emissions targets to individual industrial entities, such as power plants or factories.

The ultimate buyers of *Carbon Credits* are often individual companies that expect their emissions to exceed their quota of allowances. National governments, some of which may not have transferred responsibility for meeting Kyoto obligations to industry, and have a net deficit of allowances, may also buy credits for their own account. Since *Carbon Credits* are tradable instruments with an unregulated price, financial investors have started buying them for pure trading purposes. This market is expected to grow substantially, with banks, brokers, funds, arbitrageurs, and private traders eventually participating.

Enforcement

If the Enforcement Branch determines that an Annex I country is not in compliance with its emissions limitation, then that country is required to make up the difference plus an additional 30%. In addition, that country will be suspended from making transfers under an emissions-trading program. However, it is not clear what other pressures can be brought to bear on a country that flouts the agreement.

8.1.3 Current positions of governments

Australia

The Kyoto protocol granted Australia permission for an 8% increase. Nonetheless, Australia has refused to ratify the Agreement. Anon. (I) provides more details. Australia is heavily dependent on coal, and it is claimed that even if they shut down all their coal-fired power plants, China would more than make up the difference with increased emissions in less than a year. However, the main opposition party on Australia is in favor of the Kyoto Protocol.

Canada

Canada ratified the treaty and is required to reduce emissions to 6% below 1990 levels during the 2008–2012 commitment period. However, there has been dissension from Alberta (Canada's primary oil and gas producer). As of 2003, the federal government claimed to have spent or committed 3.7 billion dollars on climate change programs. However, by 2004, CO_2 emissions had risen to 27% above 1990 levels (which compares unfavorably with the 16% increase in emissions by the U.S. during that time) (Anon. (I)).

In January 2006, a Conservative minority government was elected that is far from enthusiastic about Kyoto, and on April 25, 2006, it was announced that Canada would have no chance of meeting its targets under Kyoto, and would look to participate in the U.S.-sponsored Asia–Pacific Partnership on Clean Development and Climate. Canada and its government received criticism from environmental groups and from other governments for its climate change positions.

Canada's federal government has introduced legislation to set mandatory emissions targets for industry, but they will not take effect until an estimated 2050. The government has since begun working with opposition parties to improve the legislation.

A bill was put forth by Liberals aiming to force the government to "ensure that Canada meets its global climate change obligations under the Kyoto Protocol." The bill passed the House of Commons on February 14, 2007 with a vote of 161–113, and is under consideration by the Senate. If passed, the bill would give the government 60 days to form a detailed plan of action. The government has flatly refused to abide by the bill, which may spark a constitutional crisis, lawsuit, or non-confidence motion if the bill becomes law.

People's Republic of China

In 2004 the total greenhouse gas emissions from the People's Republic of China were about 54% of the U.S. emissions. However, China is now building one coal-fired power plant per week, and plans to continue doing so for years. Various predictions suggest China will overtake the U.S. in total greenhouse emissions between late 2007 and 2010 and then continue to expand the rate of emissions (Anon. (I)).

China insists that the gas emissions level of any given country is a multiplication of its per capita emission and its population. Because of its huge population, China considers criticism of its energy policy unjust.

European Union

All 15 members of the European Union agreed to Kyoto in 2002. The EU produces around 22% of global greenhouse gas emissions, and has agreed to a cut, on average, of 8% from 1990 emission levels. In January 2007, the European Commission announced plans for an EU energy policy that included a unilateral 20% reduction in GHG emissions by 2020. The EU has consistently been one of the major supporters of the Kyoto Protocol, negotiating hard to get wavering countries on board. The EU created an emissions trading system in an effort to meet these tough targets. Quotas were introduced in six key industries: energy, steel, cement, glass, brick making, and paper/cardboard.

Germany

On June 28, 2006, the German government announced it would exempt its coal industry from requirements under the Kyoto agreement.

United Kingdom

The energy policy of the U.K. fully endorses goals for carbon dioxide emissions reduction and has committed to proportionate reduction in national emissions on a phased basis. The U.K. is a signatory to the Kyoto Protocol.

The U.K. currently appears to be on course to meet its Kyoto limitation for greenhouse gases, assuming that the Government is able to curb rising carbon dioxide emissions between 2006 and the period 2008-2012. However, annual net carbon dioxide emission levels in the UK have actually risen by around 2% since 1997. Furthermore, it now seems highly unlikely that the Government will be able to honor its manifesto pledge to cut carbon dioxide emissions by 20% from 1990 levels by the year 2010.

France

In 2004, France shut down its last coal mine, and now produces 80% of its electricity from nuclear power. Because of this, France now has the cleanest air of any industrialized country, and the cheapest electricity bills in all of Europe.

India

Among the major world economies, India's economy is the least energy-intensive. India signed and ratified the Protocol in 2002. Since India is exempted from the framework of the treaty, it is expected to gain from the Protocol.

Russia

Russia approved the treaty in November 2004. The Kyoto Protocol limits emissions to a percentage increase or decrease from their 1990 levels. Since 1990, the economies of most countries in the former Soviet Union have collapsed, as have their greenhouse gas emissions. Because of this, Russia should have no problem meeting its commitments under Kyoto, as its current emission levels are substantially below its limitations. It is debatable whether Russia will benefit from selling emissions credits to other countries in the Kyoto Protocol.

United States

The U.S., although a signatory to the Kyoto Protocol, has neither ratified nor withdrawn from the Protocol. The signature alone is symbolic, as the Kyoto Protocol is non-binding on the U.S. unless ratified. The U.S. was, as of 2005, the largest single emitter of carbon dioxide from the burning of fossil fuels. China is projected to take over this honor by late 2007.

On July 25, 1997, before the Kyoto Protocol was finalized (although it had been fully negotiated, and a penultimate draft was finished), the U.S. Senate unanimously passed (by a 95–0 vote) the Byrd–Hagel Resolution, which stated that the sense of the Senate was that the United States should not be a signatory to any protocol that did not include binding targets and timetables for developing as well as industrialized nations or "would result in serious harm to the economy of the United States." On November 12, 1998, Vice-President Al Gore symbolically signed the protocol. Both Gore and Senator Joseph Lieberman indicated that the protocol would not be acted on in the Senate until there was participation by the developing nations. The Clinton Administration never submitted the protocol to the Senate for ratification. The current President, George W. Bush, has indicated that he does not intend to submit the treaty for ratification, not because he does not support the Kyoto principles, but because of the exemption granted to China. Bush also opposes the treaty because of the strain he believes the treaty would put on the economy; he emphasizes the uncertainties that are present in the climate change issue.

8.1.4 Commentary on Kyoto Protocol

The U.N. has supported studies of global climate change for a number of years through its Inter-government Panel on Climate Change (IPCC). IPCC (2001) provides not 1—but 19—separate chapters on the impacts of global warming, including over 1,000 pages.

Against this backdrop of alarmism regarding global warming, the Kyoto Protocol evolved under the auspices of the U.N.

Some public policy experts who are skeptical of global warming see Kyoto as a scheme to either slow the growth of the world's industrial democracies or to transfer wealth to the Third World in what they claim is a global socialism initiative. Others claim that the costs of the Kyoto Protocol outweigh the benefits, and the standards that Kyoto sets are too optimistic. Others see a highly inequitable and inefficient agreement that would do little to curb greenhouse gas emissions, and they are right. While the conspiracy theories of Jaworowski (2007) seem to be rather paranoid, his quotations by a high-level U.N. diplomat

> "We may get to the point where the only way of saving the world will be for industrial civilization to collapse";

and by U.S. State Department officials

> "We have got to ride the global warming issue. Even if the theory of global warming is wrong, we will be doing right thing in terms of economic policy and environmental policy."
>
> "A global warming treaty must be implemented even if there is no scientific evidence to back the [enhanced] greenhouse effect"

cannot but help his case. There are idealists in the U.N. who want to save the world from calamity, real or imagined. And there are politicians everywhere, willing to "go with the flow" if it is politically expedient.

Nevertheless, if action were taken to reduce greenhouse gas emissions in the 21st century, the number one culprit is clearly China. With its rapid growth in greenhouse gas emissions, China will soon become not merely the world's greatest generator of greenhouse gases, but the world's leader in emissions by a wide margin. Exemption of China from any controls at all under the Kyoto Protocol defies logic.

But there are other forms of pollution besides greenhouse gases, and China is clearly the greatest source of pollution in the world. The Kyoto Protocol does nothing about that.[1]

It is noteworthy that even the *Los Angeles Times*, a loyal believer in greenhouse gases causing global warming, believes that the Kyoto Protocol is fatally flawed. As a *Los Angeles Times* editorial[2] pointed out:

> "The choice of 1990 as a base year simply rewards countries whose economies have shrunk since then and punishes growth. Russia, Eastern Europe, Germany

[1] It is noteworthy that China already is the world's #1 polluter. The satellite picture of Chinese pollution at *http://visibleearth.nasa.gov/view_rec.php?id=1036* demonstrates the extent of pollution from Chinese coal burning. But with all the hoopla about global warming, hardly anyone worries about conventional pollution anymore.

[2] *Los Angeles Times* editorial, June 11, 2007.

and Britain are strong backers of Kyoto, and if one looks at the costs and benefits of the pact, it's no wonder. Today, these countries emit either less than they did in 1990 or just a little bit more. In Britain, that's because the privatization of the coal industry led to a decline in coal-fired power plants in favor of natural gas; elsewhere, it's because the collapse of the Soviet Union was followed by the closing of filthy Soviet-era industrial plants, while economies in Russia and much of Eastern Europe stagnated. The U.S. economy, meanwhile, has grown significantly since 1990, with a corresponding rise in power demand that ... has caused carbon dioxide emissions to jump 20.4%. What a global carbon-trading scheme boils down to, then, is a massive wealth transfer from the U.S. to Russia. U.S. polluters would pay billions of dollars to buy carbon credits from other countries mostly Russia, because it would have the most to sell. Why should we inject huge sums into a country with a rotten human rights record, rampant corruption and opposing geopolitical views? And what did Russia do to earn the cash, other than shrink?

Further, because there is no world body that polices greenhouse gas emissions, countries and polluters are on the honor system—we have to trust them to be honest about how much they're polluting. Governments in Russia or Ukraine aren't capable of monitoring emissions from every pollution source even if they wanted to, and under Kyoto, there's no reason for them to want to. After all, if Ukraine claims to be cleaner than it really is, rich countries such as the U.S. and Japan will shower it with money for carbon credits. And corrupt governments will tend to distribute credits unfairly, using them to reward political supporters and reducing the market's effectiveness.

India and China are left out ... If China keeps growing at its current rate, its per capita income is expected to reach U.S. levels within 25 years. Once that happens ... there might be 1.1 billion vehicles in China. Currently, there are only 800 million vehicles in the entire world. Meanwhile, China builds a new coal-fired power plant every week to stoke its growth, and ... in a quarter of a century, its CO_2 emissions will be double those of the other industrialized nations combined. India, the world's fourth-biggest polluter, is also growing at a blistering pace. Unless these two countries can be persuaded to embrace green power, they will render Kyoto and every other attempt to reduce greenhouse gases moot. Unfortunately, they're not eager to change their ways. Last Monday, China unveiled its climate-change plan in response to pressure from the G-8; it made no commitments to any quantifiable carbon reductions and rejected international efforts to impose them. India also refuses to consider anything that might slow its economic development."

The *Los Angeles Times* then went on to propose

"... a new, improved version of Kyoto that brings India and China onboard and commits them to 'grow green,' but still leaves the tougher cuts up to those nations better able to make them, such as the U.S., Canada, Japan and Europe."

It is not clear to this writer why China, the world's worst polluter (other than CO_2) should get any favoritism. The *Los Angeles Times* also said:

> "A better treaty would scrap the unworkable carbon-trading scheme and instead impose new taxes on carbon-based fuels."

This sounds like a good idea but can it be made to work? Or, is it like the mice deciding that they need to put a bell around the cat's neck?

8.2 ECONOMICS: WILL IT COST MORE TO DO NOTHING?

8.2.1 The Stern Report

The Stern Report (CCSP, 2007) is a lengthy study (about 600 pages) on the economics of global climate change. The Report presupposed that (1) drastic climate impacts will occur if no action is taken, and (2) we have the means to take action to prevent climate change. Based on this, the economic study reached the conclusion that it will cost less to invest in climate control now, than to pay later for the problems created by future climate change.

However, the Stern Report is based on a number of scientific and technical assertions that at best are quite uncertain, and at worst, may simply be wrong. The Stern Report estimated that the current CO_2 equivalent level ("CO_2e") is about 430 ppm (375 ppm of CO_2 + about 55 ppm equivalent from other greenhouse gases). A fundamental basis of the Stern Report is stated as:

> "The level of 550 ppm CO_2e could be reached as early as 2035. At this level there is at least a 77% chance—and perhaps up to a 99% chance, depending on the climate model used—of a global average temperature rise exceeding 2°C ... On current trends, average global temperatures will rise by 2–3°C within the next fifty years or so."

However, limitations on the availability of fossil fuels will prevent CO_2e from reaching such levels, and it is far from certain how large a temperature increase will result from increased CO_2e. In the past, an increase in CO_2 (not equivalent) of 100 ppm from pre-industrial to early 21st century has used up about 38% of original fossil fuel resources. The temperature rise during that period was about 0.6°C, but only part of that rise can be attributed to greenhouse gases. Why should we believe that a rise of another 100 ppm of CO_2 (not equivalent) will produce a 2°C–3°C temperature rise?

The Stern Report delineates the putative impacts of global warming in great detail: floods, reduced water supplies for one-sixth of the world's population, declining crop yields, leaving hundreds of millions without the ability to produce or purchase sufficient food, spread of disease, displacement of 200 million people by rising sea levels, extinction of 15% to 40% of species, destruction of the Amazon rainforest, etc. The Stern report indicates that it could be much worse if a potential temperature rise of 5°C to 6°C occurs.

According to the Stern report,

> "... the poorest countries and people will suffer earliest and most. And if and when the damages appear, it will be too late to reverse the process. Thus we are forced to look a long way ahead ... Climate change may initially have small positive effects for a few developed countries, but is likely to be very damaging for the much higher temperature increases expected by mid- to late-century."

However, the Stern Report admits that "there is much to learn about these risks" but insists that "the temperatures that may result from unabated climate change will take the world outside the range of human experience." Since the human experience includes ice ages, this is certainly an exaggeration.

There are three problems with the impacts listed by the Stern Report: (1) we don't know what the future CO_2e will rise to, (2) we don't know what temperature changes will result from a putative increase in CO_2e and how they will vary regionally, and (3) the speculations on how any given temperature rise will affect the world economies are quite subjective.

The Stern Report carried out detailed academic exercises predicting future reductions in gross domestic products due to global warming. However, the Stern Report cautions:

> "Economic forecasting over just a few years is a difficult and imprecise task. The analysis of climate change requires, by its nature, that we look out over 50, 100, 200 years and more. Any such modeling requires caution and humility, and the results are specific to the model and its assumptions. They should not be endowed with a precision and certainty that is simply impossible to achieve. Further, some of the big uncertainties in the science and the economics concern the areas we know least about (for example, the impacts of very high temperatures), and for good reason—this is unknown territory."

But the Stern Report maintains that despite these uncertainties,

> "The main message from these models is that when we try to take due account of the upside risks and uncertainties, the probability-weighted costs look very large. Much (but not all) of the risk can be reduced through a strong mitigation policy, and we argue that this can be achieved at a far lower cost than those calculated for the impacts. In this sense, mitigation is a highly productive investment."

Until now, North America and Europe have produced around 70% of all the CO_2 emissions due to energy production, while developing countries have accounted for less than one-quarter. However, most future emissions growth will come from today's developing countries.

The Stern Report insists: "the world does not need to choose between averting climate change and promoting growth and development." It argues for "decarbonization" of energy technologies to achieve climate stabilization. This requires that annual emissions be brought down to the level that balances the Earth's natural capacity to remove greenhouse gases from the atmosphere. The Stern Report indicates that the rate of CO_2e emission[3] in 2000 was about 41 Gt/yr (equivalent to $41/3.67 = 11.2$ Gt/yr of carbon). However, Figure 6.7 suggests a much lower figure. The Stern Report postulates a number of future scenarios in which annual CO_2e emissions rise in the near term (to ~48 Gt/yr to ~63 Gt/yr) and then fall back after 2040, dropping to about 20 Gt/yr by 2100. It indicates that if the peak CO_2e emission rate were less than 50 Gt/yr around 2030 to 2040, and it dropped to 30 Gt/yr in 2050 and 20 Gt/yr by 2100, stabilization of CO_2e at around 550 ppm might be achievable. However, these cuts will have to be made in the context of a world economy in 2050 that may be three to four times larger than today, so the emissions per unit of GDP would need to be about 0.20 to 0.25 of current levels by 2050.

Achieving these deep cuts in emissions will have a cost. Greenhouse gas emissions can be cut in four ways.

1. Reducing demand for emissions-intensive goods and services.
2. Increasing efficiency.
3. Action on non-energy emissions, such as avoiding deforestation.
4. Switching to lower carbon technologies for power, heat, and transport.

The Stern Review estimates the annual costs of stabilization at ~550 ppm CO_2e to be around 1% of GDP by 2050 (3%–4% of present GDP), a level that is claimed to be "significant but manageable".

The Stern Report claims that by 2050, energy efficiency has the potential to be the biggest single source of emissions savings in the energy sector. Non-energy emissions make up one-third of total greenhouse gas emission. A substantial body of evidence suggests that action to prevent further deforestation could be relatively cheap compared with other types of mitigation. Large-scale uptake of a range of clean power, heat, and transport technologies is required for radical emission cuts in the medium to long term. The power sector around the world will have to be decarbonized by at least 60%, and perhaps as much as 75%, by 2050 to stabilize at or below 550 ppm CO_2e. Deep cuts in the transport sector are likely to be more difficult in the shorter term, but will ultimately be needed.

The Stern Report says that the shift to a low-carbon global economy will take place despite "an abundant supply of fossil fuels." It says that stocks of hydrocarbons that are profitable to extract (under current policies) are more than enough to take the world to levels of greenhouse gas concentrations well beyond 750 ppm CO_2e, which conflicts with the estimates given in Section 6.5. It is postulated that:

[3] It should be noted that CO_2e emissions include CO_2 and all other greenhouse gas emissions weighted by their relative effectiveness. The relation between CO_2 emission and carbon emission rate is that CO_2 emission is $(44/12) = 3.67$ times the carbon emission rate.

> "Even with very strong expansion of the use of renewable energy and other low-carbon energy sources, hydrocarbons may still make over half of global energy supply in 2050. Extensive carbon capture and storage would allow this continued use of fossil fuels without damage to the atmosphere."

It is not clear in the Stern Report how GDP impacts vary with country. Discussions of GDP seem to be limited to a world average. The argument seems to be that the consequences of business as usual in the 21st century are disastrous for the whole world, and the cost of stabilization at, say, 550 ppm are less than the cost of global-warming impacts. To achieve such stabilization, the Stern Report provides hundreds of pages on policy responses for mitigation and adaptation, and international collective action (*à la* Kyoto). That would certainly be a boon for bureaucracy. The Stern Report appears to be based on unfounded expectations of disaster and the economic analyses of consequences are of dubious credibility. When impending shortages of fossil fuel are taken into account, it is likely that many of the proposed mitigations will take place through market forces without micromanagement by the U.N.

8.2.2 Nordhaus Review of Stern Report

Nordhaus (2006) wrote a review of the Stern review. On the positive side, Nordhaus said that (1) the Stern Review is an impressive document, (2) he suspects that the results are fundamentally correct in sign if not in size, and (3) the Stern Review argues correctly that it is critical to have a harmonized carbon tax or similar regulatory device both to provide incentives to individual firms and households, and to stimulate research and development in low-carbon technologies.

On the negative side, Nordhaus claimed that the Stern Report's use of a near-zero (0.1%) social discount rate is unfounded and leads to very unrealistic conclusions. Most of Nordhaus' review was concerned with this aspect (Nordhaus, 2006).

The social discount rate has to do with social time preference; it measures the importance of the welfare of future generations relative to the present.

> "It is calculated in percent per year, like an interest rate, but refers to the discount in future utility or welfare, not future goods or dollars. A zero social discount rate means that future generations into the indefinite future are treated equally with present generations; a positive social discount rate means that the welfare of future generations is reduced or discounted compared to nearer generations. Philosophers and economists have conducted vigorous debates about how to apply social discount rates in areas as diverse as economic growth, climate change, energy policy, nuclear waste, major infrastructure programs such as levees, and reparations for slavery" (Anon. (K)).

On a far smaller scale, each individual has a similar problem in deciding how much of their current income to sequester into 401K and other tax shelter plans for future retirement vs. taking current income for current expenses in living. Achieving a balance between current needs and preparing for the future is a problem that confronts individuals, institutions, and governments. Nordhaus showed that the basis for the extreme economic impacts in the Stern report rests on "selectively chosen studies that emphasized high damage estimates, some of which are highly speculative." More importantly, Nordhaus demonstrated some considerable legerdemain in reporting losses from global warming. Nordhaus asks:

> "How do damages, which average around 5 percent of output over the next two centuries turn into a [claimed] 14.4 percent reduction in consumption now and forever? The answer lies in the way that near-zero discounting magnifies distant impacts. With near-zero discounting, the low damages in the next two centuries get overwhelmed by the long-term average over many centuries."

Nordhaus posed this illustration:

> "Suppose that scientists discover that a wrinkle in the climatic system will cause damages equal to 0.01 percent of output starting in 2200 and continuing at that rate thereafter. How large a one-time investment would be justified *today* to remove the wrinkle starting *after two centuries*? The answer is that a payment of 15 percent of world consumption today (approximately $7 trillion) would pass the Stern Review's cost–benefit test. This seems completely absurd. The bizarre result arises because the value of the future consumption stream is so high with near-zero discounting that we would trade off a large fraction of today's income to increase a far-future income stream by a very tiny fraction ... Hence, the damage puzzle is resolved. The large [reported] damages from global warming reflect large and speculative damages in the far-distant future; the impacts now, as in today, are small; and ... the [proposed] 20 percent cut in consumption from global-warming might be reduced by an order of magnitude if alternative assumptions about discounting are used."

Nordhaus went on to say:

> "A further unattractive feature of the Review's near-zero social discount rate is that it puts present decisions on a hair-trigger in response to far-future contingencies. Under conventional discounting, contingencies many centuries ahead have a tiny weight in today's decisions. Decisions focus on the near future. With the Review's discounting procedure, by contrast, present decisions become extremely sensitive to uncertain events in the distant future."

Nordhaus provides further examples of absurd requirements for present investment to cover unlikely small impacts in the distant future if a zero social discount rate is used.

In his "summary verdict", Nordhaus raised the questions:

"How much and how fast should the globe reduce greenhouse-gas emissions? How should nations balance the costs of the reductions against the damages and dangers of climate change?"

He pointed out:

> "The Stern Review answers these questions clearly and unambiguously: we need urgent, sharp, and immediate reductions in greenhouse-gas emissions."

Nordhaus then mentioned that economists are always saying:

> "On the one hand this and on the other hand that."

Harry Truman wanted a one-handed economist.

> "The Stern Review is a Prime Minister's dream come true. It provides decisive and compelling answers instead of the dreaded conjectures, contingencies, and qualifications. However, a closer look reveals that there is indeed another hand to these answers. The radical revision of the economics of climate change proposed by the Review ... depends decisively on the assumption of a near-zero social discount rate. The Review's unambiguous conclusions about the need for extreme immediate action will not survive the substitution of discounting assumptions that are consistent with today's market place. So the central questions about global-warming policy—how much, how fast, and how costly remain open. The Review ... does not answer these fundamental questions."

8.3 U.S. CONGRESS: MEETING THE CLIMATE CHANGE CHALLENGE

In October 2007, Chairman Dingell's Energy and Commerce Committee of the U.S. Congress released its first white paper in a series on "Meeting the Climate Change Challenge."[4] This was claimed to be "the next step in the legislative process leading to enactment of a mandatory, economy-wide climate change program." The essential basis for this program is the belief that:

> "The United States should reduce its greenhouse gas emissions by between 60 and 80 percent by 2050 to contribute to global efforts to address climate change. To do so, the United States should adopt an economy-wide, mandatory greenhouse gas reduction program ... The central component of this program should be a cap-and-trade program. The cap-and-trade program will have increasingly stringent caps on greenhouse gas emissions, eventually reaching a level that reduces emissions by 60 to 80 percent in 2050. The Government will distribute allowances

[4] *http://energycommerce.house.gov/Climate_Change/White_Paper.100307.pdf*

equal to the level of allowed greenhouse gas emissions. Allowances can then be bought and sold."

It is not clear from the white paper whether the Committee means a 60%–80% reduction from projected levels in 2050 based on a business-as-usual scenario, or a 60%–80% reduction from present levels. However, the wording seems to suggest a reduction from present levels. Considering that, under a business-as-usual scenario, energy usage in the U.S. is likely to grow between now and 2050, that would imply an even greater percentage reduction from projected levels in 2050 under business as usual. Assuming that energy usage in the U.S. in 2050 under business as usual would increase by, say, 40% compared with today, that would imply that the required reduction would be between 72% and 86% compared with energy usage in the U.S. in 2050 under a business-as-usual scenario.

An epidemic of insanity has apparently invaded the U.S. House of Representatives. Such a program will send the U.S. reeling back toward the lifestyle of the 18th century, bringing on a far worse economic depression than that of the 1930s. This program does not require that the U.S. supply its people and its industries with the energy needed to operate. It merely requires that emissions be reduced. Non-emitting energy presently accounts for perhaps 20% of the total energy mix in the U.S., and much of that is hydropower and nuclear power. The prospects for increasing hydropower are limited, and furthermore many environmentalists have turned away from hydropower because of its negative ecological impacts. The prospects for expanded nuclear power are quite uncertain. That being the case, the likely candidates for achieving the putative 72% to 86% reduction compared with energy usage in the U.S. in 2050 under a business-as-usual scenario are

1. Improved efficiency (drastically downsized vehicles, widespread use of hybrid vehicles, new standards for buildings, ...)
2. Vast increase in solar, wind, bio-energy, and other renewable energy sources
3. Huge cutback in energy usage, a major change in lifestyle.

Improved efficiency can make a contribution, but there are limits. Furthermore, the American public will fight tooth and nail for the right to drive large gas-eaters. The potential for expansion of use of renewables is highly debatable and remains to be seen. In the opinion of this writer, there is no way that renewables can come close to filling the gap left by a 72% and 86% reduction in emissions in 2050. Inevitably, it appears that the consequence of this program would be to drive America back to a lifestyle reminiscent of the 18th century. It would seem appropriate that before requiring one to sail across the ocean, it would be useful to make sure that one has a boat that does not leak.

Aside from the economic consequences of this policy, it is also myopic because it only deals with one country. As bad as the Kyoto Protocol is, at least it made an attempt to deal with emissions on a global scale. Piecemeal policies by individual nations that ignore China are unlikely to be effective.

9

Final remarks

9.1 CONCLUSIONS

The climate of the Earth has oscillated through wild variations with long, extended ice ages interspersed by relatively short interglacial periods of warmth. The last ice age peaked around 20,000 YBP and the current interglacial (Holocene) commenced about 10,000 YBP. The historical record shows that sharp transitions from extreme cold to warm have occurred in time periods of centuries or even decades. The Earth's climate appears to be delicately balanced between these extremes and can tip one way or another when perturbed. If the polar areas are sufficiently cold, they can trap out water vapor from the atmosphere, forming large ice sheets that will usurp a significant fraction of the world's water resources. The ice sheets provide positive reinforcement of cooling trends by reflecting incident solar irradiance. However, heat is delivered to the polar areas via solar energy, ocean currents, and to a lesser extent from air masses, providing a balance in which limited glaciation occurs in polar areas. When the solar irradiance or the ocean currents vary, the heat input to the polar areas changes, and this can lead to expansion or contraction of polar glaciation. There are various theories that attempt to explain major climate changes based on changes in the Sun, changes in the Earth's orbit about the Sun, or changes in ocean currents, but none of these is entirely satisfactory, and it is difficult to test these theories with data. The past ~10,000 years (the *Holocene*) has been a rather lengthy period of relatively benign climate with occasional moderate fluctuations.

Climatologists have attempted to characterize the Earth's climate during the past century or so, and during the past millennium or two. This is important in (i) establishing trends that may have evolved in the past century or so from industrialization and urbanization of the Earth, and (ii) defining the range of past fluctuations in climate prior to industrialization as a conjectural baseline of expected variations independent of human intervention. If it were possible to unambiguously extract (i) and (ii) from the data, anthropogenic-induced changes could then be compared with expected fluctuations. If such anthropogenic changes were found to be considerably greater than natural fluctuations, that would provide an experimental basis for concern about human impacts on climate.

One important factor is the question of how temperatures on Earth have varied over the past century (or more in some cases) as measured by monitoring stations dispersed around the world. While the scientists who process such data have made affirmative claims for these data, the fact remains that the network for monitoring world temperatures suffers from a number of maladies including uneven spatial and temporal representation of large areas, poor maintenance and recording at many stations, effects of urban heating and land use of stations, and uncertainties in the measurement of sea temperatures (see Section 3.2.5). In addition, the number of stations reporting data decreases sharply as one moves backward in time in the 20th century. Climatologists typically work in terms of a single global average temperature, or hemispheric average temperatures. In order to estimate how such averages have varied with time during the past century or so, a space–time grid is typically created from station temperature data. Unfortunately, the sparseness of spatial and temporal coverage creates considerable uncertainty in these averages—more so than the purveyors will admit to. Furthermore, such averages (i) have little physical or thermodynamic significance, (ii) tend to average out regional variations that convey more incisive information, and (iii) can be constructed in various ways to lead to different results. Nevertheless, the widely believed conclusion is that the global average temperature has increased by roughly 0.6°C to 0.8°C in the past century. While this warming has been far from uniform, there is no doubt that, on balance, the Earth is warmer today than it was 120 years ago. But 120 years ago, the Earth was emerging from the LIA. There is considerable evidence that the Earth began pulling out of the LIA in the mid-19th century, well before the build-up of CO_2 concentrations in the second half of the 20th century. Figures A.1 and A.2 (see Appendix) show that glacier retreat and sea level rise were well under way in the latter part of the 19th century, and continued at roughly the same pace through the 20th century. Thus, attributing the cause of these effects to a build-up of greenhouse gases defies logic (Robinson, Robinson, and Soon, 2007).

There is also evidence that the temperature rise of the 20th century occurred in two steps, one from 1900 to about 1940, and the other from about 1976 to the present. The initial rise occurred prior to massive build-up of CO_2 in the atmosphere. The dip from 1940 to 1976 has been attributed to aerosols, but this explanation is somewhat speculative. The sharp rise after 1976 coincides with a change in the Pacific Ocean in which the usual upwelling of deep cold waters seems to have suddenly diminished (see Section 5.2.11). In addition, the regions of greatest temperature rise are near the greatest concentration of urban centers.

In attempting to extend temperature estimates backward in time prior to the advent of surface measurements, climatologists have relied on a variety of temperature proxies that leave remnants from an earlier time that were formed via a temperature-dependent process, from which (in principle) the temperatures at the times of formation can be extracted. Unfortunately, all proxies are subject to confounding influences of one type or another that add noise to the signal and introduce considerable uncertainty in the veracity of the derived temperatures.

In the past decade, a number of climatologists attempted to integrate the results of a large number of proxies with varying spatial and temporal coverage in an effort to extract a historical global average (or hemispheric average) temperature over the past millennium or two. The accuracy of such procedures is limited by the sparse spatial and temporal coverage provided by the proxies, especially for times prior to about 1600 (see Table 2.2). However, an even more serious problem with these models has emerged. The use of principal components analysis to discover the principal trends in the integrated data was not carried out properly, and the resultant temperature profile derived from these models had the characteristic *hockey stick* form in which the temperature of the Earth was estimated to be almost flat with little variation for a thousand years (or more) prior to the 20th century, followed by a steep rise in the 20th century. This result was interpreted to mean that the human intervention of the 20th century produced an alarming rate of temperature rise, and this led to a number of extravagant claims that the last few years of the 20th century were the hottest in several millennia. This became a rallying point for global climate alarmists and the *hockey stick* has been widely promulgated by the U.N., Al Gore, and numerous other organizations. McIntyre and McKitrick (M&M) pointed out this error, but the climatologists ignored the criticism and stubbornly defended their incorrect procedures. A close-knit group of co-proposing climatologists control manuscript publication in journals, and this *paleo-climatological group* has managed to exclude the major criticisms from the journals, so they have been relegated to blogs.

There is anecdotal evidence to suggest that a relatively warm MWP occurred in the time frame of about 900–1000 and a relatively cold LIA occurred from perhaps 1600 to 1850. However, the magnitude and extent of these fluctuations remain uncertain.

Thus, we have a controversy. If the *hockey stick* picture were correct, that would provide support for the belief that human intervention has drastically altered a pattern of a flat temperature profile for a thousand years (or more). However, we know that the *hockey stick* result is incorrect. On the other hand, if the fluctuations in the MWP and the LIA were of comparable magnitude with the temperature rise of the 20th century, we might conclude that the current warming could be just another natural fluctuation. However, we don't have enough data to pin down the temperature changes in the MWP and the LIA. We do know that the temperatures around 1880 represented the final vestiges of the LIA, and since 1880 temperature was about 0.6°C to 0.8°C lower than today, we can be fairly sure that at the depth of the LIA in the 18th century, temperatures were at least 1°C cooler than they are today. The fact that the LIA was colder than the present climate may reflect unusual cold during the LIA rather than unusual warmth today. The real issue is how current temperatures compare with those in the MWP, for this would provide insight into how unusual the current warmth is. Unfortunately, the data are not accurate enough to answer this question.

Data taken over the past 50 years show that the CO_2 concentration has risen continuously and now well exceeds the levels found in ice cores from past interglacial periods. The pre-industrial level appears to be about 275 ppm, and it is presently about 375 ppm. Ice core data suggest that the rise in CO_2 began in the late 1800s, at about the time that temperatures started rising. The coincidence between the CO_2 increase and the temperature rise has suggested that the rise in CO_2 (together with other greenhouse gases) produced the observed rise in temperatures via the greenhouse gas effect. In order to examine this hypothesis, another genre of climatologists has developed global climate models in which the Earth is mathematically divided into cells that interact with nearest neighbors and evolve in time according to equations that attempt to represent all the physical processes that take place. The goal of these models has typically been to estimate the rise in global average temperature that will occur due to a future doubling of CO_2 concentration from the pre-industrial level of 275 ppm, although some models have also considered a quadrupling of CO_2 concentration. The greenhouse heating effect of CO_2 is limited. Typical models predict that a doubling of CO_2 would produce (by itself) a temperature rise of perhaps 1°C. However, the warming that results from the CO_2 greenhouse effect would increase evaporation of water, and the increased water vapor content in the atmosphere would amplify the warming via a water vapor greenhouse effect. Some models predict that this would add 2°C, bringing the total rise to about 3°C. However, the modeling of the entire water vapor cycle is primitive. Furthermore, the effect of clouds and aerosols are poorly understood. Because of uncertainties, different models predict a net temperature rise from a doubling of CO_2 that vary by a factor of 3 from one model to another. Unfortunately, it is difficult to test these models against actual data. Some investigators have attempted to run their models backward in time to see if they reproduce the known temperature variations of the 20th century. In this respect, they had to cope with the fact that warming has not been monotonic, and there was a temperature dip from about 1940 to 1978 (see Section 3.2.4). One can invoke aerosols to partially explain this, but models tested with one eye on the data used for testing, tend to explain everything and predict nothing. It seems likely that increased CO_2 produces some global heating, but how much remains very uncertain.

> There is a major conflict between the facts that, on the one hand, moderate changes in CO_2 concentration were associated with very large temperature changes during past ice age–interglacial cycles, while, on the other hand, there currently is a huge increase in CO_2 concentration compared with past interglacials, but a much smaller difference in temperature. The putative relationship between CO_2 concentration and temperature is inconsistent.

A number of modelers have theorized future growth of CO_2 concentration in the 21st century and used their climate models to thereby estimate the future temperature rises in the 21st century. Many of these have assumed future emission rates of CO_2 that are far beyond what seems to be possible from estimated fossil fuel resources. Even the least aggressive of these use CO_2 emissions in the 21st century that are unlikely because of fossil fuel limitations, likely controls on greenhouse gas emissions, and the advent of renewable energy resources.

A major source of uncertainty in understanding the Earth's climate, past and future, is the possibility of variation in the irradiance emitted by the Sun. Solar irradiance can only be measured above the Earth's atmosphere and we only have data since 1980, and not all of these data are credible. Nevertheless, we do know quite a bit about the Sun. We have observations of the solar cycle and the relevance of sunspots and other surface markings to this cycle. Sunspot data go back several hundred years. Our data indicate that sunspot activity has varied considerably over the past 200 years, and we have anecdotal data to suggest that sunspots disappeared altogether from about 1645 to 1715. A number of investigators have attempted to model past solar irradiance based on sunspot indices, length of the solar cycle, comparison with Sun-like stars, and other phenomena. None of these is very credible. As a result, we simply do not know how much the solar irradiance has varied in the past or how much it might vary in the future. This adds further uncertainty to climate models. Dr. John R. Christy said: "[I] cringe when I hear overstated-confidence from those who project evolution of global weather patterns over the next 100 years, ... Mother Nature ... operates at a level of complexity that is, at this point, beyond ... the tools available to us ... I see jump-to-conclusions advocates and, unfortunately, some scientists who see in every weather anomaly the specter of a global-warming apocalypse." (November 1, 2007 *Wall Street Journal*.)

The subject of global climate change seems to have bifurcated into two groups, each opposed to one another, each certain that they are correct, and each predisposed to interpret everything from a one-sided viewpoint. One group, the alarmists, believe that insidious global warming will cause great havoc and suffering in the 21st century if we don't move quickly to suppress greenhouse gas emissions. The great majority of climatologists are alarmists. Unfortunately, their insistence on use of the *hockey stick* result, their extravagant predictions of future CO_2 emissions, their excessive predictions of catastrophe, and their inordinate belief in climate models, provides the opposition with considerable ammunition for attack. Many alarmists are motivated by high ideals; they want to protect the planet. But it appears that the underpinnings of many are based on a similar situation that occurs in earthquake science: the big one is coming. The opposition, whom I call naysayers, tend to be less well informed, often quite shallow, and equally one-sided. One major exception is the excellent M&M team and the Climate Audit blog.

The IPCC has taken an alarmist position. In its reports, it has devoted 1,000 pages to descriptions of the negative impacts of climate change. Much of this is grossly exaggerated. The only tangible possibility for a serious consequence in the next 100 years is a rise in sea level. Even this has been exaggerated. Nevertheless, the consequence of the IPCC activities has led to the Kyoto Protocol in which the countries of the world have banded together to constrain future greenhouse gas emissions. Unfortunately, the Protocol is severely flawed in its uneven treatment of developed vs. developing countries, its unrealistic requirements in the short run, and its creation of a world market for emission rights. Quite properly, the U.S. has refused to sign it.

9.2 THE NINE QUESTIONS

In the Foreword of this book, nine essential questions were raised. Here, I provide short summary responses to these questions.

(1) How well has the world monitored near-surface temperatures of the 30% land and 70% ocean areas on Earth during the past 100 years or more, and how well can we characterize the changes in climate over that time span?
    ✓ While the purveyors of these temperature data networks seem to be well satisfied with their data, others have pointed out their inadequacies (e.g. Sections 3.1.2 and 3.2.5). Station data are suspect because at many sites, there were (1) changes in the observing time during the station's history, (2) changes in instrumentation, (3) station relocations, (4) poor siting due to nearby reflectors or shades, and (5) bias caused by urbanization. In addition, spatial and temporal coverage over many regions was very sparse. In recent years, new techniques have been added (space observation of the troposphere, ocean temperature network), but these have had severe growing pains and their histories have been too short to convey useful trends (see Sections 3.2.6 and 5.2.9).

(2) What is the utility and significance of a single global average temperature?
    ✓ Use of a single average global or hemispheric temperature tends to cancel out regional variations, and one ends up with only small apparent net changes. The utility of such a global average temperature is limited and the Earth's climate is better described in terms of regional variations (see Section 3.1.4).

(3) How has the Earth's climate varied over the past ice ages, the Holocene, the last millennium, and the past century, and what can we infer about the "natural" variability of the climate prior to industrialization by humankind?
    ✓ The Earth's climate has gone through wild gyrations from cold to warm over the past few hundred thousand years. The Holocene has been a primarily benign period with much smaller fluctuations. The last millennium has experienced an MWP and an LIA, but the extent and amplitude of these variations is difficult to resolve. In the last century, we have emerged from the LIA, and global temperatures have risen by about 0.6°C to 0.8°C. However, this rise has not been uniform spatially, and there have been notable downturns imbedded in this overall uptrend. We remain unable to distinguish the current trend as clearly distinct from natural fluctuations, although it is possible that some greenhouse effect is contributing.

(4) How reliable are proxies for historical temperatures? What do we really know about past temperature variations? Is the *hockey stick* version of millennium temperatures credible, in which temperatures were flat for two thousand years prior to a sudden rise in the 20th century?
    ✓ There are many challenges in using proxies to infer historical temperatures, as discussed in Section 1.1.2.2. Proxies suffer from wide variations between analyses using similar data (see Figure 2.30), and even wider variations when

disparate data are analyzed (see Figure 2.19, see color section). In combining many proxies to generate historical global average temperatures, principal component analysis has been misapplied, leading to an invalid *hockey stick* result (see Section 2.2.3). We simply do not know how much the temperature has varied quantitatively over the past 1,000 years, but we do know that it was warm around 1000 and cold from about 1600 to 1850.

(5) How does the current global-warming trend compare with past fluctuations in the Earth's climate, and what is the likelihood that the warming trend we are experiencing now is primarily just another in a series of natural climate fluctuations as opposed to a direct result of human production of greenhouse gases?
   ✓ We don't know whether the current warming trend is greater than that experienced in the MWP or further back in time, in various interglacial periods. We don't know whether the current warming trend is mainly a natural fluctuation or mainly a result of the greenhouse gas effect. The acceleration in warming that occurred after 1976 may be tied to the change in the Southern Oscillation Index that occurred at that time, but it is unclear which is the cause and which is the effect (see Section 5.2.11).

(6) How credible are the global climate models that claim that greenhouse gases produced most of the temperature rise of the 20th century, and forecast much greater impacts in the 21st century?
   ✓ Global climate models suffer from a number of maladies and uncertainties, particularly the treatment of water vapor, clouds and aerosols, and uncertainty about variations in solar irradiance over multi-decade time periods. The wide range in results testifies to the lack of precision in these models. The models are heavily focused on greenhouse gas effects, and they all (to a greater or lesser degree) claim that the temperature rise of the past century is mainly due to greenhouse gas effects. However, much of that rise was early in the century, prior to major greenhouse gas build-up, and there was a dip from 1940 to 1978 that has only been "explained" after the fact by invoking aerosol effects. The climate models will undoubtedly improve in the future, but right now, they are not nearly as credible as their developers claim.

(7) How good were the "good old days?" Was the climate of the Little Ice Age ideal, should we abhor warming from that baseline, and do we want to return to the climate of the 19th century?
   ✓ Without necessarily realizing it, most alarmists implicitly assume that the climate of the mid-19th century was ideal, and regard the warming of the 20th century as highly detrimental. However, there are numerous references in the literature to climatic hardships from the cold of the 19th century.[1]

[1] For example, *http://kclibrary.nhmccd.edu/19thcentury1820.htm*: "The bitterly cold winters of 1825–26 and 1826–27 caused great hardship in that country [Germany] and motivated many Germans to leave their homeland." Hardships endured due to the cold climate of the LIA are documented in *Climate of Fear*, by Thomas Gale Moore, Cato Institute, 1998.

Balling, Vose, and Weber (1998) found that the coldest period in Europe since 1751 was around 1890. But this is just the period that most climatologists use as a baseline period against which to compare global warming in the 20th century. As Balling, Vose, and Weber (1998) said:

> "... it is entirely possible that the warming in the record of the past century has been caused by an unusually cool period 100 years ago as opposed to an unusually warm period in recent decades."

(8) How will limits on fossil energy supplies constrain future CO_2 production and climate change, even if the climate models are accurate?

✓ Most temperature projections for the 21st century using climate models assume an annual rate of production of CO_2 that is very unlikely to be sustainable far into the century as fossil fuel resources fall short of energy demand by a growing world population that desires a more modern technological existence. Projections of a quadrupling of CO_2 are unrealizable. The maximum rise in CO_2 will be a doubling by the time (end of 21st century?) when most fossil fuels are depleted.

(9) How can the world provide itself with the energy needed for a burgeoning population that will demand more and more energy in the future, considering the finite limits on fossil fuel resources?

✓ No one knows the answer to this question, but it is clear that the world has not even begun to face up to this serious problem in any significant way. The prospects for renewable energy remain uncertain, and nuclear energy introduces many problems. Lack of availability of water is a growing problem that rivals energy. All of this is driven by the impending rise in population.

Appendix

Review of the film *An Inconvenient Truth*

Al Gore's film *An Inconvenient Truth* has been widely hailed and to a lesser extent, criticized. The website

http://www.sourcewatch.org/index.php?title = An_Inconvenient_Truth

provides links to more than 50 reports and reviews of the film. In general, those on the political left (e.g., Arianna Huffington, Carl Pope) embrace Gore's findings, and those on the political right (e.g., Glenn Beck, Jonah Goldberg) reject them.

Lewis (2007) provided a very detailed and thorough rebuttal to Al Gore's film (and book) *An Inconvenient Truth* (AIT), although he presented a very one-sided view, just as Al Gore provided a very one-sided view from the opposite vantage point. In this Appendix, only the film is reviewed. Lewis' review was very helpful in preparing this Appendix.

Al Gore's film is full of innuendos and implications in which he occasionally flashes graphs and data, but by the time your eyes focus on them, they are gone from the screen. The film jumps around and flits from one point to another in a dizzying sequence of sound bites made for an audience with an attention span of 10 seconds or less. While it is all very impressive visually, the actual transfer of data to the audience is minimal. Occasionally, Al Gore leaves the topic of global warming for a moment and provides some introspection into his own life. The defeat for the presidency and the accident to his son stand out. In doing this, he provides a satisfying connection to Al Gore, the human being, as opposed to Al Gore the advocate.

Scene 1. The film opens with scenes of factories belching out black smoke. Such scenes recur several times in the film. But, as Marlo Lewis said:

> "The 'smoke' is probably steam, but it looks dark and ominous against the inferno colors of a fading sunset. Thus, film viewers are set up to believe they are literally seeing CO_2 spew out of smokestacks, even though CO_2 is as invisible

> as oxygen. Pictorially, AIT presents CO_2 as an air pollutant, anticipating Gore's later oft-repeated description of CO_2 as 'global warming pollution.' This iconic and rhetorical depiction of CO_2 as pollution is inaccurate and manipulative."

I don't know why, but I am reminded of the opening scene of Charlie Chaplin's *Modern Times*. Charlie sees a truck laden with timber roar around the corner, which drops its red warning flag. He picks up the flag but the truck is gone. Just then, a communist throng swings around another corner, sweeping Charlie in the vanguard waving a red flag ...

Scene 2. The scene switches from belching smoke to a placid stream with trees and flowers and grass. The message is: you can either have nature or pollution; choose one! This was followed by pictures of the Earth from space, showing pollution filling up the atmosphere. As before, this is misleading because CO_2 is colorless and furthermore, since the recent emphasis on global warming, few people seem to worry about conventional pollution anymore.

Scene 3. Next, we see quick flashes of melting ice (which ice? where? when?) and hurricanes blowing. A graph is flashed but it cannot be read. No data are transferred, only fear is communicated.

Scene 4. Then Al Gore asserts (correctly) that we should not assume that humankind is too puny to impact the Earth.

Scene 5. Al Gore goes on to explain the greenhouse effect reasonably well, pointing out that it is a good thing that we have a greenhouse effect or we would be very cold. However, he again illustrates the argument improperly with belching black smoke, mixing metaphors of "global warming" and "pollution". For those who found this description too difficult to comprehend, he provides a cartoon of melting ice cream, but unfortunately he describes the greenhouse effect in terms of little green monsters that repel reflected sunlight from Earth, whereas the green monsters actually absorb IR radiant energy and re-emit it.

Scene 6. Next, he shows the jagged curve of rising CO_2 concentration, although the scene switches around so fast that all you get is a vague sense of a saw-tooth rising to the right. He provides a nice, concise explanation for why there is a yearly saw-tooth pattern.

Scene 7. The next topic is mountain glaciers. He begins with photos of Kilimanjaro before and after global warming. Unfortunately, as Cullen *et al.* (2006) showed, and Lewis discusses, the depletion of glaciers on Kilimanjaro has more to do with changing precipitation patterns than temperature change. However, Al Gore is correct that many mountain glaciers are retreating. The Earth is warming and there is no better example of its effect than the contracting mountain glaciers. Lewis makes the point that these retreats began prior to the major build-up of CO_2.

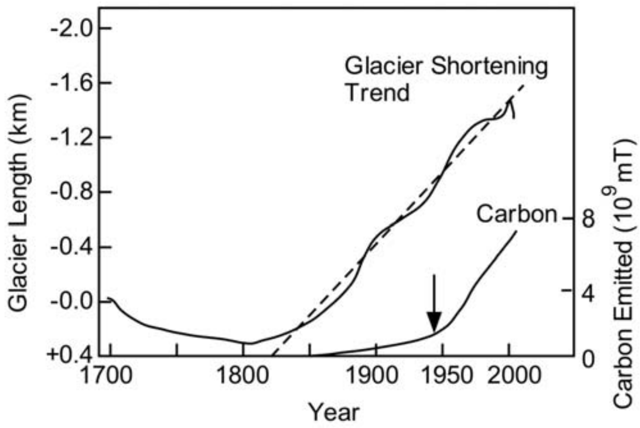

Figure A.1. Comparison of timing of retreat of glaciers with timing of carbon emissions. The glacier length is normalized against data for 169 world glaciers. The vertical arrow shows the transition point for more rapid carbon emission. Adapted from Robinson, Robinson, and Soon (2007).

The critical issue here is what is normal? The key mistake that Al Gore makes over and over again is that he uses the depths of the LIA as his baseline for comparison, and, of course, we have had significant warming since then. If we treat the LIA as the "normal" climate, then compared with this baseline we are undergoing significant warming. As Figure A.1 shows, the extreme expansion of mountain glaciers experienced during the LIA was followed by a retreat as the LIA waned at the end of the 19th century. Much of this occurred prior to the build-up of CO_2 concentrations in the atmosphere. Yes, we have had significant warming since the LIA, and this is evidenced in the retreat of mountain glaciers, but can we attribute this to a CO_2-induced greenhouse effect? Retreat of glaciers in the later stages might be partly due to a greenhouse gas effect, but the strong retreat prior to $\sim$1930 can hardly be due to greenhouse gases.

Robinson, Robinson, and Soon (2007) compared the timing of the retreat of glaciers with the timing of carbon emissions as shown in Figure A.1. It can be seen that the trend toward glacier shortening began in the mid-19th century, long before greenhouse gases had built up to high levels. In fact, 84% of greenhouse gas production took place after 1940. As Robinson, Robinson, and Soon (2007) point out, the melting of glaciers lags a temperature increase by perhaps 20 years, so the disparity between carbon emissions and warming is even greater.

Should we treat the climate of the LIA as "normal?" I hope not. Today's climate is far more temperate and pleasant for many people in the world, with occasional exceptions, than the climate of the LIA. I would rather think of the LIA as an aberration instead of a "normal" baseline.

Scene 8. Al Gore goes on to provide a very brief, sketchy sound bite on the history of Earth temperatures over the last millennium based on the work of his friend, Lonnie Thompson and colleagues (Thompson *et al.*, 1998). As Chapter 2 of this book amply demonstrates, the history of Earth temperatures over the last millennium is a complex subject that has been studied by many investigators, and Thompson *et al.*'s work is just one element of this. Al Gore claims that the MWP did not exist, and he treats the LIA as a period of normalcy. He is a subscriber to the *hockey stick* that we have adequately disposed of in Section 2.2.3. As always, when the LIA is used as a baseline, temperatures do indeed rise during the 20th century. But Al Gore does not explain why temperatures rose early in the century prior to the main build-up of CO_2, and does not discuss the slip from 1940 to 1978, nor does he discuss the inadequacies of the temperature measurement network or the problems in defining a global average temperature.

Scene 9. Al Gore discusses the ice ages of the past 650,000 years, and shows a strong correlation of CO_2 with temperature. However, he does not discuss the phasing of these, and implies that rising temperature produces more CO_2, rather than *vice versa*. As we showed in Sections 1.2.4.3 and 6.1.3, the rise in CO_2 typically lagged the rise in temperature by about 1,000 years. As shown in Figure 7.4 (color section), ice core measurements across glacial–interglacial cycles suggest that the CO_2 concentration never exceeded $\sim$300 ppm during interglacials. However, there are some indications that this might not be so (see Figure 6.6).

As we discussed in Section 6.1.4, there are quantitative problems in understanding the effects of CO_2 concentration on temperature (and *vice versa*). If the difference between an ice age and an interglacial is a change in CO_2 concentration from $\sim$200 ppm to $\sim$280 ppm, why isn't the Earth burning up at 383 ppm?

Nevertheless, Al Gore is right that the present CO_2 concentration of $\sim$380 ppm is alarmingly high, and provides cause for concern. While Lewis and other naysayers seem to be unconcerned about this CO_2 level, and have even suggested it may be beneficial to plant growth, sober reflection suggests that it is important to understand the effects of this rise (and future increases) in CO_2.

Scene 10. Al Gore deplores the lack of action in Congress in the late 1980s, and then goes on to describe his own personal agony when his son was hit by a car in 1989. This made him more conscious of the possibility of losing what is precious, and he then transfers this thought to the environment.

Scene 11. At this point, Al Gore goes into a diatribe about recent hot years setting "all-time records". Indeed, we have set some records when compared with the LIA as a baseline. In a period of warming after the LIA, it is only natural that with continued warming, some records will be set. However, that does not prove that prior to the LIA (such as during the MWP, or earlier in the Holocene) temperatures were not higher than they are today. It all depends on how far back you want to look. There is one glaring error in the Gore presentation. The European heat wave of 2003 that was so devastating is portrayed by Al Gore as a product of global warming, whereas as Lewis points out (with several references to various detailed studies), this was an unusual fluctuation in air mass circulation, unrelated to global warming.

However, it is true that global warming seems to have accelerated after 1976, and some have attributed this rise in temperatures to a change in the Pacific Ocean with warm surface waters prevailing (see Section 5.2.11).

Scene 12. The contention is made that warmer temperatures produce more fierce storms such as Katrina. The screen is aglow with whistling winds, flooded cities, and people in despair from storm damage. In fact, Al Gore specifically claims that globally warmed Gulf waters were responsible for the increase in Katrina's strength after it left Florida. The implication of the film is that the Earth is besieged by waves of storms of unprecedented intensity. Lewis discussed this issue in some detail. Webster *et al.* (2005) found a doubling of the number of Category 4 and 5 hurricanes in the 15-year period 1990–2004, as compared with 1975–1989. However, this article pointed out that they

> "... deliberately limited this study to the satellite era because of the known biases before this period, which means that a comprehensive analysis of longer-period oscillations and trends has not been attempted. There is evidence of a minimum of intense cyclones occurring in the 1970s, which could indicate that our observed trend toward more intense cyclones is a reflection of a long-period oscillation."

Klotzbach (2006) found only a 10% growth in global Category 4 and 5 hurricanes from 1986–1995 to 1996–2005, of which most were in the Southern Hemisphere. In another publication, Klotzbach said:

> "These findings indicate that there has been very little trend in global tropical cyclone activity over the past twenty years, and therefore, that a large portion of the dramatic increasing trend found by Webster *et al.* and Emanuel is likely due to the diminished quality of the datasets before the middle 1980s. One would expect that if the results of Webster *et al.* and Emanuel were accurate reflections of what is going on in the climate system, then a similar trend would be found over the past twenty years, especially since SSTs have warmed considerably (about 0.2°C–0.4°C) during this time period."

Lewis refers to a website produced by Patrick Michaels[1] that argues that production of strong hurricanes is cyclic and was also high in the 1950s, and that no attribution of storm intensity to global warming can properly be made.

Robinson, Robinson, and Soon (2007) present data that show that the number of tornados in the U.S. has been on a downward trend from 1950 to 2005. They also show that there has been no statistical increase in the annual number of Atlantic hurricanes that make landfall from 1900 to 2005. The period after 1998 has been relatively high, but there is no evidence yet that this is any more than a fluctuation of the same magnitude as has occurred previously. Similarly, the annual number of violent Atlantic hurricanes shows no statistical trend from 1945 to 2005, although the period since 1995 has been above average. It is impossible to tell whether this is just a

[1] *http://www.capmag.com/article.asp?ID=4418*

fluctuation of the same magnitude as has occurred previously, or whether it is the early emergence of a new trend.

These are issues that require further study. But Al Gore is sure he has the answers.

Scene 13. In a personal note, Al Gore describes his disappointment at losing the presidency, but mentions that this led him to re-devote himself to environmental issues.

Scene 14. In the next scene, all the vagaries of climate fluctuation such as heavy rains and drought in any and all regions were blamed on global warming. This section begins with a bar chart, but it was not clear what is plotted. Floods in India and China and desertification in Africa, you name it, were all attributed to CO_2. Striking photos of Lake Chad in Africa (before and after) show boats lined up at the shore of a dry lake. Lewis concluded that "Lake Chad's decline probably has nothing to do with global warming" based on a scientific study that attributed the Lake's condition to "a combination of regional climate variability and societal factors such as population increase and overgrazing."

Scene 15. Al Gore returned to the scenes of his youth, his double life in a Washington apartment, and a Midwest farm. He describes his idyllic life on the farm in a climate that "was unchanged since the last ice age." This, of course, is misleading, when one considers the LIA, the MWP, and the various fluctuations in the Holocene (see Sections 1.3 and 2.1).

Scene 16. Next, he discusses the Arctic. He conveys the impression that the entire Arctic is warming uniformly, whereas the warming is variable as we showed in Section 3.2.3. There is evidence of a significant reduction in the Arctic ice pack, but as we pointed out in Section 7.3, wind patterns and other factors than temperature may be playing a significant role in this regard.

Scene 17. He presents a likely explanation for some of the sudden climate changes experienced at the transition from the last ice age to the Holocene. However, he states this as a firm fact, rather than the speculation that it is.

Scene 18. We see Ronald Reagan, George Bush Sr., and Senator Imhof making idiotic statements arguing against protection of the environment, although global warming and conventional pollution seem not to be distinguishable here. The conclusion Gore reaches is that the public (and its leaders) are not yet convinced.

Scene 19. Here, Al Gore blames most of the afflictions of humankind (beetles, mosquitoes, vermin, flu, tuberculosis, West Nile virus, etc.) on global warming.

Scene 20. The devastation of coral reefs is presented. Lewis discusses this issue is some detail. Arguments can be made on either side.

Scene 21. Al Gore makes it seem as if the entire Antarctica Ice Sheet is almost ready to disintegrate. He repeats the phrase: "Scientists were astonished!" However, as we showed in Sections 3.2.3.1 and 7.3, most of the endangered part of Antarctica is the Peninsula, and the East Antarctic Ice Sheet is actually growing faster than the West Antarctic Ice Sheet is diminishing. He shows "moulins" in Greenland (see Figure 7.4, color section). He then discusses sea level rise and describes the effects of flooding from a putative 20 to 40-foot rise in sea level. China, India, Holland, and New York would be inundated.

Sea level rise is discussed in Section 7.3. Sea level rise is the most credible potential impact of global warming, and future reductions in the Greenland Ice Sheet are of greatest concern. Fortunately, there is some evidence that as losses occur at the margins of this ice sheet, more ice is being added (via snow) to the center. Nevertheless, this needs careful monitoring. While the effect of future global warming on the Greenland Ice Sheet is a legitimate concern, the connection of this warming to the CO_2 greenhouse effect remains uncertain. Figure A.2 shows that the current trend in sea level rise has persisted for 150 years, and began long before the rise in CO_2 emissions. As we mentioned previously, 84% of greenhouse gas production took place after 1940. This trend has not been affected by the great increase in CO_2 emissions after 1940 (Robinson, Robinson, and Soon, 2007).

Scene 22. Al Gore then visits China with its "huge coal resources". He points out that China is rapidly becoming a leading CO_2 generator. In the process, he once again shows black smoke billowing from Chinese power plants, which as we have shown previously, is not CO_2. One must wonder why Al Gore supports Kyoto, which absolves China from any controls on CO_2 emissions. Al Gore tries to mitigate the Chinese emissions by presenting them on a per capita basis but in less than 10

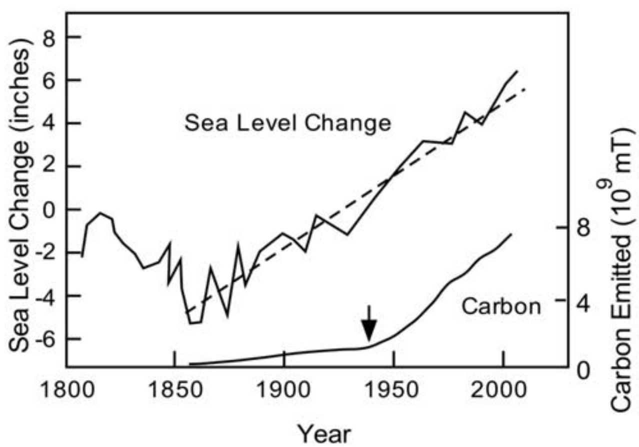

Figure A.2. Comparison of timing of sea level rise with timing of carbon emissions. The vertical arrow shows the transition point for more rapid carbon emission. Adapted from Robinson, Robinson, and Soon (2007).

years, China will be the world's worst CO_2 emitter. In addition, China is the world leader in conventional pollution.[2]

Scene 23. Al Gore traces the growth of world population during his lifetime from 2 billion to 6.6 billion with the prospect of it reaching 9 billion by the time he dies. He rightly emphasizes that this population growth has strained the Earth's capacity to provide food, water, and natural resources to the people of the world. However, he makes no proposal to place international constraints on family size, which is likely to be a critical need in mitigating future global warming.

Scene 24. Here, Al Gore diverts to the subject of tobacco, and his sister's untimely death from lung cancer. He uses this as an illustration of the fact that human nature often requires a long time to deal with a problem, but in the case of global warming, he asserts that we don't have time.

Scene 25. Al Gore asserts that essentially the entire science community agrees with his precepts regarding global warming as evidenced by a survey of 928 scientific articles. This argument is like: "30,000,000 Frenchmen Can't Be Wrong." While there are a number of contrary references, Al Gore is correct that the overwhelming majority of climatologists are concerned about global warming, and most of them believe the CO_2-induced greenhouse effect as a major factor. Solar physicists are less prone to endorse CO_2 and tend to lean toward solar variations as at least a contributor to climate change. Some climatologists have emphasized changes in the oceans as a major factor in climate change. However, climate modelers have been fairly unanimous in emphasizing temperature growth since the LIA and the role of the greenhouse effect in producing this warming.

Al Gore points out that the oil and gas lobby opposes all efforts to reduce carbon emissions and mentions an egregious case of a Bush appointee in "cahoots" with the oil and gas lobby. He also points out the actions of NASA and EPA Administrators in changing publications by scientists to conform to Republican political prejudices. In this, he is certainly correct. In fact, it is most strange that the far right in American politics seems to uniformly disbelieve global warming, but the connection to their other agenda (Christianization of America, anti-abortion, and low taxes for the wealthy) is difficult to understand.

However, Al Gore does not mention that

(i) Climatologists need funding for their work and they are unlikely to obtain funding if they don't identify a major problem facing humanity.
(ii) Like earthquake analysts who are always predicting the "big one is coming",

[2] With the current emphasis on greenhouse gases, we seem to have forgotten about conventional pollution (nitrogen and sulfur oxides, soot, ozone depletion, etc.). The satellite picture of Chinese pollution at *http://visibleearth.nasa.gov/view_rec.php?id=1036* demonstrates the extent of conventional pollution from China. In Graham Greene's book *Our Man in Havana*, the War Office is delighted to find a new super-weapon because "it will make the atomic bomb a conventional weapon," and "nobody worries about conventional weapons."

climatologists tend to be alarmists to call attention to the importance of their work.

(iii) The climatologists who use proxies to infer historical temperatures and derive global average temperatures are close-knit and have often co-published with one another. This *paleo-climatological group* has prevented valid criticism of their work from being published (see Section 2.2.3.7).

(iv) Those who generate global climate models use the world's biggest computers for which funding can only be justified to investigate a crisis.

(v) Most of the criticism of global-warming alarmism appears on Internet "blogs" which is ignored by the elite climatological science community. Yet, some of this criticism is valid.

(vi) Finally, the validity of a scientific theory is not a matter of voting (Foster, 2001).

Scene 26. We are treated to a view of more billowing black smoke. This is followed by a picture of scales with gold bars on one side, and the Earth on the other side. We are asked to choose between making money and saving the Earth. However, we are also assured that by saving the Earth we will also create wealth, although the details seem muddled.

He then suggests approaches to reduce emissions by increasing the efficiency of vehicles, buildings, appliances, etc., carbon sequestration, expansion of renewable energy. He points out the terrible disparity of mileage requirements for American cars vs. Europe and Asia. In this respect, he is right. American gasoline is too cheap, and cars are too big and heavy and too powerful. Even if you don't believe in global warming, the balance of payments and America's dependence on OPEC dictate that the U.S. needs to downsize vehicles and raise the price of gasoline. Increasing the efficiency of systems and renewable energy is vital and requires expanded tax incentives. Carbon sequestration needs further study. All of these steps are good for America and the world. Here, Al Gore is on target, independently of greenhouse gases.

Unfortunately, Al Gore concludes this scene with a strong endorsement of the Kyoto accords, which as we show in Chapter 8, is ill-conceived, impractical, and grossly unfair.

Scene 27. Al Gore closes with a pep talk. He mentions all of the crises that have faced the U.S., including the revolutionary war in 1776, the Civil War, women's suffrage, World War II, going to the Moon, conquering polio, and restoring the ozone layer. He says that if we put our minds and hearts to it, we can deal with global warming. However, in all the examples given, there was a clear-cut problem of known dimensions, whereas in global warming everything is much more nebulous.

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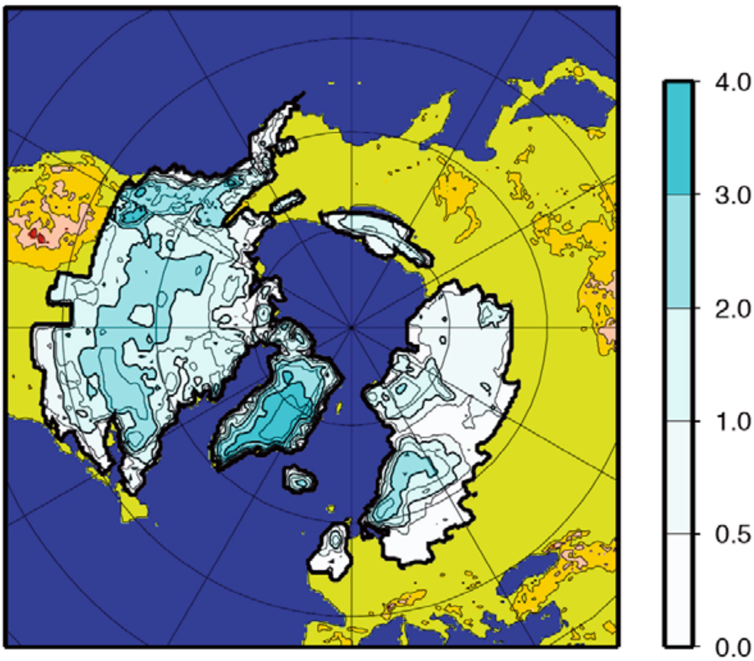

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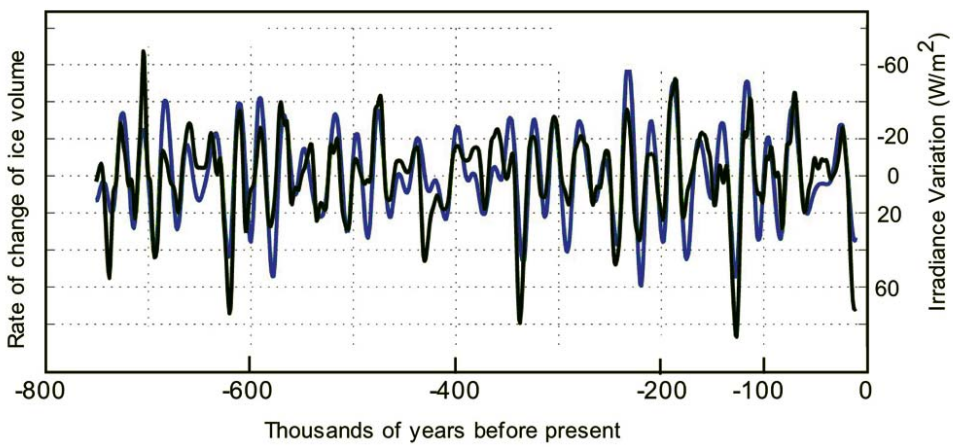

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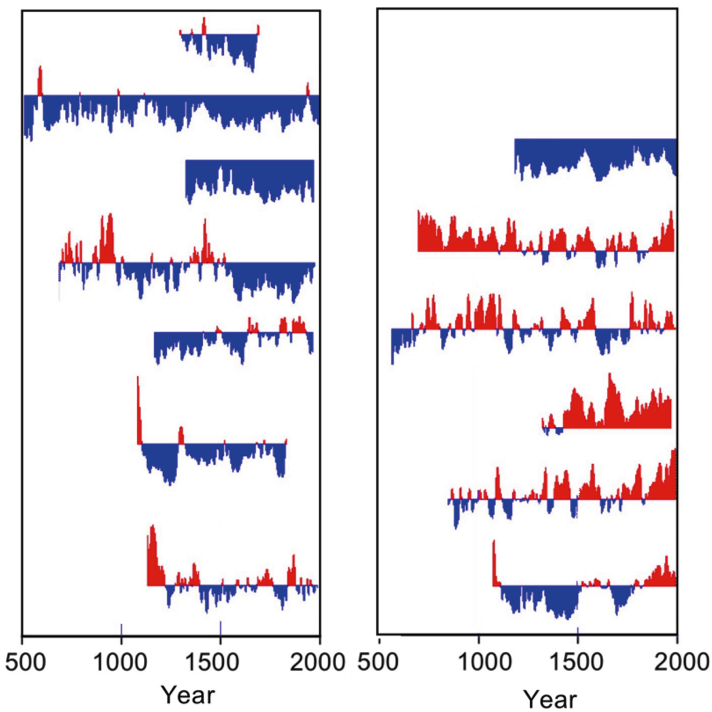

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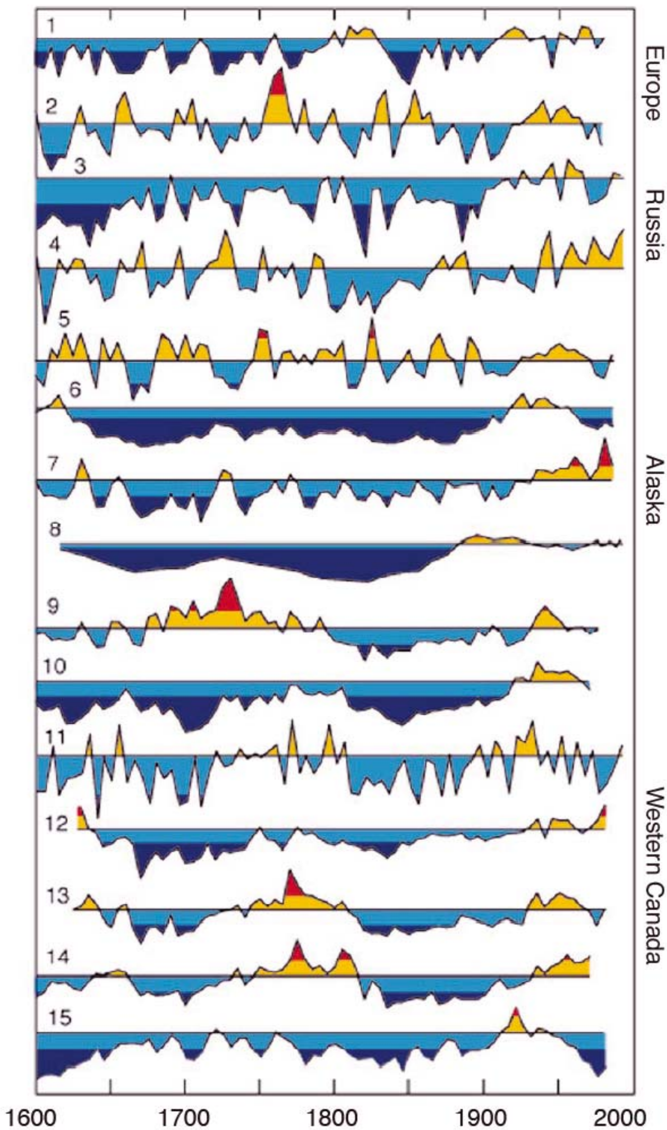

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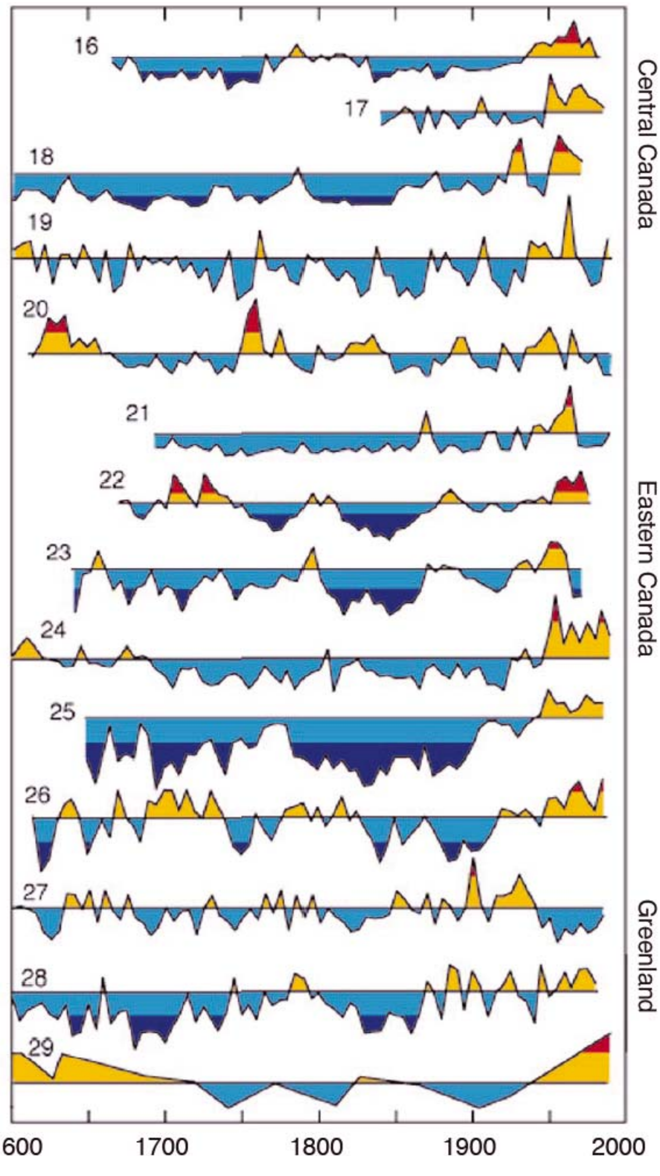

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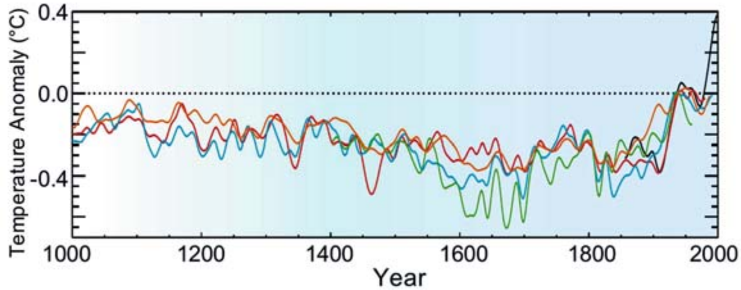

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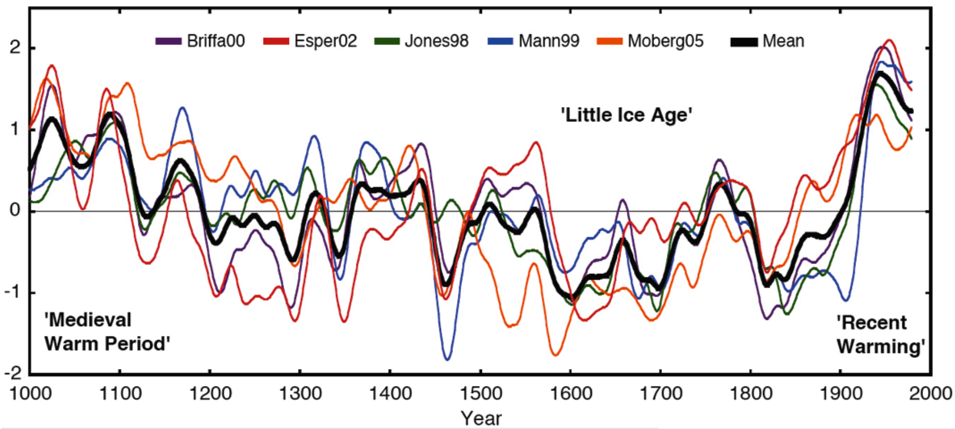

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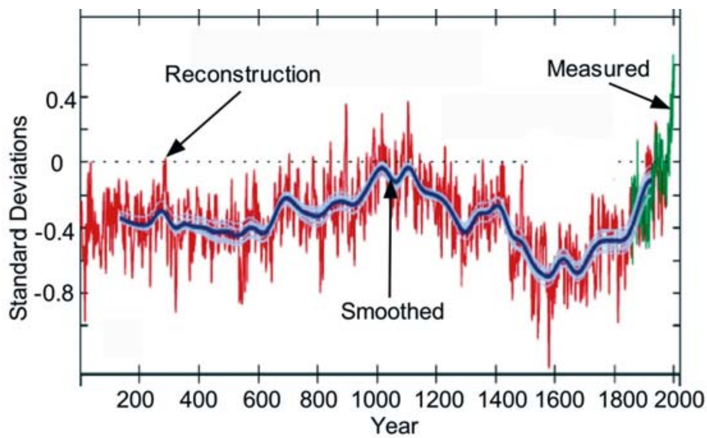

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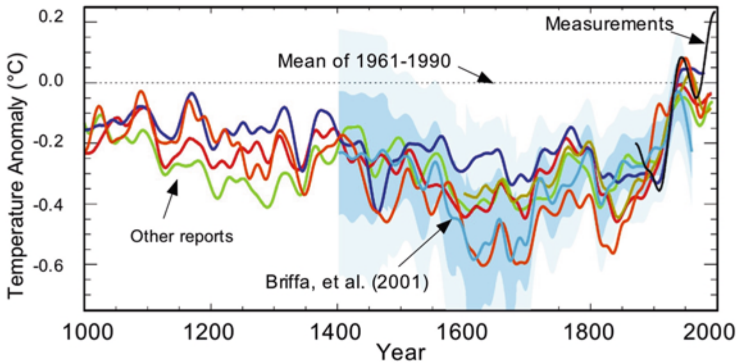

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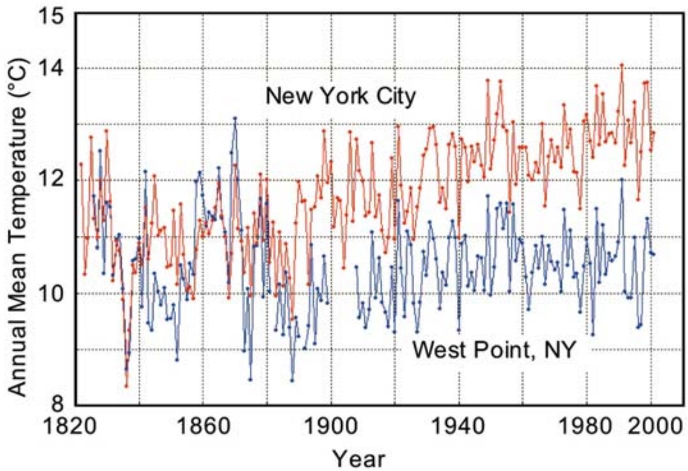

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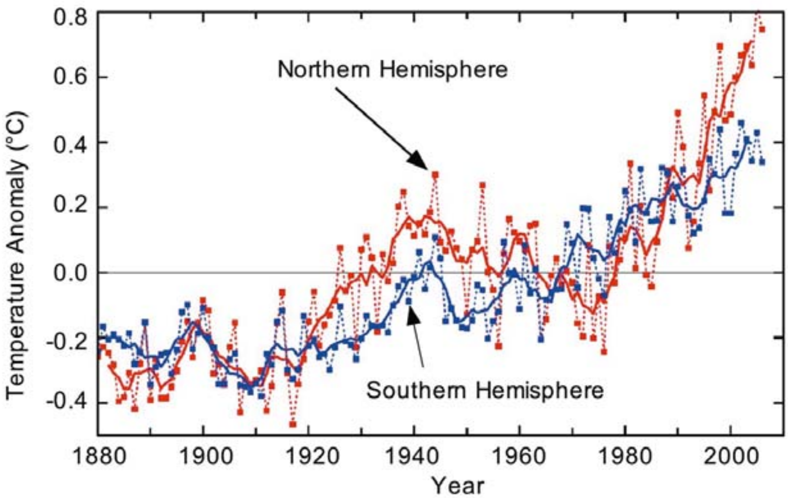

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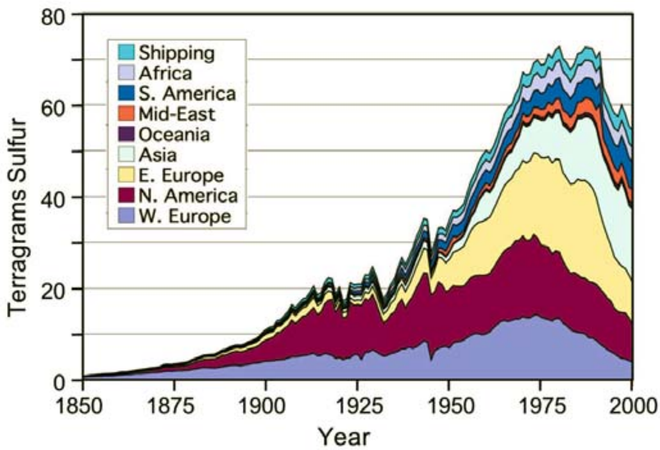

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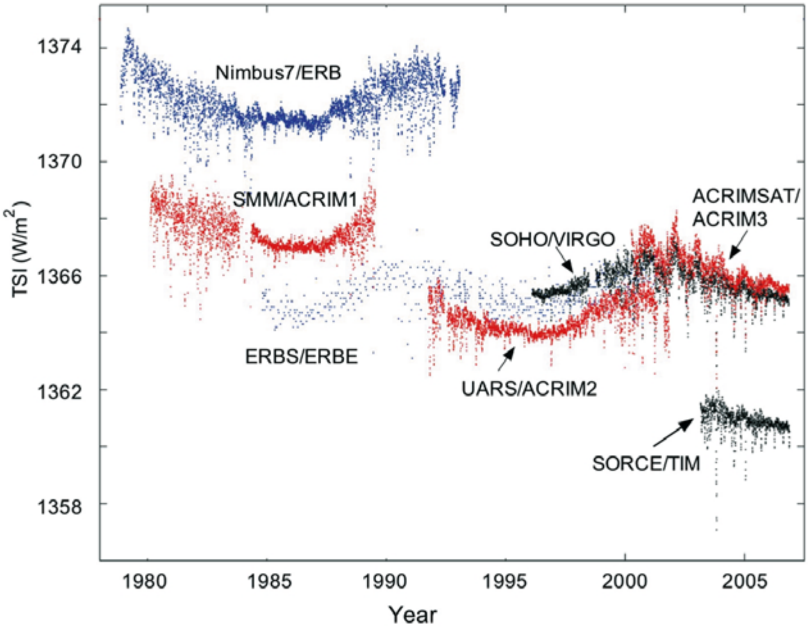

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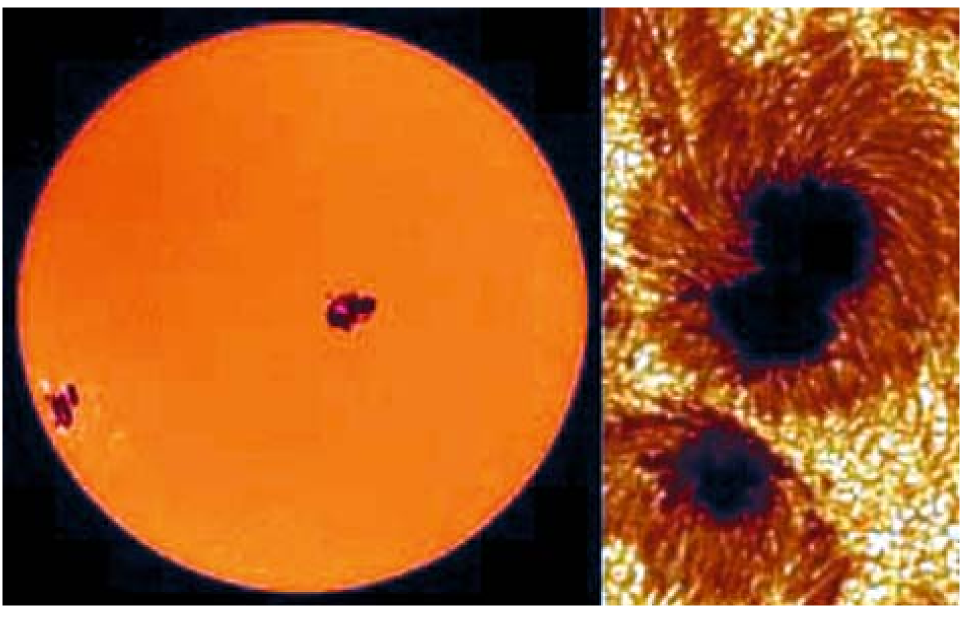

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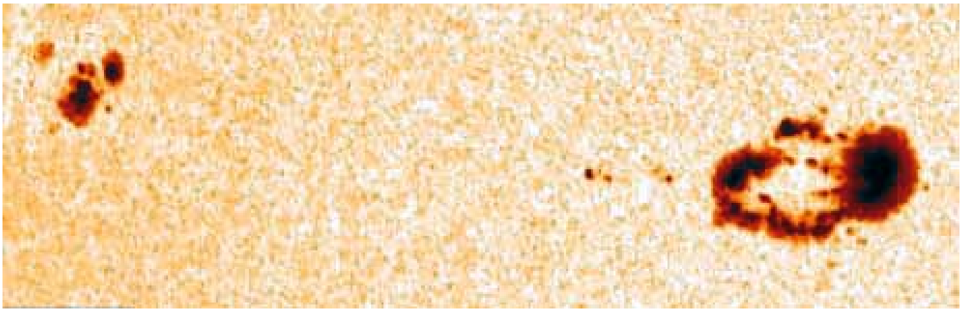

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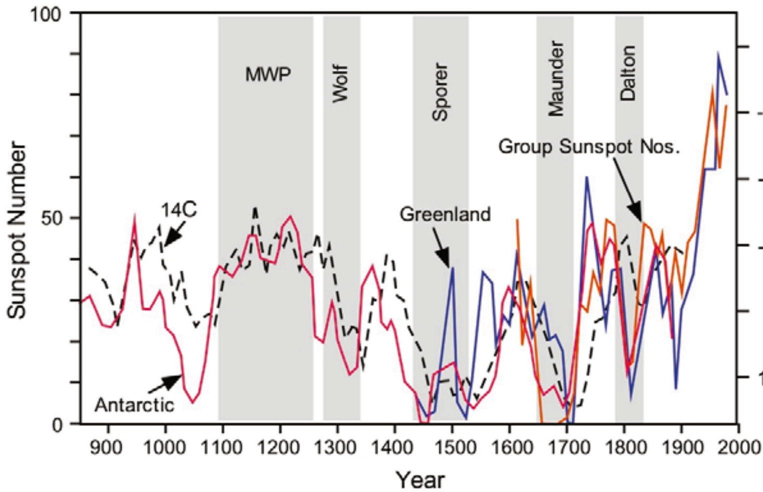

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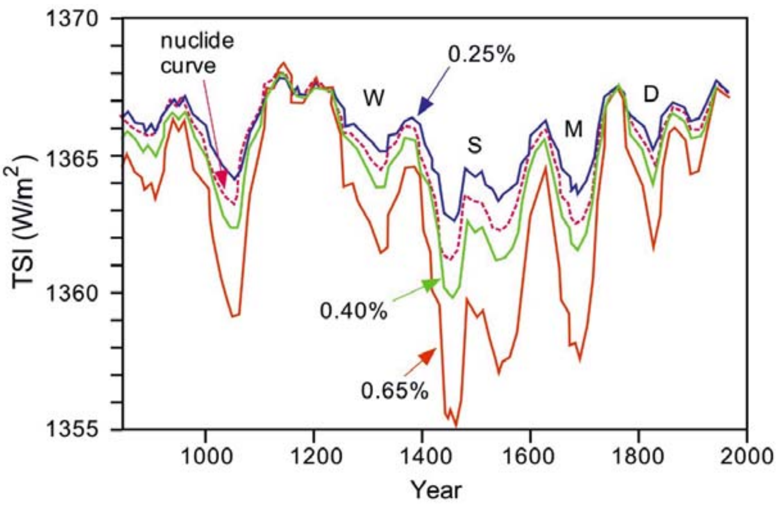

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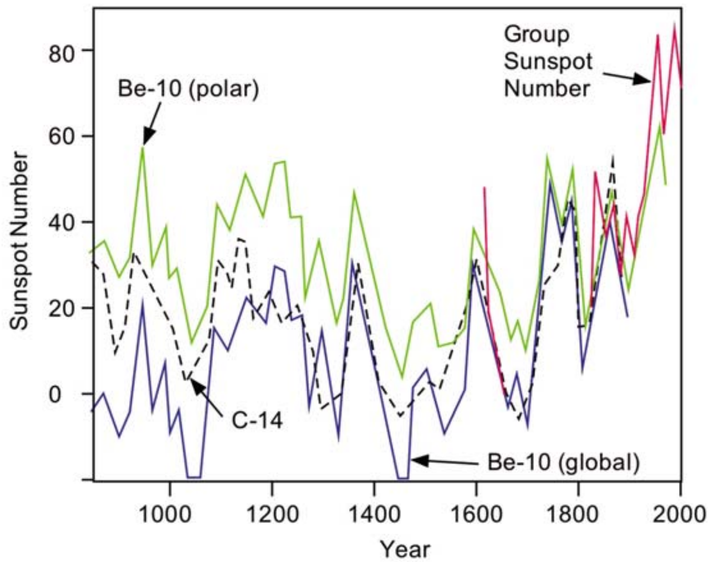

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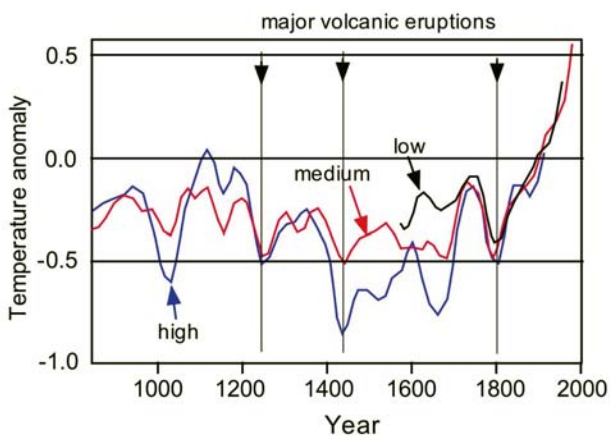

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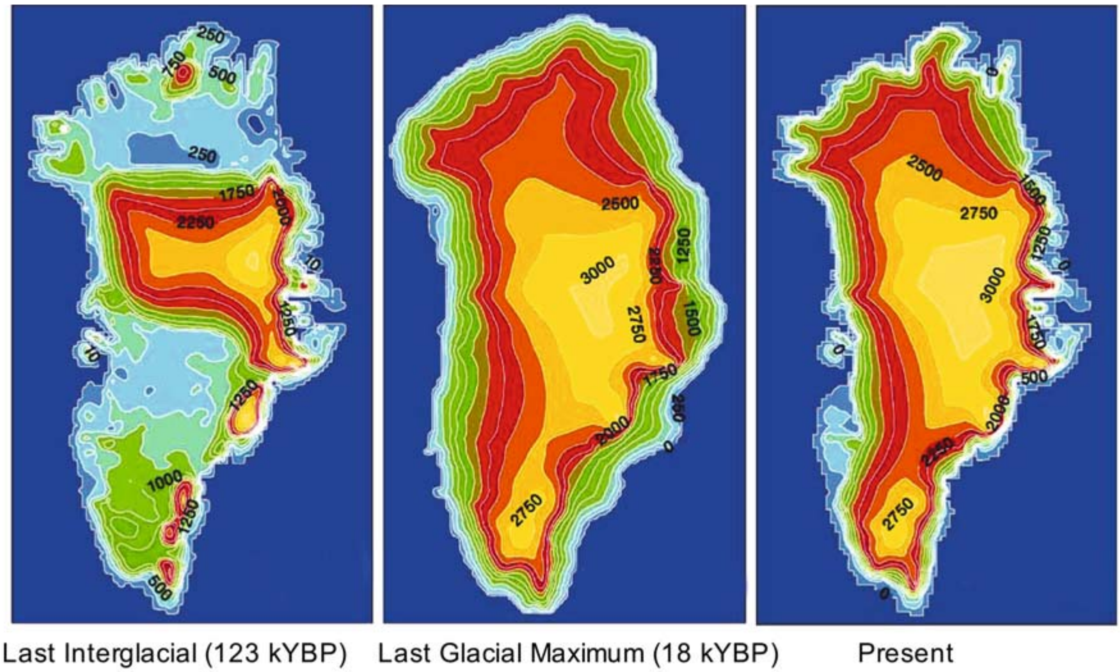

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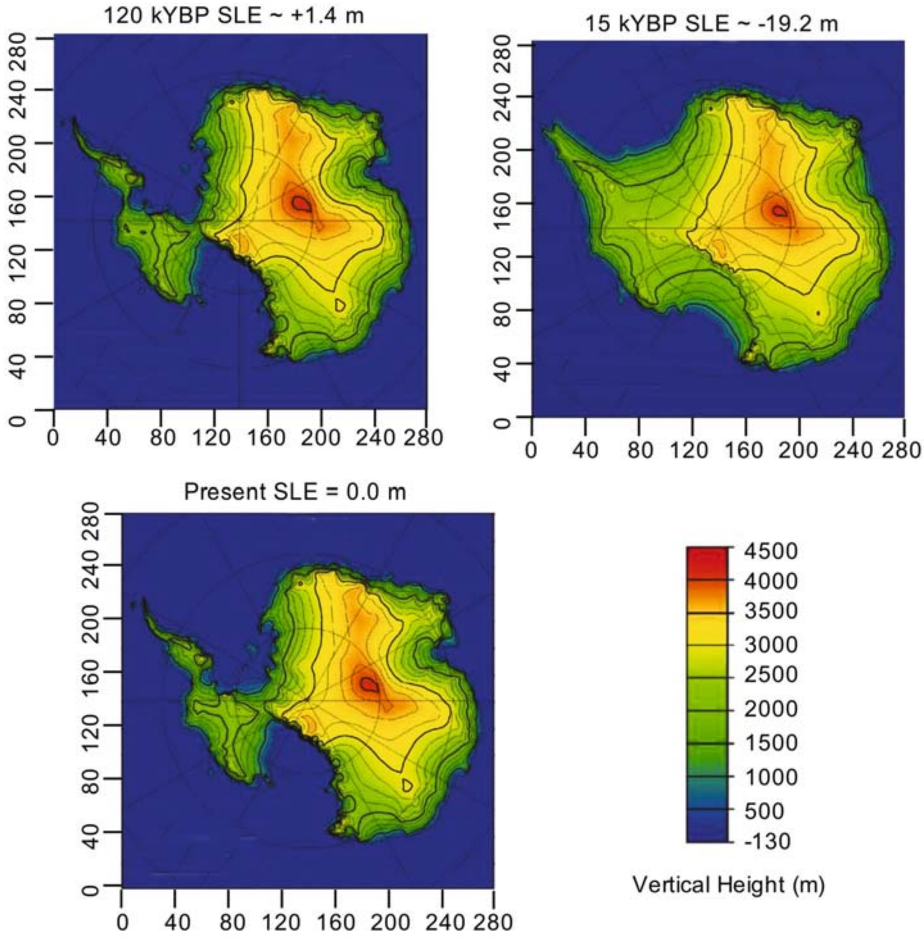

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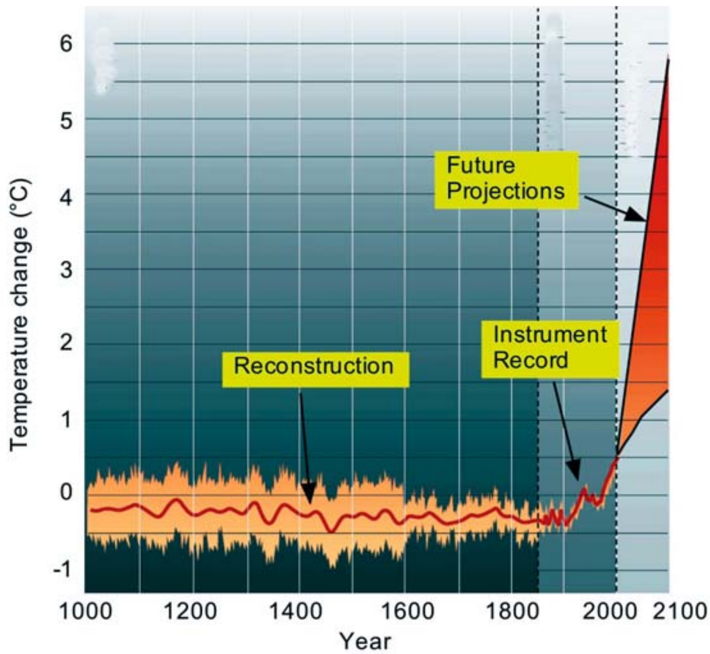

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