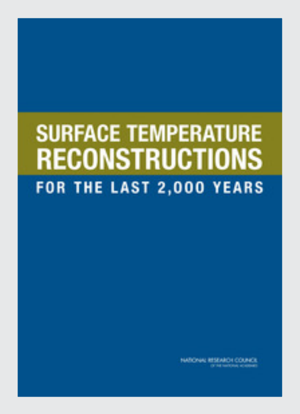

Surface Temperature Reconstructions for the Last 2,000 Years (2006)

DETAILS

160 pages | 7 x 10 | PAPERBACK
ISBN 978-0-309-10225-4 | DOI 10.17226/11676

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SUGGESTED CITATION

National Research Council 2006. *Surface Temperature Reconstructions for the Last 2,000 Years*. Washington, DC: The National Academies Press. https://doi.org/10.17226/11676.

SURFACE TEMPERATURE RECONSTRUCTIONS FOR THE LAST 2,000 YEARS

Committee on Surface Temperature Reconstructions for the Last 2,000 Years

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street NW Washington, DC 20001

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International Standard Book Number-10: 0-309-10225-1 (Book)
International Standard Book Number-13: 978-0-309-10225-4 (Book)
International Standard Book Number-10: 0-309-66144-7 (PDF)
International Standard Book Number-13: 978-0-309-66144-7 (PDF)

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, D.C. 20055; (800) 624-6242 or (202)334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America

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Foreword

Our understanding of climate and how it has varied over time is advancing rapidly as new data are acquired and new investigative instruments and methods are employed. Thus in 2005, I suggested to the U.S. Congress that the National Research Council (NRC) could help answer questions about the data and methods that have been used in constructing records of Earth's surface temperatures from times when there were no scientific instruments, using proxy indicators. How has temperature varied over the last 2,000 years? How certain is the answer to this question?

Subsequently, this study was requested by Representative Sherwood Boehlert, chairman of the Committee on Science, U.S. House of Representatives. Chairman Boehlert asked for a clear and concise report in a relatively short period of time, and the NRC agreed to undertake the study quickly. An *ad hoc* committee was formed, with the group carefully composed to include the breadth and depth of expertise and perspectives needed to analyze all aspects of how surface temperatures are estimated and interpreted and to comment generally on climate science. The NRC asked the committee to summarize current scientific information on the temperature record for the past two millennia, describe the main areas of uncertainty and how significant they are, describe the principal methodologies used and any problems with these approaches, and explain how central is the debate over the paleoclimate temperature record to the state of scientific knowledge on global climate change.

The committee has prepared a report that, in my view, provides policy makers and the scientific community with a critical view of surface temperature reconstructions and how they are evolving over time, as well as a good sense of how important our understanding of the paleoclimate temperature record is within the overall state of scientific knowledge on global climate change. The report does not make policy recommendations.

I thank the members of the committee, who worked intensely to produce this careful report in a short period of time and contributed much personal time, insight, and energy.

The NRC staff and all those who contributed papers, data, graphics, and other information, as well as the independent experts who participated in the rigorous review process, were essential participants.

Ralph J. Cicerone, President
National Academy of Sciences
Chair, National Research Council

Preface

This committee was asked to describe and assess the state of scientific efforts to reconstruct surface temperature records for the Earth over approximately the last 2,000 years. (The full Statement of Task appears in Appendix A.) Normally, a technical issue such as surface temperature reconstructions might not generate widespread attention, but this case brings interesting lessons about how science works and how science, especially climate science, is communicated to policy makers and the public. The debate began in 1998 when a paper by Michael Mann, Raymond Bradley, and Malcolm Hughes was published in the journal *Nature*. The authors used a new methodology to combine data from a number of sources to estimate temperatures in the Northern Hemisphere for the last six centuries and later for the last 1,000 years. This research received wide attention, in part because it was illustrated with a simple graphic, the so-called hockey stick curve, that many interpreted as definitive evidence of anthropogenic causes of recent climate change. The research was given prominence in the 2001 report of the Intergovernmental Panel on Climate Change and then was picked up by many in the wider science community and by the popular media.

Science is a process of exploration of ideas—hypotheses are proposed and research is conducted to investigate. Other scientists work on the issue, producing supporting or negating evidence, and each hypothesis either survives for another round, evolves into other ideas, or is proven false and rejected. In the case of the hockey stick, the scientific process has proceeded for the last few years with many researchers testing and debating the results. Critics of the original papers have argued that the statistical methods were flawed, that the choice of data was biased, and that the data and procedures used were not shared so others could verify the work. This report is an opportunity to examine the strengths and limitations of surface temperature reconstructions and the role that they play in improving our understanding of climate. The reconstruction produced by Dr. Mann and his colleagues was just one step in a long process of research, and it is not (as sometimes presented) a clinching argument for anthropogenic global warming, but rather one of many independent lines of research on global climate change.

Using multiple types of proxy data to infer temperature time series over large geographic regions is a relatively new area of scientific research, although it builds upon the considerable progress that has been made in deducing past temperature variations at single sites and local regions. Surface temperature reconstructions often combine data from a number of specialized disciplines, and few individuals have expertise in all aspects of the work. The procedures for dealing with these data are evolving—there is no one "right" way to proceed. It is my opinion that this field is progressing in a healthy manner. As in all scientific endeavors, research reported in the scientific literature is often "work in progress" aimed at other investigators, not always to be taken as individual calls for action in the policy community.

With this as context, the committee considered the voluminous literature pertinent to its charge and received briefings and written contributions from more than two dozen people. We have organized our report knowing that we have at least two different audiences—the science community and the policy community. The principal conclusions of the committee are listed in the Summary and explained in the Overview using nontechnical language. More extensive technical justifications for the committee's conclusions, including references, are presented in the chapters that follow.

Finally, let me thank the members of the Committee on Surface Temperature Reconstructions for the Last 2,000 Years. The committee worked tirelessly to assess the status of this field of research so that the public can see exactly what is involved, what we currently know about it, and what the prospects are for improving our understanding. We have tried to make clear how this piece of the climate puzzle fits into the broader discussions about global climate change.

Gerald R. North, *Chair*
Committee on Surface Temperature Reconstructions
for the Last 2,000 Years

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

David Brillinger, University of California, Berkeley
David Chapman, University of Utah
Julia Cole, University of Arizona
Thomas Crowley, Duke University
Alexander Flax, Independent consultant
Claus Fröhlich, PMOD Technologies
Ricardo Garcia-Herrera, Universidad Complutense de Madrid
Peter Huybers, Woods Hole Oceanographic Institution
Richard Muller, Lawrence Berkeley Laboratory
Robert Stine, University of Pennsylvania
Lonnie Thompson, The Ohio State University
Connie Woodhouse, National Oceanic and Atmospheric Administration
Carl Wunsch, Massachusetts Institute of Technology

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Andrew R. Solow, Woods Hole Oceanographic Institution, and Louis J. Lanzerotti, New

Jersey Institute of Technology. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Summary

Because widespread, reliable instrumental records are available only for the last 150 years or so, scientists estimate climatic conditions in the more distant past by analyzing *proxy evidence* from sources such as tree rings, corals, ocean and lake sediments, cave deposits, ice cores, boreholes, glaciers, and documentary evidence. For example, records of Alpine glacier length, some of which are derived from paintings and other documentary sources, have been used to *reconstruct* the time series of surface temperature variations in south-central Europe for the last several centuries. Studying past climates can help us put the 20th century warming into a broader context, better understand the climate system, and improve projections of future climate.

Starting in the late 1990s, scientists began combining proxy evidence from many different locations in an effort to estimate surface temperature changes averaged over broad geographic regions during the last few hundred to few thousand years. These *large-scale surface temperature reconstructions* have enabled researchers to estimate past temperature variations over the Northern Hemisphere or even the entire globe, often with time resolution as fine as decades or even individual years. This research, and especially the first of these reconstructions published in 1998 and 1999 by Michael Mann, Raymond Bradley, and Malcolm Hughes, attracted considerable attention because the authors concluded that the Northern Hemisphere was warmer during the late 20th century than at any other time during the past millennium. Controversy arose because many people interpreted this result as definitive evidence of anthropogenic causes of recent climate change, while others criticized the methodologies and data that were used.

In response to a request from Congress, this committee was assembled by the National Research Council to describe and assess the state of scientific efforts to reconstruct surface temperature records for the Earth over approximately the last 2,000 years and the implications of these efforts for our understanding of global climate change.

Figure S-1 shows a compilation of large-scale surface temperature reconstructions from different research groups, each using its own methodology and selection of proxies, as well as the instrumental record (beginning in 1856) of global mean surface temperature.

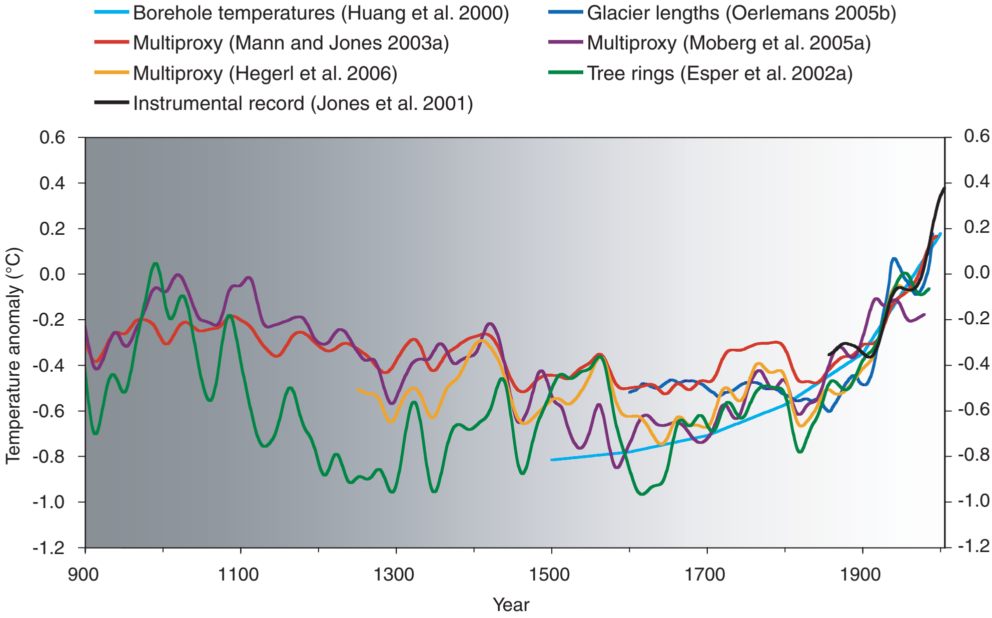

FIGURE S-1 Smoothed reconstructions of large-scale (Northern Hemisphere mean or global mean) surface temperature variations from six different research teams are shown along with the instrumental record of global mean surface temperature. Each curve portrays a somewhat different history of temperature variations and is subject to a somewhat different set of uncertainties that generally increase going backward in time (as indicated by the gray shading). This set of reconstructions conveys a qualitatively consistent picture of temperature changes over the last 1,100 years and especially over the last 400. See Figure O-5 for details about each curve.

After considering all of the available evidence, including the curves shown in Figure S-1, the committee has reached the following conclusions:

- The instrumentally measured warming of about 0.6°C during the 20th century is also reflected in borehole temperature measurements, the retreat of glaciers, and other observational evidence, and can be simulated with climate models.
- Large-scale surface temperature reconstructions yield a generally consistent picture of temperature trends during the preceding millennium, including relatively warm conditions centered around A.D. 1000 (identified by some as the "Medieval Warm Period") and a relatively cold period (or "Little Ice Age") centered around 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 justified by the consistency of the evidence from a wide variety of geographically diverse proxies.
- Less confidence can be placed in large-scale surface temperature reconstructions for the period from A.D. 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 A.D. 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.
- Very little confidence can be assigned to statements concerning the hemispheric mean or global mean surface temperature prior to about A.D. 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.

The main reason that our confidence in large-scale surface temperature reconstructions is lower before A.D. 1600 and especially before A.D. 900 is the relative scarcity of precisely dated proxy evidence. Other factors limiting our confidence in surface temperature reconstructions include: the relatively short length of the instrumental record (which is used to calibrate and validate the reconstructions); the fact that all proxies are influenced by a variety of climate variables; the possibility that the relationship between proxy data and local surface temperatures may have varied over time; the lack of agreement as to which methods are most appropriate for calibrating and validating large-scale reconstructions and for selecting the proxy data to include; and the difficulties associated with constructing a global or hemispheric mean temperature estimate using data from a limited number of sites and with varying chronological precision. All of these considerations introduce uncertainties that are difficult to quantify.

Despite these limitations, the committee finds that efforts to reconstruct temperature histories for broad geographic regions using multiproxy methods are an important contribution to climate research and that these large-scale surface temperature reconstructions contain meaningful climatic signals. The individual proxy series used to create these reconstructions generally exhibit strong correlations with local environmental conditions, and in most cases there is a physical, chemical, or physiological reason why the proxy reflects local temperature variations. Our confidence in the results of these reconstructions becomes stronger when multiple independent lines of evidence point to the same general result, as in the case of the Little Ice Age cooling and the 20th century warming.

The basic conclusion of Mann et al. (1998, 1999) was that the late 20th century warmth in the Northern Hemisphere was unprecedented during at least the last 1,000 years. This conclusion has subsequently been supported by an array of evidence that includes both additional large-scale surface temperature reconstructions and pronounced changes in a variety of local proxy indicators, such as melting on ice caps and the retreat of glaciers around the world, which in many cases appear to be unprecedented during at least the last 2,000 years. Not all individual proxy records indicate that the recent warmth is unprecedented, although a larger fraction of geographically diverse sites experienced exceptional warmth during the late 20th century than during any other extended period from A.D. 900 onward.

Based on the analyses presented in the original papers by Mann et al. and this newer supporting evidence, the committee finds it plausible that the Northern Hemisphere was warmer during the last few decades of the 20th century than during any comparable period over the preceding millennium. The substantial uncertainties currently present in the quantitative assessment of large-scale surface temperature changes prior to about A.D. 1600 lower our confidence in this conclusion compared to the high level of confidence we place in the Little Ice Age cooling and 20th century warming. Even less confidence can be placed in the original conclusions by Mann et al. (1999) that "the 1990s are likely the warmest decade, and 1998 the warmest year, in at least a millennium" because the uncertainties inherent in temperature reconstructions for individual years and decades are larger than those for longer time periods and because not all of the available proxies record temperature information on such short timescales.

Surface temperature reconstructions for periods prior to the industrial era are only one of multiple lines of evidence supporting the conclusion that climatic warming is occurring in response to human activities, and they are not the primary evidence.

Surface temperature reconstructions also provide a useful source of information about the variability and sensitivity of the climate system. To within existing uncertainties, climate model simulations show that the estimated temperature variations during the two millennia prior to the Industrial Revolution can be explained plausibly by estimated variations in solar radiation and volcanic activity during the same period.

Large-scale surface temperature reconstructions have the potential to further improve our knowledge of temperature variations over the last 2,000 years, particularly if additional proxy evidence can be identified and obtained from areas where the coverage is relatively sparse and for time periods before A.D. 1600 and especially before A.D. 900. Furthermore, it would be helpful to update proxy records that were collected decades ago, in order to develop more reliable calibrations with the instrumental record. Improving access to data used in publications would also increase confidence in the results of large-scale surface temperature reconstructions both inside and outside the scientific community. New analytical methods, or more careful use of existing ones, may also help circumvent some of the existing limitations associated with surface temperature reconstructions based on multiple proxies. Finally, because some of the most important potential consequences of climate change are linked to changes in regional circulation patterns, hurricane activity, and the frequency and intensity of droughts and floods, regional and large-scale reconstructions of changes in other climatic variables, such as precipitation, over the last 2,000 years would provide a valuable complement to those made for temperature.

Overview

The Earth warmed by roughly 0.6°C (1°F) during the 20th century and is projected to warm by an additional ~2–6°C during the 21st century.[1] Paleoclimatology, or the study of past climates, can help place this warming in the context of natural climate variability. Lessons learned from studying past climates can also be applied to improving projections of how the climate system will respond to future changes in greenhouse gas concentrations and other climate forcings, as well as how ecosystems and societies might be affected by climate change.

Widespread, reliable instrumental records are available only for the last 150 years or so. To study how climatic conditions varied prior to the time of the Industrial Revolution, paleoclimatologists rely on *proxy evidence* such as tree rings, corals, ocean and lake sediments, cave deposits, fossils, ice cores, borehole temperatures, glacier length records, and documentary evidence. For example, records of Alpine glacier length, some of which are derived from paintings and other documentary evidence, have been used to *reconstruct* the time series of surface temperature variations in south-central Europe for the last several centuries. Until recently, most reconstructions of climate variations over the last few thousand years focused on specific locations or regions. Starting in the 1990s, researchers began to combine proxy records from different geographic regions, often using a variety of different types of records, in an effort to document large-scale climate changes over the last few millennia. Most of these *large-scale surface temperature reconstructions* have focused on hemispheric average or global average surface temperatures over the last few hundred to few thousand years. These reconstructions, and in particular the following questions, are the focus of this report:

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[1] This Overview is written for a nontechnical audience and uses minimal referencing. The arguments and evidence to support the committee's findings are discussed and referenced in Chapters 1–11. This statement, for example, is supported by original research by Smith and Reynolds (2005), Jones et al. (2001), and Hansen et al. (2001), as discussed in Chapter 2.

- What kinds of proxy evidence can be used to estimate surface temperatures for the last 2,000 years?
- How are proxy data used to reconstruct surface temperatures over different geographic regions and time periods?
- What is our current understanding of how the hemispheric mean or global mean surface temperature has varied over the last 2,000 years?
- What conclusions can be drawn from large-scale surface temperature reconstructions?
- What are the limitations and strengths of large-scale surface temperature reconstructions?
- What do climate models and forcing estimates tell us about the last 2,000 years?
- How central are large-scale surface temperature reconstructions to our understanding of global climate change?
- What comments can be made on the value of exchanging information and data?
- What might be done to improve our understanding of climate variations over the last 2,000 years?

What kinds of proxy evidence can be used to estimate surface temperatures for the last 2,000 years?

Instrumental Records

Combining instrumental records to calculate large-scale surface temperatures requires including a sufficient number of instrumental sites with wide geographic distribution to get a representative estimate. Instrumental temperature records extend back over 250 years in some locations, but only since the middle of the 19th century has there been a sufficient number of observing stations to estimate the average temperature over the Northern Hemisphere or over the entire globe. Tropical measurements are particularly useful for estimating global mean temperature because tropical temperature variations tend to track global mean variations more closely.

Documentary and Historical Records

In many parts of the world, the surface temperature record can be extended back several centuries by examining historical documents such as logbooks, journals, court records, and the dates of wine harvests. This evidence shows that several regions were relatively cool from about 1500 to 1850, a period sometimes referred to as the Little Ice Age. Historical evidence also suggests that Europe and East Asia, in particular, experienced periods of relative warmth during the medieval interval from roughly A.D. 900 to 1300. In contrast to the widespread warming of the 20th century, the timing of these earlier warm episodes appears to have varied from location to location, but the sparseness of data precludes certainty on this point.

In areas where writing was not widespread or preserved, archeological evidence such as excavated ruins can also sometimes offer clues as to how climate may have been changing at certain times in history and how human societies may have responded to those changes. However, the interpretation of historical, documentary, and archeological evidence is often confounded by factors such as disease outbreaks and societal changes. Hence, climatologists more often rely on natural proxy evidence to produce quantitative reconstructions of past climates and use historical and archeological evidence, when it is available, to provide a consistency check.

Tree Rings

Tree ring formation is influenced by climatic conditions, especially in areas near the edge of the geographic distribution of tree species. At high latitudes and/or at high elevations, tree ring growth is related to temperature, and thus trees from these sites are commonly used as a basis for surface temperature reconstructions. Cores extracted from the trees provide annually resolved time series of tree ring width and of wood properties, such as density and chemical composition, within each ring. In some cases, records from living trees can be matched with records from dead wood to create a single, continuous chronology extending back several thousand years.

Tree ring records offer a number of advantages for climate reconstruction, including wide geographic availability, annual to seasonal resolution, ease of replication, and internally consistent dating. Like other proxies, tree rings are influenced by biological and environmental factors other than climate. Site selection and quality control procedures have been developed to account for these confounding factors. In the application of these procedures, emphasis is placed on replication of records both within a site and among sites and on numerical calibration against instrumental data.

Corals

The annual bands in coral skeletons also provide information about environmental conditions at the time that each band was formed. This information is mostly derived from changes in the chemical and isotopic composition[2] of the coral, which reflects the temperature and isotopic composition of the water in which it formed. Since corals live mostly in tropical and subtropical waters, they provide a useful complement to records derived from tree rings. Coral skeleton chemistry is influenced by several variables, and thus care must be taken when selecting coral samples and when deriving climate records from them. Thus far, most of the climate reconstructions based on corals have been regional in scale and limited to the last few hundred years, but there is now work toward establishing longer records by sampling fossil corals.

Ice Cores

Oxygen isotopes measured in ice cores extracted from glaciers and ice caps can be used to infer the temperature at the time when the snow was originally deposited. For the most recent 2,000 years, the age of the ice can in most places be determined by counting annual layers. The isotopic composition of the ice in each layer reflects both the temperature in the region where the water molecules originally evaporated far upwind of the glacier and the temperature of the clouds in which the water vapor molecules condensed to form snowflakes. The long-term fluctuations in temperature

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[2] ***Isotopic composition*** of a particular element is the relative abundance of atoms of that element with differing numbers of neutrons in their nuclei.

reconstructions derived from ice cores can be cross-checked against the vertical temperature profiles in the holes out of which they were drilled (see below). Ice-isotope-based reconstructions are available only in areas that are covered with ice that persists on the landscape (e.g., Greenland, Antarctica, and some ice fields atop mountains in Africa, the Andes, and the Himalayas). The interpretation of oxygen isotope measurements in tropical ice cores is more complicated than for polar regions because it depends not only on temperature but also on precipitation in the adjacent lowlands.

Marine and Lake Sediments

Cores taken from the sediments at the bottoms of lakes and ocean regions can be analyzed to provide evidence of past climatic change. Sediment cores can be analyzed to determine the temperature of the water from which the various constituents of the sediment were deposited. This information, in turn, can be related to the local surface temperature. Records relevant to temperature include oxygen isotopes, the ratio of magnesium to calcium, and the relative abundance of different microfossil types with known temperature preferences (such as insects) or with a strong temperature correlation (e.g., diatoms and some other algae). Changes in the properties of sediments are also of interest. For example, during cold epochs icebergs streaming southward over the North Atlantic carried sand and gravel and deposited it in sediments at the latitudes where they melted; the properties of this material are indicative of the generally colder conditions in the region where the icebergs originated.

Ocean and lake sediments typically accumulate slowly, and the layering within them tends to be smoothed out by bottom-dwelling organisms. Hence it is only in regions where sedimentation rates are extraordinarily high (e.g., the Bermuda Rise, the northwest coast of Africa) or in a few oxygen-deprived areas (e.g., the Santa Barbara Basin, the Cariaco Basin off Venezuela, or in deep crater lakes) that sediments can be dated accurately enough to provide information on climate changes during the last 2,000 years. More slowly accumulating sediments from ocean basins throughout the world are one of our main sources of information on climate variations on timescales of millennia and longer.

Boreholes

Past surface temperatures can also be estimated by measuring the vertical temperature profile down boreholes drilled into rock, frozen soils, and ice. Temperature variations at the Earth's surface diffuse downward with time by the same process that causes the handle of a metal spoon to warm up when it is immersed in a cup of hot tea. The governing equation for this process can be used to convert the vertical profile of temperature in a borehole into a record of surface temperature versus time. Features in the vertical temperature profile are smoothed out as they propagate downward, resulting in a loss of information. Hence, large-scale surface temperature reconstructions based on borehole measurements typically extend back only over a few centuries, with coarse time resolution.

Hundreds of holes have been drilled to depths of several hundred meters below the surface at sites throughout the Northern Hemisphere and at a smaller number of sites in the Southern Hemisphere. Many of these "boreholes of opportunity" were drilled for other reasons such as mineral exploration. Specialists acknowledge several different types of errors in borehole-based temperature reconstructions, such as an imperfect match between ground temperature and near-surface air temperature, but available evidence indicates that these errors do not significantly influence reconstructions for large regions using many boreholes. Boreholes drilled through glacial ice to extract ice cores are free from many of these problems and can be analyzed jointly with the oxygen isotope record from the corresponding core, yielding a much longer and more accurate temperature reconstruction than is possible with boreholes drilled through rock or permafrost. However, ice-based boreholes are available only in areas with a thick cover of ice.

Glacier Length Records

Records of the lengths of many mountain glaciers extend back over several hundred years. Relatively simple models of glacier dynamics can be used to relate changes in glacial extent to local changes in temperature on timescales of a few decades. The rates of warming inferred from this technique compare quite well with local instrumental measurements over the last century or so.

Most glacier length records are derived from direct observations reported in the historical record, such as paintings that show how far local glaciers extended into their valleys at specific times in history. Natural evidence can also be used to infer past glacial extent. For example, organic materials such as shrubs have recently been uncovered behind rapidly retreating glaciers in several locations. These relics, which were killed and incorporated into the ice when they were overtaken by the glacier at a time when the glacier was advancing, can be dated using radiocarbon to estimate how long it has been since the glacier was last absent from that location.

Other Proxies

Several other types of proxy evidence have been used to reconstruct surface temperatures on a regional basis. For example, calcium carbonate formations in caves, such as stalagmites, and layered organisms found in marine caves called *sclerosponges* have been analyzed, using methods similar to those used to analyze coral skeletons, to obtain information on past climate variations.

How are proxy data used to reconstruct surface temperatures?

Knowledge of chemical, biological, and/or ecological processes is used to guide the sampling, analysis, and conversion of natural proxy data into surface temperature reconstructions. Borehole temperature measurements and glacier length records can be converted to temperature time series using physically based models with a few key variables. For all other proxies used for the reconstructions discussed in this report, statistical techniques are employed to define the relationship between the proxy measurements and the concurrent instrumental temperature record, and then this relationship is used to reconstruct past temperature variations from the remaining proxy data. The basic methodology is shown schematically in Figure O-1 and described in more detail in the paragraphs that follow. There are variations in the way in which these methods are applied to different proxies and variations in the way that different research groups apply these methods.

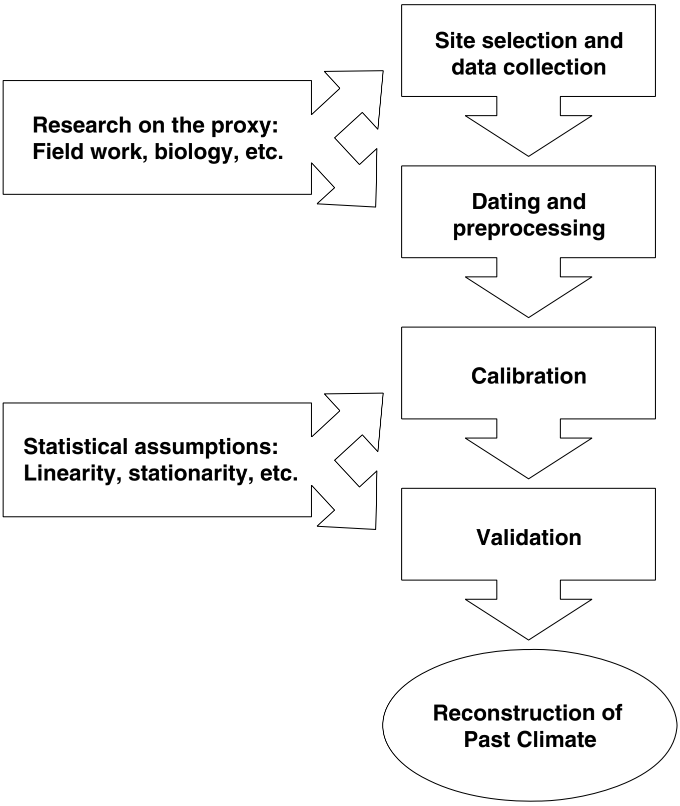

FIGURE O-1 Schematic diagram of the general methodology used to reconstruct past climates, including surface temperature reconstructions.

1. *Site selection and data collection*—choosing and sampling the particular site and proxy to be used for the reconstruction. In principle, proxy and site selection should be based on an understanding of the physical, chemical, physiological, and/or ecological processes that determine how the proxy reacts to local environmental conditions. In practice, the type and amount of proxy data available at any given location are limited, and the relationship between the proxy and the climate variable of interest is not exactly known. Researchers follow established techniques to collect and measure the samples, while looking for sites where proxy records are as long, continuous, and representative of the target climatic variable as possible.

2. *Dating and preprocessing*—synchronizing the individual proxy records so they can be plotted on a common time axis. For tree rings, dating is accurate to the calendar year. Dating of corals, ice cores, and historical documents is also often accurate to within a year. Other proxies typically have lower temporal resolution. Adjustments may be performed at this stage to reduce the variations in the proxy time series that are

related to nonclimatic factors. Time histories derived from different samples from the same area may also be averaged or spliced together to construct longer and more representative proxy records.

3. *Calibration*—placing a temperature scale on the "proxy thermometer." This step typically involves the use of a statistical technique called *linear regression*. Data can be collected on how proxies respond to temperature in the laboratory or in the field, in which case statistical tests of theoretical or empirical constraints can be used to guide the reconstruction. Since these experimental and monitoring activities cannot be performed for every single proxy record, many reconstructions rely on linear regression to derive an empirical relationship between the proxy time series and the surface temperature in the region of interest. The manner in which this methodology is applied (e.g., whether the regression is based on annual means, 10-year means, or 30-year means, and whether trends are removed from the data) varies from study to study.

4. *Validation*—testing whether the empirical relationship derived in step 3 has measurable skill, and quantitatively assessing its performance. Typically, portions of the instrumental record are withheld during calibration. The linear regression coefficients derived from the calibration are then used to reconstruct the temperature time series from the proxy data during this validation period, and the reconstructed temperatures are compared with the corresponding instrumental temperature record. A number of different metrics may be used to assess the skill of the reconstruction during the validation step.

5. *Reconstruction*—the regression algorithm developed in step 3 is applied to the proxy data that are available prior to the instrumental record to extend the temperature reconstruction back in time. Error bars are sometimes assigned to the reconstruction based on how well it matches the observed surface temperature variations during the validation period in step 4. In general, the width of the error bars will vary in time according to the quantity and quality of available proxy evidence. As discussed in further detail below, these error bars do not account for all of the uncertainties present in the reconstruction.

Although calibration against instrumental data is a necessary step to determine how well proxies reflect climate, proxy records are not perfect thermometers; that is, the true relationship between the proxy and the local surface temperature is not known exactly. Furthermore, all proxies are influenced by variables other than temperature, and it can be difficult to account for these confounding factors. The use of linear regression in the calibration step is also a concern because reconstructions derived from linear regression models based on the method of least squares exhibit less variability than the instrumental records they are calibrated against. Additional variance can be lost if the individual proxy records within the reconstruction are not spliced together properly. Finally, in applying these methods it is assumed that the correlation between the proxy data and the instrumental record will hold up over the entire period of the reconstruction, but this assumption is difficult to test.

Large-Scale Surface Temperature Reconstructions

Several surface temperature reconstructions carried out since the mid-1990s involve the synthesis of data from many different locations, often from disparate sources such as tree rings, corals, and ice cores, to infer patterns of temperature variations over large geographic areas.[3] The methodology used to carry out these large-scale surface temperature reconstructions is broadly similar to the methodology described in the preceding section, but modified in the following ways. In step 1, instead of choosing sites to sample, one chooses the particular set of proxies to be used as the basis for the reconstruction. The reconstruction might be based on just one kind of proxy or a combination of several different kinds of proxies (in which case it is referred to as a *multiproxy* reconstruction), which may have been sampled by a number of different researchers at different times without knowledge that their data would be used for this purpose. To obtain enough spatial coverage, some of the reconstructions include proxies that may be more sensitive to precipitation than they are to temperature, in which case statistical techniques are used to infer the temperature signal, exploiting the spatial relationship between temperature and precipitation fields.

There are two general approaches that are commonly used to perform the calibration, validation, and reconstruction steps (steps 3, 4, and 5 in Figure O-1) for large-scale surface temperature reconstructions. In the first approach, proxies are calibrated against the time series of the dominant patterns of spatial variability in the instrumental temperature record and the results are combined to yield a time series of large-scale average temperature. In the second approach, the individual proxy data are first composited and then this series is calibrated directly against the time series of large-scale temperature variations.

Both the number and the quality of the proxy records available for surface temperature reconstructions decrease dramatically moving backward in time. At present fewer than 30 annually resolved proxy time series are available for A.D. 1000; relatively few of these are from the Southern Hemisphere and even fewer are from the tropics (Figure O-2). Although it is true that fewer sites are required for defining long-term (e.g., century-to-century) variations in hemispheric mean temperature than for short-term (e.g., year-to-year) variations, the coarse spatial sampling limits our confidence in hemispheric mean or global mean temperature estimates prior to about A.D. 1600 and makes it difficult to generate meaningful quantitative estimates of global temperature variations prior to about A.D. 900. Moreover, the instrumental record is shorter than some of the features of interest in the preindustrial period, so there are very few statistically independent pieces of information in the instrumental record for calibrating and validating long-term temperature reconstructions.

Climate Models and the Climate System

Part of the natural variability in the Earth's temperature is generated by processes operating within the confines of the climate system and part of it is generated by *forcings* external to the climate system. For the last 2,000 years, these external forcings include volcanic eruptions, variations in the intensity of incoming solar radiation, and changes in greenhouse gas concentrations. The direct effect of these forcings on the Earth's global mean surface temperature is modified by the presence of *feedbacks* in

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[3] This report focuses on reconstructions of global mean or hemispheric mean surface temperature. Reconstructions for the Northern Hemisphere are more common because the number of proxy records available from the Southern Hemisphere is limited.

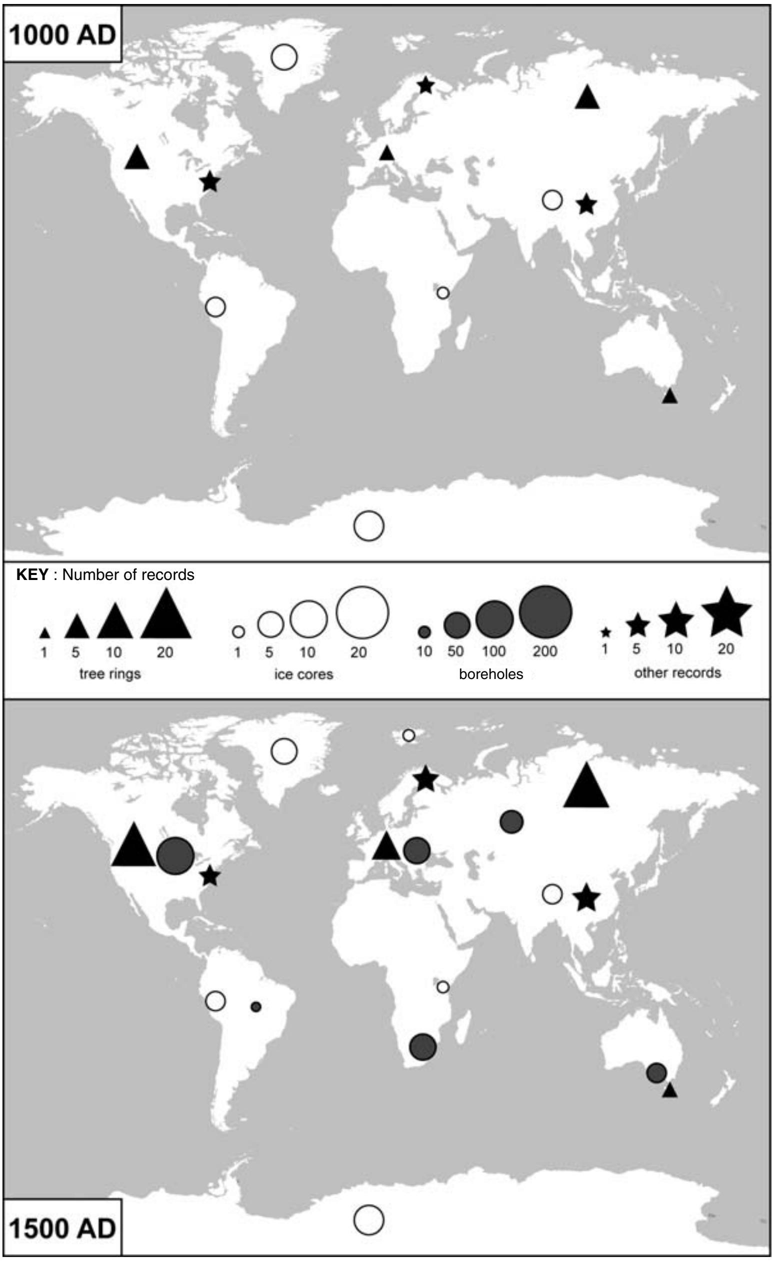

FIGURE O-2 Regional distribution of tree ring, borehole, ice core, and "other" records used to create the large-scale surface temperature reconstructions in Figure S-1 (and Figure O-5) for (top) A.D. 1000 and (bottom) A.D. 1500. "Other records" include marine and lake sediment cores, cave carbonates, and documentary records. The indicated distribution is approximate; for example, several deep-sea sediment cores are not indicated geographically. SOURCE: Data from Huang et al. (2000), Mann and Jones (2003a), Esper et al. (2002a), and Moberg et al. (2005a).

the climate system, such as the one involving the increase in water vapor with increasing temperature. Climate models are often used to estimate the strength of the various feedbacks in the climate system and the overall *sensitivity* of the Earth's global mean surface temperature to a prescribed forcing, such as a doubling of atmospheric carbon dioxide concentration.

Climate sensitivity can also be estimated by forcing climate models with the observed or reconstructed external forcings of the climate system over a certain time period and comparing the model response to the observed or reconstructed surface temperature during the same period. This strategy can be applied to past climatic variations on timescales ranging from a few years (in the case of a single volcanic eruption) to tens of thousands of years (as in the simulation of the Ice Ages). Modeling climate variations on the timescale of the last 2,000 years is particularly challenging because the external forcings that operate on this timescale are relatively small and are not as well known as the forcings in the above examples.

What is our current understanding of how the hemispheric mean or global mean surface temperature has varied over the last 2,000 years?

To understand the current state of the science surrounding large-scale surface temperature reconstructions, it is helpful to first review how these efforts have evolved over the last few decades. In a chapter titled "Observed Climate Variability and Change," IPCC (1990) presented a schematic depiction, reproduced in Figure O-3, of global temperature variations extending from 1975 back to A.D. 900. The Medieval Warm Period and Little Ice Age labels that appear in the graphic refer to features in European and other regional time series that were assumed to be indicative of global mean conditions. The peak-to-peak amplitude of the temperature fluctuations was

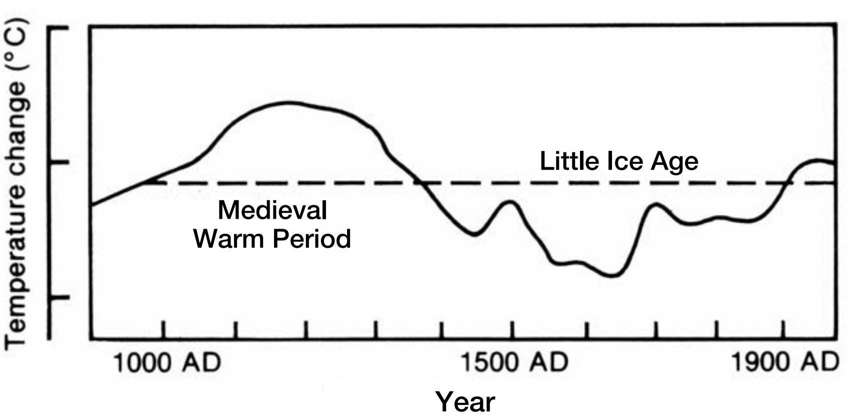

FIGURE O-3 Schematic description of global temperature variations in degrees Celsius for the last 1,100 years published more than 15 years ago. SOURCE: IPCC (1990). Reprinted with permission; copyright 1990, IPCC.

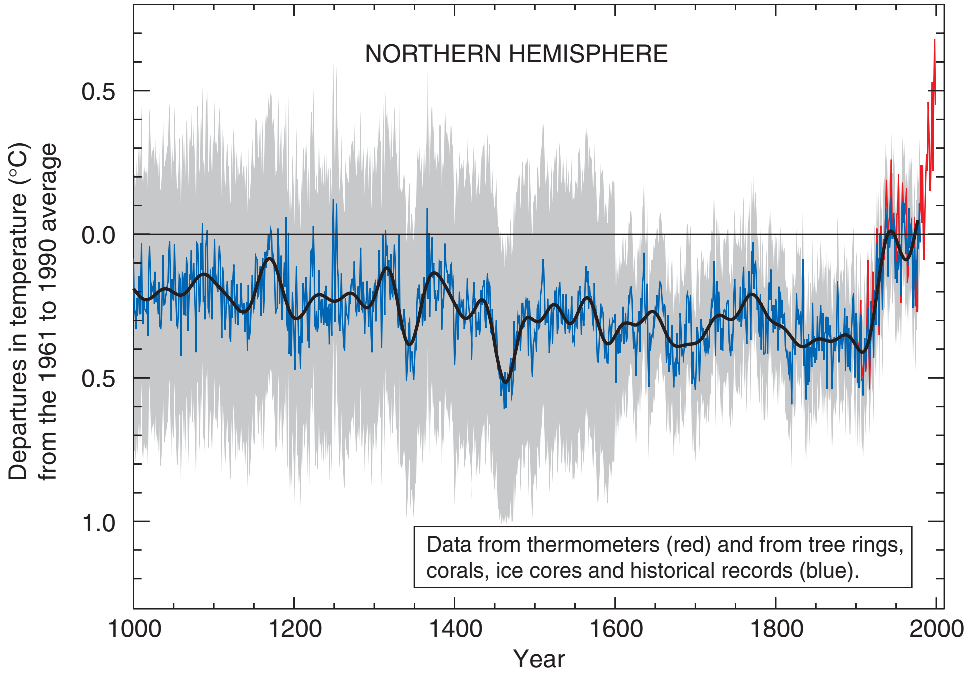

FIGURE O-4 Multiproxy reconstruction of Northern Hemisphere surface temperature variations over the past millennium (blue), along with 50-year average (black), a measure of the statistical uncertainty associated with the reconstruction (gray), and instrumental surface temperature data for the last 150 years (red), based on the work by Mann et al. (1999). This figure has sometimes been referred to as the "hockey stick." SOURCE: IPCC (2001). Reprinted with permission; copyright 2001, IPCC.

depicted as being on the order of 1°C. The pronounced warming trend that began around 1975 was not indicated in the graphic.

IPCC (2001) featured the multiproxy Northern Hemisphere surface temperature reconstruction reproduced in Figure O-4, which includes error bars. In comparison to the previous figure, the reconstructed surface temperature variations prior to the 20th century were less pronounced, and the 20th century warming was rendered more dramatic by the inclusion of data after 1975. On the basis of the results summarized in this figure, the IPCC concluded that "the increase in temperature in the 20th century is likely[4] to have been the largest of any century during the last 1,000 years. It is also likely that, in the Northern Hemisphere, the 1990s was the warmest decade and 1998 the warmest year."

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[4] The IPCC defines "likely" as having an estimated confidence of 66–90 percent, or better than 2 to 1 odds. Note that this falls well short of the high confidence level (>95%) considered standard for strong quantitative arguments.

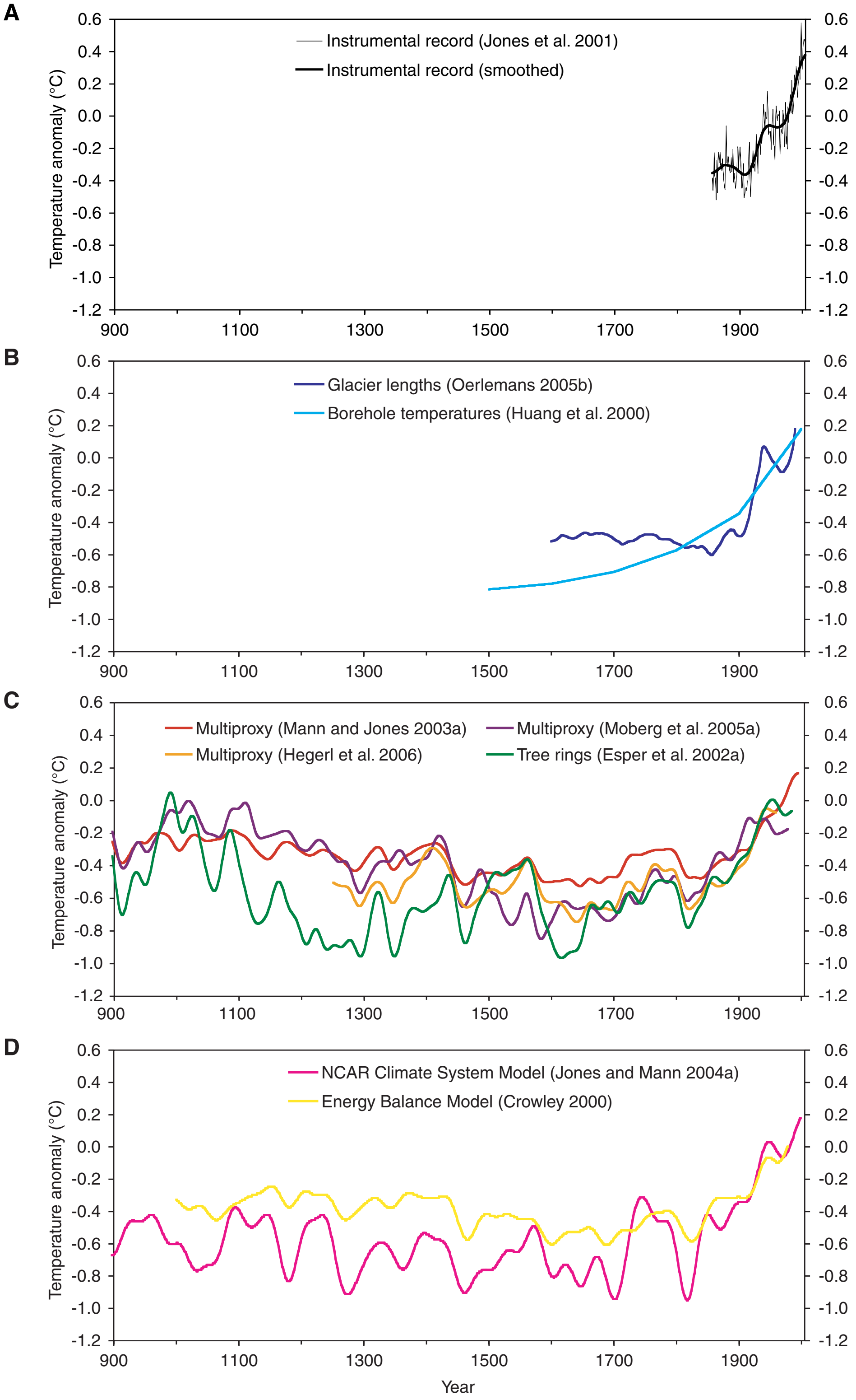
Despite the wide error bars, Figure O-4 was misinterpreted by some as indicating the existence of one "definitive" reconstruction with small century-to-century variability prior to the mid-19th century. It should also be emphasized that the error bars in this particular figure, and others like it, do not reflect all of the uncertainties inherent in large-scale surface temperature reconstructions based on proxy data.

A more recent and complete description of what we know about the climate of the last two millennia can be gleaned from an inspection of Figure O-5, which was prepared by this committee to show the instrumental record compiled from traditional thermometer readings, several large-scale surface temperature reconstructions based on different kinds of proxy evidence, and results from a few paleoclimate model simulations. Figure O-5 is intended only to provide an illustration of the current state of the science, not a comprehensive review of all currently available large-scale surface temperature estimates.

The instrumental record shown in panel A is compiled from traditional thermometer readings that measure the temperature of the air just above the land surface (or, for ocean points, the temperature of the water just below the ocean surface). Panel B shows a global surface temperature reconstruction based on changes in the lengths of many mountain glaciers, which shrink when the climate warms and grow when the climate cools, and also a global surface temperature reconstruction based on borehole temperature measurements. Panel C shows a compilation of several recent multiproxy-based and tree-ring-based Northern Hemisphere surface temperature reconstructions, each performed by a different paleoclimate research group using its own selection of proxies and its own calibration and validation protocols. Panel D shows results from two climate model experiments forced with time-varying estimates of natural climate forcings over the last 1,000 years plus anthropogenic forcing since the start of the Industrial Revolution.

Each of the curves in Figure O-5 has different uncertainties and somewhat different geographical and seasonal emphasis; no one curve can be said to be the best representation of the actual variations in Northern Hemisphere or global mean surface temperature during the last 1,100 years. Nor is it possible to assign error bars to either individual reconstructions or the ensemble of reconstructions that reflect all of the uncertainties inherent in the conversion of proxy data into large-scale surface temperature estimates.

FIGURE O-5 Large-scale surface temperature variations since A.D. 900 derived from several sources. Panel A shows smoothed and unsmoothed versions of the globally and annually averaged instrumental temperature record (Jones et al. 2001). Panel B shows global surface temperature reconstructions based on glacier length records (Oerlemans 2005b) and borehole temperatures (Huang et al. 2000). Panel C shows three multiproxy reconstructions (Mann and Jones 2003a, Moberg et al. 2005a, and Hegerl et al. 2006) and one tree-ring-based reconstruction (Esper et al. 2002a, scaled as described in Cook et al. 2004) of Northern Hemisphere mean temperature. Panel D shows two estimates of Northern Hemisphere temperature variations produced by models that include solar, volcanic, greenhouse gas, and aerosol forcings, as described by Jones and Mann (2004b). All curves have been smoothed using a 40-year low-pass filter (except for the unsmoothed instrumental data), each curve has been aligned vertically such that it has the same mean as the corresponding instrumental data during the 20th century, and all temperature anomalies are relative to the 1961–1990 mean of the instrumental record.


A
Instrumental record (Jones et al. 2001)
Instrumental record (smoothed)
B
Glacier lengths (Oerlemans 2005b)
Borehole temperatures (Huang et al. 2000)
C
Multiproxy (Mann and Jones 2003a)
Multiproxy (Moberg et al. 2005a)
Multiproxy (Hegerl et al. 2006)
Tree rings (Esper et al. 2002a)
D
NCAR Climate System Model (Jones and Mann 2004a)
Energy Balance Model (Crowley 2000)
Temperature anomaly (°C)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
900
1100
1300
1500
1700
1900
Year

Despite these limitations, the large, diverse, and coherent collection of evidence represented by the samples shown in Figure O-5 indicates that global surface temperatures were relatively cool between 1500 and 1850 (the Little Ice Age) and have risen substantially from about 1900 to present. The tree-ring-based and multiproxy-based surface temperature reconstructions shown in panel C also suggest that the Northern Hemisphere was relatively warm around A.D. 1000, with at least one reconstruction showing surface temperatures comparable in warmth to the first half of the 20th century. The timing, duration, and amplitude of warm and cold episodes vary from curve to curve, and none of the large-scale surface temperature reconstructions show medieval temperatures as warm as the last few decades of the 20th century.

What conclusions can be drawn from large-scale surface temperature reconstructions?

Based on its deliberations, the plots shown in Figure O-5, and the evidence described in the chapters that follow and elsewhere, the committee draws the following conclusions:

- The instrumentally measured warming of about 0.6°C during the 20th century is also reflected in borehole temperature measurements, the retreat of glaciers, and other observational evidence, and can be simulated with climate models.
- Large-scale surface temperature reconstructions yield a generally consistent picture of temperature trends during the preceding millennium, including relatively warm conditions centered around A.D. 1000 (identified by some as the "Medieval Warm Period") and a relatively cold period (or "Little Ice Age") centered around 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 justified by the consistency of the evidence from a wide variety of geographically diverse proxies.
- Less confidence can be placed in large-scale surface temperature reconstructions for the period from A.D. 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 A.D. 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.
- Very little confidence can be assigned to statements concerning the hemispheric mean or global mean surface temperature prior to about A.D. 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.

Our confidence in the validity of large-scale surface temperature reconstructions is based, in part, on the fact that the individual proxy data series used to create these reconstructions generally exhibit strong correlations with local environmental conditions. In most cases, there is a physical, chemical, or physiological reason why the proxy reflects local temperature variations. Our confidence is stronger when multiple independent lines of evidence point to the same result, as in the case of the Little Ice Age cooling and of the 20th century warming.

Although the reconstructions based on borehole temperature composites and glacier length records in Figure O-5 do not extend back far enough to provide an independent check on the tree-ring- and multiproxy-based reconstructions for periods prior to the 16th century, there is additional evidence pointing toward the unique nature of recent warmth in the context of the last one or two millennia. This evidence includes the recent melting on the summits of ice caps on Ellesmere Island and Quelccaya and other Andean mountains, the widespread retreat of glaciers in mountain ranges around the world (which in some places has exposed decomposing organic matter that dates to well before A.D. 1000), the recent disintegration of the Larsen B ice shelf in Antarctica, and the fact that ice cores from both Greenland and coastal Antarctica show evidence of 20th century warming (whereas only Greenland shows warming during medieval times). Ice cores from the Andes and Tibetan plateau and the recession of the ice caps on mountains in equatorial Africa, which reflect both temperature and hydrologic processes, also suggest that the 20th century climate is unusual in the context of the last few thousand years.

What are the limitations and strengths of large-scale surface temperature reconstructions?

The main reason that our confidence in large-scale surface temperature reconstructions is lower for periods before about A.D. 1600 is the relative scarcity of precisely dated proxy evidence. Other factors limiting our confidence in these reconstructions include:

- The relatively short length of the instrumental record (about 150 years) only provides a few pieces of independent information to both calibrate and validate surface temperature reconstructions over large spatial scales and multidecade time periods. Instrumental records used for calibration and validation of proxy data have also been collected during a period when both global mean temperatures and human impacts on the environment have increased substantially.
- Although care is taken when selecting, analyzing, and interpreting proxy data, there is always the possibility that the relationship between the proxy and local surface temperature may have varied over time. Most proxies are sensitive to temperature only during certain times of year, and the proxy may reflect temperature variations on timescales longer than the calibration period.
- In the absence of a consensus as to which methods or statistical formulas are most appropriate for calibrating and validating these reconstructions, different choices made by different investigators and research groups also contribute to the differences between them. In some cases the choice of whether or not to include one or more proxy records in a reconstruction has also been a factor.

- The reliability of large-scale temperature time series derived from observations at a small number of sites and with varying levels of chronological precision is still unresolved. It is widely agreed that fewer sites are required for defining century-to-century fluctuations than year-to-year fluctuations, but errors in the reconstructions that are specifically attributable to the limited spatial sampling are difficult to quantify.

The committee identified the key strengths of large-scale surface temperature reconstructions as:

- Proxy records are meaningful recorders of environmental variables. These records are selected and sampled on the basis of established criteria, and the connections between proxy records and environmental variables are well justified in terms of physical, chemical, and biological processes.
- Tree rings, the dominant data source in many large-scale surface temperature reconstructions, are derived from regional networks with extensive replication that reflect temperature variability at the regional scale.
- Most surface temperature reconstructions incorporate proxy evidence from a variety of sources and wide geographic areas, and the resulting temperature estimates are often robust with respect to the removal of individual records.
- The same general temperature trends emerge from different reconstructions. Some reconstructions focus on temperature-sensitive trees, others focus on geochemical and sedimentary proxies, and others infer the temperature signal by exploiting the spatial relationship between temperature and precipitation fields.

Our overall confidence in the general character of the reconstructions for the period from around A.D. 1600 onward is high because different reconstructions based on different types of proxy evidence, different selections of proxy data of a given type, and different methodologies yield similar results. Our confidence in statements concerning how temperature may have varied before 1600, and in particular concerning the warmth of the Northern Hemisphere during medieval times compared to that of the last few decades, is lower because of the limited amount of proxy evidence available and the uncertainties in reconstructing a large-scale average temperature from such limited datasets.

The basic conclusion of Mann et al. (1998, 1999) was that the late 20th century warmth in the Northern Hemisphere was unprecedented during at least the last 1,000 years. This conclusion has subsequently been supported by an array of evidence that includes both additional large-scale surface temperature reconstructions and pronounced changes in a variety of local proxy indicators, such as melting on ice caps and the retreat of glaciers around the world. Not all individual proxy records indicate that the recent warmth is unprecedented, although a larger fraction of geographically diverse sites experienced exceptional warmth during the late 20th century than during any other extended period from A.D. 900 onward.

Based on the analyses presented in the original papers by Mann et al. and this newer supporting evidence, the committee finds it plausible that the Northern Hemisphere was warmer during the last few decades of the 20th century than during any comparable period over the preceding millennium. The substantial uncertainties currently present in the quantitative assessment of large-scale surface temperature changes prior to about A.D. 1600 lower our confidence in this conclusion compared to the high level of confidence we place in the Little Ice Age cooling and 20th century warming. Even less confidence can be placed in the original conclusions by Mann et al. (1999) that "the 1990s are likely the warmest decade, and 1998 the warmest year, in at least a millennium" because the uncertainties inherent in temperature reconstructions for individual years and decades are larger than those for longer time periods, and because not all of the available proxies record temperature information on such short timescales.

What do climate models and forcing estimates tell us about the last 2,000 years?

On the basis of satellite-based monitoring, which began in the late 1970s, it is clear that the rapid global warming of the last few decades is not attributable to an increase in the Sun's emission. The measurements indicate that the Sun's emission has not changed significantly during this period, apart from small variations in association with the 11-year sunspot cycle. Whether variations in the Sun's brightness on longer timescales are large enough to constitute a significant climate forcing is still a matter of debate. It has been hypothesized that reduced solar radiation during the so-called Maunder Minimum in the sightings of sunspots from 1645 to 1715 could have contributed to the coldness of the Little Ice Age.

Sulfate aerosols formed from gases injected into the stratosphere during major volcanic eruptions are known to increase the fraction of the incident solar radiation reflected back to space, cooling the lower atmosphere and the uppermost layers of the ocean. Even though most of the particles settle out of the stratosphere within a year or two, the cooling persists because it takes the ocean several years to cool down and a decade or longer to warm back up. Proxy evidence indicates that the period around A.D. 1000, during which warm intervals are evident in many of the proxy records, corresponded to an extended interval of low volcanic activity in which the incoming solar radiation was relatively unobstructed by the presence of stratospheric aerosols.

Reconstructions of temperatures and external forcings during the 2,000 years preceding the start of the Industrial Revolution are not yet sufficiently accurate to provide a definitive test of the climate sensitivities derived from climate models, mostly because the external forcings on this timescale (mainly solar variability and variations in volcanic activity) are not very well known. Climate model simulations forced with estimates of how solar emission, volcanic activity, and other natural forcings might have varied over this time period, however, are broadly consistent with surface temperature reconstructions (see panel D of Figure O-5).

How central are large-scale surface temperature reconstructions to our understanding of global climate change?

Surface temperature reconstructions have the potential to provide independent information about climate sensitivity and about the natural variability of the climate system that can be compared with estimates based on theoretical calculations and climate models, as well as other empirical data. However, large-scale surface temperature reconstructions for the last 2,000 years are not the primary evidence for the widely accepted views that global warming is occurring, that human activities are contributing, at least in part, to this warming, and that the Earth will continue to warm over the next century. The primary evidence for these conclusions (see, e.g., NRC 2001) includes:

- measurements showing large increases in carbon dioxide and other greenhouse gases beginning in the middle of the 19th century,
- instrumental measurements of upward temperature trends and concomitant changes in a host of proxy indicators over the last century,
- simple radiative transfer calculations of the forcing associated with increasing greenhouse gas concentrations together with reasonable assumptions about the sign and magnitude of climate feedbacks, and
- numerical experiments performed with state-of-the-art climate models.

Supporting evidence includes:

- The observed global cooling in response to volcanic eruptions is consistent with sensitivity estimates based on climate models.
- Proxy evidence concerning the atmospheric cooling in response to the increased ice cover and the decreased atmospheric carbon dioxide concentrations at the time of the last glacial maximum is consistent with sensitivity estimates based on climate models.
- Documentation that the recent warming has been a nearly worldwide phenomenon.
- The stratosphere has cooled and the oceans have warmed in a manner that is consistent with the predicted spatial and temporal pattern of greenhouse warming.

Surface temperature reconstructions for the last 2,000 years are consistent with other evidence of global climate change and can be considered as additional supporting evidence. In particular, the numerous indications that recent warmth is unprecedented for at least the last 400 years and potentially the last several millennia, in combination with estimates of external climate forcing variations over the same period, support the conclusion that human activities are responsible for much of the recent warming. However, the uncertainties in the reconstructions of surface temperature and external forcings for the period prior to the instrumental record render this evidence less conclusive than the other lines of evidence cited above. It should also be noted that the scientific consensus regarding human-induced global warming would not be substantively altered if, for example, the global mean surface temperature 1,000 years ago was found to be as warm as it is today.

What comments can be made on the value of exchanging information and data?

The collection, compilation, and calibration of paleoclimatic data represent a substantial investment of time and resources, often by large teams of researchers. The committee recognizes that access to research data is a complicated, discipline-dependent issue and that access to computer models and methods is especially challenging because intellectual property rights must be considered. Our view is that all research benefits from full and open access to published datasets and that a clear explanation of analytical methods is mandatory. Peers should have access to the information needed to reproduce published results, so that increased confidence in the outcome of the study can be generated inside and outside the scientific community. Other committees and organizations have produced an extensive body of literature on the importance of open access to scientific data and on the related guidelines for data archiving and data access (e.g., NRC 1995). Paleoclimate research would benefit if individual researchers, professional societies, journal editors, and funding agencies continued to improve their efforts to ensure that these existing open-access practices are followed.

Tree ring researchers have recognized the importance of data archiving since 1974, when the International Tree Ring Data Bank was established to serve as a permanent repository for tree ring data (measurements, chronologies, and derived reconstructions). Its holdings are available online via the World Data Center for Paleoclimatology, as are a number of other proxy data from ice cores, corals, boreholes, lake and ocean sediments, caves, and biological indicators. As proxy datasets become increasingly available on the Web, all researchers are given the opportunity to analyze data, test methods, and provide their own interpretation of the existing evidence via recognized, peer-reviewed scientific outlets.

What might be done to improve our understanding of climate variations over the last 2,000 years?

Surface temperature reconstructions have the potential to further improve our knowledge of temperature variations over the last 2,000 years, particularly if additional proxy evidence can be identified and obtained. Additional proxy data that record decadal-to-centennial climate changes, especially for the period A.D. 1–1600, would be particularly valuable. New data from the Southern Hemisphere, the tropics, and the oceans would improve our confidence in global temperature reconstructions, while additional data from regions that have already been sampled would help reduce the uncertainties associated with current reconstructions. In addition, many existing proxy records were collected decades ago and need to be updated in order to perform more reliable comparisons with instrumental records. Better data coverage would also make it possible to test whether or not past temperature changes had the same pattern as the warming during the last century.

New methods, or more careful use of existing ones, may also help circumvent some of the existing limitations of large-scale surface temperature reconstructions based on multiple proxies. Each individual proxy provides a record of environmental change, but the process of combining these signals into a spatially averaged temperature signal requires careful statistical evaluation. It might be possible to circumvent some of the limitations associated with these reconstructions by employing a number of complementary strategies in analyzing the proxy data, including using them to constrain climate models, and by attempting to calibrate the proxy data against climatic variables in different ways.

Finally, some of the most important consequences of climate change are linked to changes in precipitation, especially the frequency and intensity of droughts and floods, as opposed to temperature alone. Changes in regional circulation patterns, snowfall, hurricane activity, and other climate elements over time are also of interest. Hence, it would be valuable to see both regional and large-scale reconstructions of changes in precipitation and other climate variables over the last 2,000 years, to complement those made for temperature. Efforts to improve the reliability of surface temperature reconstructions also need to be complemented by efforts to improve our understanding of the forcings that have contributed to climate variability over the past 2,000 years.

When analyzed in conjunction with historical and archeological evidence, paleoclimatic reconstructions can also tell us how past societies adapted to climate changes. This field of research is moving forward: Hypotheses are being tested, methods are being refined, and new ideas are being introduced.

1

Introduction to Technical Chapters

The Earth's temperature varies on a wide range of timescales and for a variety of reasons. The variability on scales of 10,000–100,000 years is paced by cyclic changes in the Earth's orbit, but strongly depends on the internal operation of the climate system and its connection with other environmental variables. The colder glacial times are marked by decreased concentrations of atmospheric greenhouse gases, which serve to amplify the cooling at the Earth's surface, resulting in temperature swings on the order of 5°C between glacial times and the warmer interglacial periods, such as the current one (Hansen 2004). Over the last 2,000 years, the changes in the Earth's orbit have been small (Lean 2005a). Variations in atmospheric concentrations of greenhouse gases were also very small during this period prior to the advent of human impacts in the 19th century (Joos 2005).

The question then of how global mean surface temperature varied over the last 2,000 years is of great interest. When analyzed in conjunction with reconstructions of solar variability, volcanic activity, and other influences on climate during this period, surface temperature reconstructions can be of use in efforts to reduce the level of uncertainty in projections of human-induced greenhouse warming. Such reconstructions provide a measure of the natural variability of the climate system, against which projections of human-induced global warming can be compared. This chapter describes how large-scale surface temperature reconstructions contribute to our understanding of the sensitivity of global mean temperature to natural and human-induced perturbations of the Earth's energy balance. It also offers a perspective on the importance of surface temperature reconstructions, as compared with other kinds of evidence, in assessing the extent to which the warming of the late 20th century is attributable to human activities.

CONCEPTS AND DEFINITIONS

This report focuses on surface temperature reconstructions over large geographic scales, in particular global mean and hemispheric mean surface temperatures. Global mean surface temperature is a particularly good indicator of the state of the climate system because it is closely related to the balance between incoming and outgoing energy at the top of the atmosphere.

Global mean surface temperature varies in response to events outside the climate system that affect the global energy balance (NRC 2005). The *external forcings* considered to be of greatest importance for climate over the last 2,000 years are changes in atmospheric concentrations of carbon dioxide and other greenhouse gases, aerosol concentrations, volcanic activity, and solar radiation. Changes in land use (clearing of forests, increasing the coverage of cultivated land, and desertification) may also contribute to climate variability, but their influence is difficult to quantify (Ruddiman 2003). Human activities have caused increases in the atmospheric concentrations of greenhouse gases and aerosols, which first became appreciable in the 19th century.

The climate system also exhibits *internal variability* that would occur even in the absence of external forcing. A familiar example of internal climate variability on a year-to-year scale is El Niño, which is a consequence of interactions between the tropical Pacific Ocean and the global atmosphere. Interactions among the more massive, slowly varying components of the climate system could give rise to internal variability of the climate system on timescales of decades to centuries that may be largely unrelated to the external forcings on those timescales.

The change in global mean surface air temperature that occurs in response to a persistent external forcing of 1 watt per square meter over the Earth's surface is defined as the *sensitivity* of the climate system (NRC 2003a). An alternative unit, used extensively in this report, is the temperature increase (in °C) that would occur in response to a doubling of the preindustrial atmospheric carbon dioxide concentration. Climate sensitivity is determined by the laws of physics and can be estimated using the methods described in the next section. The fluctuations in global mean surface temperature that occurred in response to past natural forcings provide a check on estimates of climate sensitivity. Other things being equal, the higher the sensitivity, the larger the future warming that can be expected in response to future greenhouse forcing. The strength of the various external forcings can be quantified and compared; knowledge gained from understanding the response to one kind of forcing is applicable to predicting the response to other kinds of forcing.

As in other physical systems, high climate sensitivity is indicative of the prevalence of positive climate feedbacks (NRC 2003a). The most important positive feedback in the climate system involves the increase in the concentration of atmospheric water vapor as the Earth warms. Changes in concentrations of water vapor, a greenhouse gas in its own right, amplify the warming or cooling that occurs in response to changes in concentrations of other greenhouse gases. Another positive feedback involves the decrease in the fractional area covered by snow and ice as temperatures warm, which decreases the reflectivity of the Earth as a whole. Other feedbacks involve changes in cloudiness, lapse rate, the atmospheric circulation, and land surface properties as the Earth warms or cools. The combined effect of the various positive and negative feedbacks determines the sensitivity of the climate system and the sensitivity, in turn, determines how much the Earth will warm in response to a prescribed increase in the atmospheric concentration of carbon dioxide or changes in other external forcings.

Estimation of Climate Sensitivity

The sensitivity of the climate system can be estimated in several different ways. The direct response to a doubling of preindustrial atmospheric carbon dioxide concentrations that would be observed in the absence of feedbacks is estimated on the basis of radiative transfer calculations to be about 1°C , and the water vapor feedback (calculated under the assumption of constant relative humidity) nearly doubles this response (e.g., Held and Soden 2000). Numerical experiments conducted with a variety of climate models that incorporate the full suite of climate feedbacks yield a range of climate sensitivities. The least sensitive models exhibit sensitivities roughly comparable to what would be obtained if only the water vapor feedback were included (about 2°C for a carbon dioxide doubling), whereas the most sensitive models estimate a sensitivity five times as large as radiative transfer calculations (Goosse et al. 2005, Webb et al. 2006, Winton 2006). The midrange models estimate a climate sensitivity of around 3°C for a doubling of carbon dioxide.

The sensitivity estimates derived from the models are checked by comparing observed and simulated responses to various known external forcings. For example, model simulations that consider surface temperature reconstructions for the past 700 years combined with instrumental data estimate climate sensitivity to be between 1.5 and 6.2°C (Hegerl et al. 2006).

ATTRIBUTION OF GLOBAL WARMING TO HUMAN INFLUENCES

The attribution of the large-scale warming of the late 20th century to human influences is supported in part by evidence that the warmth of the most recent one or two decades stands out above the background or natural variability of the last 2,000 years. To place this paleoclimatic evidence in context, it is necessary to consider the other evidence on which the attribution is based.

Based on evidence summarized in Chapter 2, it is known that global mean surface temperature has risen by about 0.6°C during the past century and that most of this warming took place during the period 1920–1940 and during the last 30 years. The troposphere is warming at a rate compatible with the warming of the Earth's surface (CCSP and SGCR 2006). The spatial pattern of the observed temperature trends resembles the "fingerprint" of greenhouse warming in climate models, with cooling in the stratosphere and an uptake of heat by the oceans (e.g., Meehl et al. 2004, Hansen et al. 2005, Barnett et al. 2005). The warming is also reflected in a host of other indicators: For example, glaciers are retreating, permafrost is melting, snowcover is decreasing, Arctic sea ice is thinning, rivers and lakes are melting earlier and freezing later, bird migration and nesting dates are changing, flowers are blooming earlier, and the ranges of many insect and plant species are spreading to higher latitudes and higher elevations (e.g., ACIA 2004, Parmesan and Yohe 2003, Root et al. 2003, Berteaux et al. 2004, Bradshaw and Holzapfel 2006).

It is also well established that atmospheric concentrations of greenhouse gases have been increasing due to human activities. In recent decades the increases have been documented on the basis of direct measurements at a network of stations. Increases in concentrations of carbon dioxide, methane, and nitrous oxide starting in the 19th century, following many millennia of nearly constant concentrations, are clearly discernible in air bubbles trapped in ice cores recovered from the Greenland and Antarctic ice sheets (Petit et al. 1999, Siegenthaler et al. 2005a, Spahni et al. 2005). The attribution of these increases to human activities rests on both isotopic evidence and the fact that they are consistent with inventories of emissions of these gases from the burning of fossil fuels and other human activities, taking into account the storage in the oceans and the land biosphere. Based on station and ice core measurements, the combined forcing due to the greenhouse gases injected into the atmosphere by human activities is about 2.5 watts per square meter (IPCC 2001).

Based on a climate sensitivity of 3°C for a carbon dioxide doubling, as estimated in the preceding section, a greenhouse forcing of 2.5 watts per square meter is sufficient to produce a warming of around 2°C. The observed warming during the 20th century of around 0.6°C is less than the estimated response to the greenhouse forcing for two reasons:

- it is partially offset by increases in the concentration of sulfate and other aerosols, which tend to produce cooling at the Earth's surface (e.g., Santer et al. 1995), and
- part of the warming has not been realized yet because the oceans and polar ice sheets have not had sufficient time to equilibrate with the forcing (e.g., Hansen et al. 2005).

The observed 0.6°C warming during the 20th century is much larger than the internal variability in climate models. Model simulations that include both externally forced and internal variability, including plausible prescriptions of time-varying sulfate aerosols, yield time series of global mean temperature that resemble the observations (Stott et al. 2000, Ammann et al. 2003). To the extent that the warmth of the most recent one or two decades stands out above the natural variability in mean surface temperature over the last 2,000 years, the surface temperature record serves as supporting evidence that human activities are largely responsible for the recent warming. However, the attribution of the recent global warming to human activities does not rest solely or even principally upon paleoclimate evidence.

REPORT STRUCTURE

The next chapter of this report provides a brief description of the instrumental record and some considerations that apply to estimating large-scale surface temperature variations on the basis of observations at a limited number of sites. Most of what we know about how the temperature of the Earth has varied on the timescale of the last 2,000 years is based on *proxy records*, including documentary records, archeological evidence, and a variety of natural sources including tree rings, corals, ice cores, ocean and lake sediments, borehole temperatures, and glacier length records. The sources and characteristics of the various proxy datasets are discussed in Chapters 3–8. The statistical procedures and assumptions that are used in reconstructions of surface temperatures from proxy data are discussed in Chapter 9. Paleoclimate models and an expanded discussion of variations in climate forcing over the last two millennia are presented in Chapter 10. Finally, Chapter 11 describes the synthesis of evidence derived from a variety of different proxies to produce large-scale surface temperature reconstructions. These techniques have been a subject of controversy in a number of recent papers in the refereed literature, so Chapter 11 also assesses their strengths, limitations, and prospects for improvement.

2

The Instrumental Record

- Global average temperature estimates based on the instrumental record indicate a near-level trend from 1856 to about 1910, a rise to 1945, a slight decline to about 1975, and a rise to the present. The overall increase during the 20th century was about 0.6°C, with the highest warming rates occurring in land areas poleward of 30°N.
- Instrumental temperature records extend back over 250 years in some locations, but only since the late 19th century has there been a sufficient number of observing stations to estimate the average temperature over the Northern Hemisphere or over the entire globe.
- Combining instrumental records to calculate large-scale surface temperatures requires including a sufficient number of instrumental sites with wide geographic distribution to get a representative estimate. Tropical measurements are particularly useful for estimating large-scale temperatures because they tend to more closely track global mean variations.

Most surface temperature reconstructions depend in some way on the instrumental surface temperature record. Individual and multiproxy reconstructions based on annually or seasonally resolved proxy data use this record for both calibration and validation. Other types of reconstructions—for instance, those derived from glacier lengths and borehole measurements—implicitly use local instrumental records to help develop the physical model used to turn the proxy record into a temperature record. Hence, it is useful to briefly describe the instrumental record and discuss its features and uncertainties before examining the manner in which it is employed in surface temperature reconstructions.

INSTRUMENTAL DATA

The instrumental surface temperature record ("instrumental record") is derived from traditional thermometer readings and provides the basis for generating the large-scale (global mean or hemispheric mean) surface temperature estimates used in climate change studies. The global average temperature is produced as a combination of near-surface land air temperatures and temperatures of the sea water near the surface (or sea surface temperatures [SSTs]) for the oceans. Land air temperatures are measurements taken by thermometers mounted in shelters about 1.5 meters above the land surface, or higher in areas where snow cover may be substantial. About 2,000 stations report land air temperatures for the global compilations shown in this chapter. The stations are not spatially distributed to monitor all land areas with equal density; unpopulated and undeveloped areas have always tended to have poor coverage.

SSTs are measured by ships, buoys, bathythermograph profilers, and, since 1981, satellites. Ships generally take the water temperature in one of three ways: buckets (the oldest method), hull sensors, and water drawn in to cool the engines (injection temperatures). The depths of ship measurements vary from 1 to 15 meters. Buoys are more standardized and report temperatures generally at 1 meter as well as several other depths depending on the buoy type.

Very few land air temperature records begin prior to 1856, so estimates of large-scale (i.e., global and hemispheric) averages are uncertain before that time. The average SST for all oceans is less well known than land air temperature, especially during the middle to late 19th century, when large portions of the tropical and southern oceans were poorly sampled (and these areas remain comparatively undersampled). Differences in the types of measurement methods, the generally unknown calibration of instruments, and the sparse geographic and temporal sampling in many areas contribute to uncertainties in the estimates of large-scale averages. In addition, the proxy indicators discussed in Chapters 3–8 are generally not directly sensitive to 1.5 meter air temperature. For example, borehole temperature profiles are sensitive to the ground surface temperatures, and ice isotopic ratios are sensitive to cloud-level atmospheric temperatures. Significant systematic differences can exist between temperatures at such different elevations with respect to ground, and these differences represent one of the inherent uncertainties in performing surface temperature reconstructions.

FEATURES OF THE INSTRUMENTAL RECORD

Large-Scale Averages

Figure 2-1 shows three large-scale averages of annual mean surface temperature anomalies from the HadCRUT2v dataset (Jones et al. 2001), which is commonly used in both proxy reconstructions and more general global climate studies.[1] The three estimates are for (1) global, (2) Northern Hemisphere, and (3) Northern Hemisphere extratropical land areas only (20°N–85°N). The Northern Hemisphere extratropical land area estimate has the largest variability of the three because the mid- and high-

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[1] Two other widely used compilations of global surface temperature, Hansen et al. (2001) and Smith and Reynolds (2005), yield very similar results.

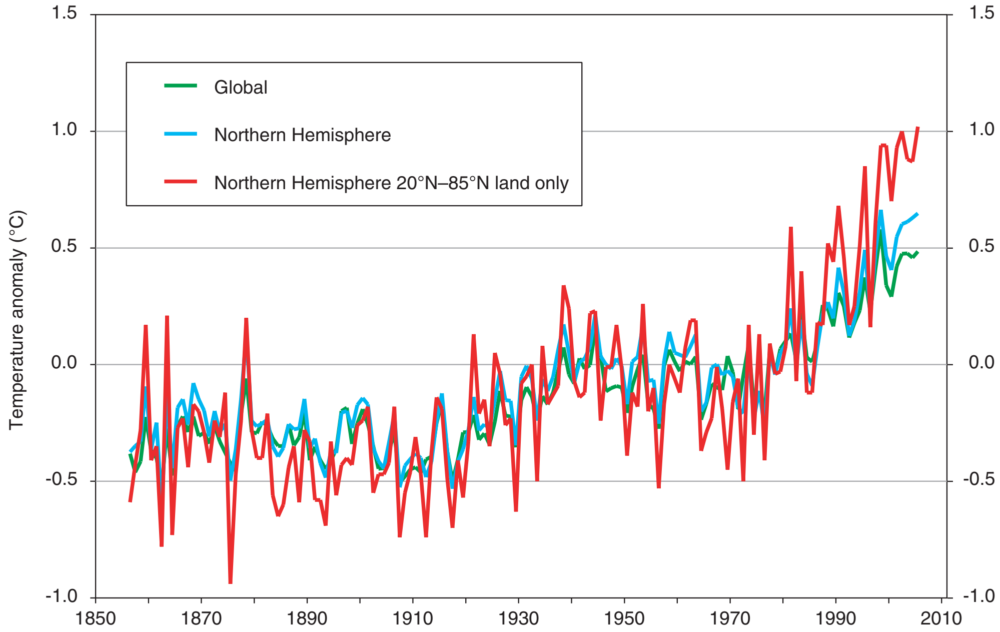

FIGURE 2-1 Global, Northern Hemisphere, and Northern Hemisphere extratropical land area annual temperature anomalies in degrees Celsius from the HadCRUT2v surface temperature dataset. SOURCE: Jones et al. (2001).

latitude continental climatic zones generally exhibit larger temperature swings on virtually all timescales than other regions of the globe. The Northern Hemisphere and global estimates exhibit less variability because of the additional influence of SSTs, which have less variability than land air temperatures from year to year, mainly due to the higher heat capacity of the ocean mixed layer compared to the land surface. The evolving pattern of fluctuations is similar in these three large-scale averages because (a) the Northern Hemisphere extratropical land area stations form a major part of the larger-scale averages and (b) the larger variations in the Northern Hemisphere extratropical land area record tend to dominate the smaller variations in the remaining regions. Since 1978, instruments on satellites have monitored the temperature of the deep atmospheric layer above the surface and, though regional differences occur, global average trends agree with the surface warming of +0.16°C per decade within ±0.04°C per decade (CCSP and SGCR 2006).

In addition to substantial year-to-year variability, the global instrumental temperature record shows the following low-frequency features: a slight decline from 1856 to 1910, a rise of ~0.4°C between 1910 and 1945, a leveling or slight decline between about 1945 and 1975, and a rise of ~0.5°C from 1975 to the present. The overall rise during the 20th century was about 0.6°C, with an additional 0.1°C reported since then. If the 150 years of relatively reliable instrumental data are divided into three 50-year segments—1856–1905 (I), 1906–1955 (II), and 1956–2005 (III)—the average global temperature anomalies for these three periods relative to the 1961–1990 mean are –0.32°C (I), –0.20°C (II), and +0.11°C (III), respectively. Given this variability, a large-scale surface temperature reconstruction would require exceptionally good accuracy, on the order of a few hundredths of a degree Celsius, to distinguish (I) from (II). To distinguish (III) from the earlier two periods, an error of ~0.15°C would be acceptable. Therefore, if the temperature variations observed during the last 150 years are representative of fluctuations over the last 2,000 years, a relatively small (and well-characterized throughout the time series) error allowance is required to distinguish in a quantitative way the global average temperature levels of the latter half of the 20th century from earlier individual 50-year periods.

Decadal averages, beginning with 1856, produce global values ranging from –0.38°C (1906–1915) to +0.42°C (1996–2005). Thus, to distinguish global mean decadal temperature anomalies into, for example, three categories (cool, average, warm) in the context of the last 150 years would require errors of ~0.2°C or less. As in other types of time series analysis, the magnitude of the climate signal must also be sufficiently greater than the magnitude of the potential errors in order to make confident statements about the relative warmth of individual periods. This must be the case over the entire length of the period under investigation to make inferences about which decades might be the warmest or the coolest. This is a particularly difficult subject for proxy-based records since there are no absolute temperature measurements on these timescales for the preinstrumental era. Hence, the estimation of error characteristics, which are discussed in detail in Chapter 9, is a major emphasis in paleoclimate reconstructions.

Seasonal and Spatial Patterns

Many proxies are most sensitive to temperature during certain seasons: For example, tree ring measurements are usually (but not always) most sensitive to mean temperatures during the summer growing season. For comparison, Figure 2-2 shows the annual and summer anomalies of the Northern Hemisphere extratropical land area temperature record. It is clear that differences occur from year to year and, in the early period, even from decade to decade between the two averaging periods. Year-to-year Northern Hemisphere temperatures vary over a wider range in winter than summer, but the annual mean temperature, being the average of four seasonal anomalies, tends to smooth out these seasonal fluctuations, which are greater in nonsummer seasons, to give roughly the same year-to-year variability as summer. However, note that the 150-year trend in annual mean Northern Hemisphere extratropical land area temperatures is more positive than the corresponding trend in summer mean temperatures (+0.063°C vs. +0.025°C per decade). This difference could be of consequence if the trend influences the statistical calibration procedures (see Chapter 9).

Figure 2-3 displays the regional trends through 2005 beginning in 1870 and in 1950. The changing distribution of measurements is evident as the map beginning in 1870 has much poorer geographic coverage, especially over land. Since 1950, most regions indicate positive surface trends, especially in mid and high northern latitudes. These observed positive trends over the last few decades are sometimes not reflected in tree-ring-based reconstructions for those regions, as further discussed in Chapter 4.

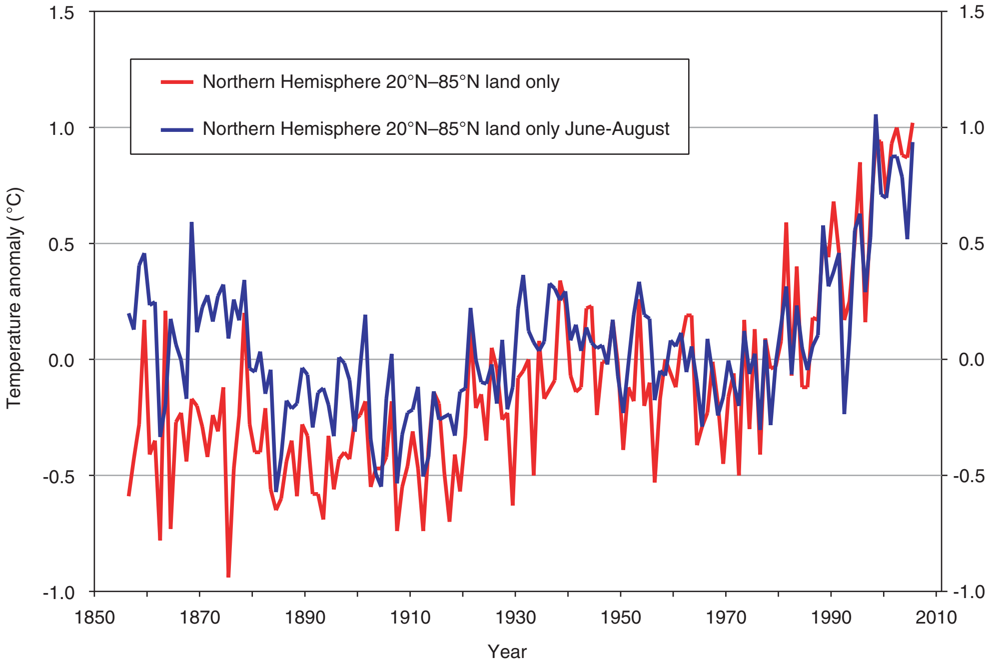

FIGURE 2-2 Annual mean and summer (June–August) mean temperature anomalies in degrees Celsius for Northern Hemisphere extratropical land areas from the HadCRUT2v surface temperature dataset. SOURCE: Jones et al. (2001).

UNCERTAINTIES AND ERRORS ASSOCIATED WITH THE INSTRUMENTAL RECORD

Because proxy-based surface temperature reconstructions often depend on either local or large-scale average land air temperatures and/or SSTs, any errors in the instrumental temperature record will reduce the confidence in the reconstructed temperature record. Several factors influence the land air temperature measurements over time. As land use has changed (e.g., from forest to urban), many thermometers in the land air temperature record have responded to the changes in the thermal properties of their surroundings, yielding temperature changes that are real but not likely due to large-scale climatic causes. The geographic distribution of the land air temperature sites has also grown significantly since 1856, so data from regions that previously had no measurements now provide a more accurate large-scale average, giving rise to larger errors in the earlier part of the record. Similarly, compilations of SST measurements suffer from poor calibration and sampling in the earlier decades. These types of problems are estimated to introduce a potential error (95 percent confidence) of ~0.10°C for the earliest decades of the global and Northern Hemisphere average temperature values (Folland et al. 2001b). In the most recent decades, improved coverage and better knowledge of instrumental biases, such as the effects of urbanization, reduce the error range to ~0.04°C (Brohan et al. in press). These potential errors are relatively small

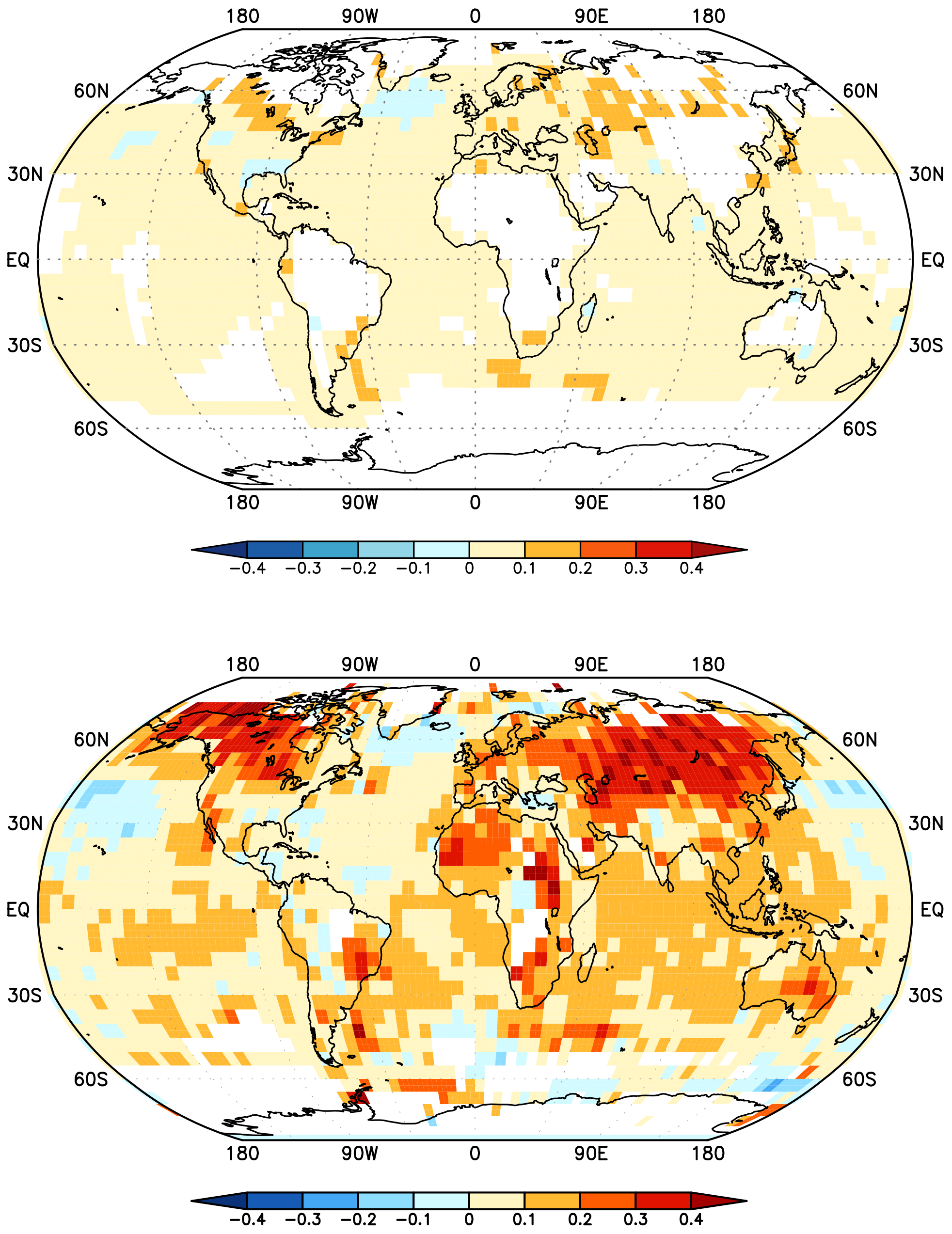

FIGURE 2-3 Observed surface temperature trends in degrees Celsius per decade through 2005 beginning in 1870 (top) and beginning in 1950 (bottom) derived from HadCRUT2v data. SOURCE: Data from Jones et al. (2001); drawing by Todd Mitchell, University of Washington, Seattle. Reprinted with permission; copyright 2006.

compared to the observed decadal temperature changes for the last 150 years described above.

Errors in the instrumental record can reduce the effectiveness of the proxy calibration process because the fundamental relationship sought from the calibration exercise may be compromised to a degree. For example, proxy–temperature relationships determined on the local scale suffer from errors arising from (a) inhomogeneous data at the land air temperature calibration site, (b) horizontal distance between the proxy location and the land air temperature site, (c) elevation differences between the proxy location and the land air temperature site, and (d) differences between the land air temperature sites that are composited to create the calibration and validation datasets. As a result, there are many opportunities for errors in the measurements and averaging techniques to influence the temperature datasets against which data methods are calibrated and verified. Fortunately, when increasing the size of the samples being averaged and tested, random and uncorrelated errors tend to cancel, enhancing the confidence in the variations produced.

There is also the added burden of dealing with new versions of particular datasets. Estimates by research groups of large-scale average temperatures for particular periods have changed somewhat over time. This occurs when the different groups (a) update the primary source data used in the large-scale averages, (b) institute new adjustment procedures, or (c) adopt new spatial or temporal averaging techniques. Thus, a proxy record calibrated or verified using an early version of an instrumental record may be altered slightly if the instrumental data against which the proxy was calibrated changes.

SPATIAL SAMPLING ISSUES

Deducing the number of sites at which surface temperature needs to be sampled in order to represent variations in global (or hemispheric) mean temperature with a specified level of accuracy is a challenge no less formidable than deducing the temperature variations themselves. The most obvious way to address this problem is to try replicating the variations in the Earth's temperature in the instrumental record using limited subsets of station data. The effectiveness of this approach is limited by the length of the observational record. One way of overcoming this limitation is to sample much longer time series of synthetic climate variations generated by climate models, but this strategy is compromised by the limited capability of the models to simulate temperature variations on the century-to-century timescale and on spatial scales that represent the highly variable character of the Earth's surface. The studies that have been performed to date suggest that 50–100 geographically dispersed sites are sufficient to replicate the variability in the instrumental record (e.g., Hansen and Lebedev 1987, Karl et al. 1994, Shen et al. 1994). These results indicate that the temperature fluctuations in the instrumental record are well resolved; that is, proxy records do generally reflect the same variability as instrument records where they overlap (Jones et al. 1997). However, they leave open the question of whether the proxy records are sufficiently numerous and geographically dispersed to resolve the major features in the time series of the temperature of the Earth extending back over hundreds or even thousands of years.

Hopes for reliable Northern Hemisphere and global surface temperature reconstructions extending back far beyond the instrumental record are based on the premise that local surface temperature variations on timescales of centuries and longer are

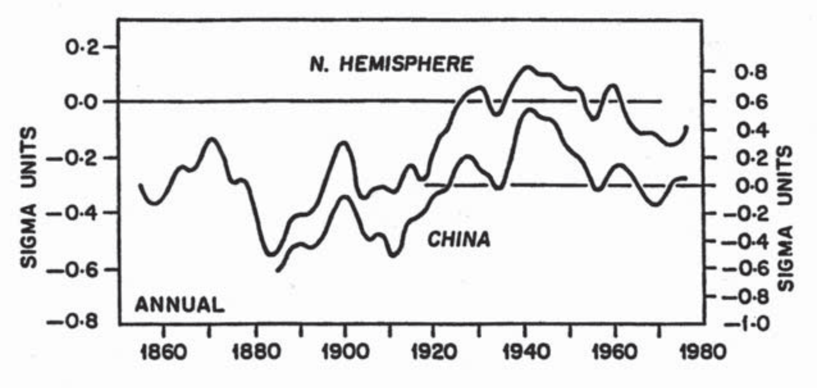

FIGURE 2-4 Smoothed time series of normalized annual mean surface air temperature averaged over China and the entire Northern Hemisphere. SOURCE: Bradley et al. (1988). Reprinted with kind permission of Springer Science and Business Media; copyright 1988.

dominated by variations in global mean temperature that occur in response to changes in the global energy balance. If this premise is correct, it follows that temperature time series at points on Earth should be more strongly correlated with the time series of the global mean temperature on these longer timescales than they are on the year-to-year timescale. Several papers offer support for this view (e.g., Leung and North 1991, Shen et al. 1994), as does the time series shown in Figure 2-4 (Bradley et al. 1988). The strong correspondence between the Northern Hemisphere and China curves indicates that much of the decade-to-decade and century-to-century variability in the mean temperature of the Northern Hemisphere since 1880 can be captured using data from the Chinese station network alone. Of course, temperature time series at individual sites within China are not as highly correlated with hemispheric mean time series as the China-mean time series in Figure 2-4, and proxy time series do not perfectly represent the true time series of surface temperature variations. Much remains to be done to place the spatial sampling requirements on a firm footing.

Another issue that arises when interpreting proxy records of surface temperature over the last 2,000 years is the degree to which temperature time series in various latitude belts are representative of the globally averaged temperature. The instrumental record of surface temperature shown in Figure 2-5 is instructive in this respect. The rise in surface air temperature that occurred during the 1920s and the slight decline during the 1950s were much more pronounced over high latitudes of the Northern Hemisphere than at lower latitudes. In contrast, the warming of the last few decades has been much more latitudinally uniform. The latitudinally dependent features in Figure 2-5 serve as a reminder that not all the variability over high latitudes, as recorded in ice core measurements and high-latitude proxies, is necessarily representative of variations in global mean temperature.

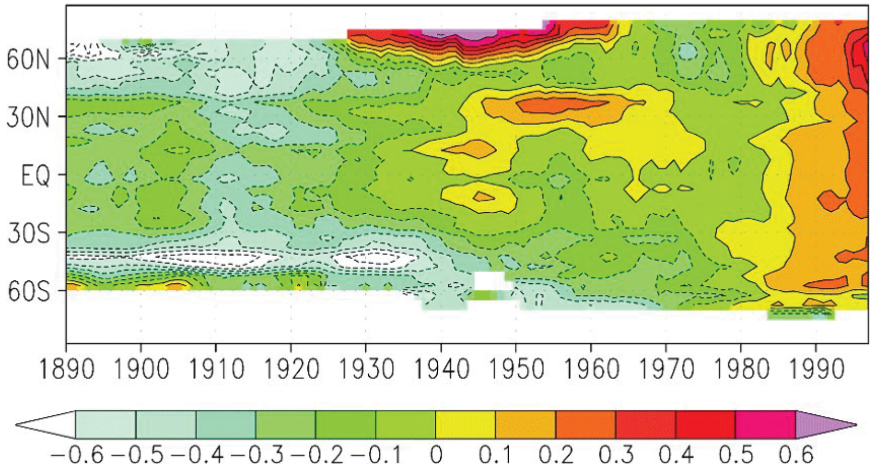

FIGURE 2-5 Smoothed zonal mean anomalies of surface temperature (in K) for the observations in each latitude band from 1890 to 1999. Anomalies are relative to the 1961–1990 climatology. SOURCE: Delworth and Knutson (2000). Reprinted with permission from AAAS; copyright 2000.

3

Documentary and Historical Evidence

- Historical observations and documents provide valuable, seasonally specific information about past temperatures and other features of climate, but prior to about A.D. 1700 the evidence thins out and often becomes discontinuous.
- Europe and East Asia are the two regions of the world where temperature series more than 200 years long have been successfully developed from documentary evidence in a repeatable and consistent way. This evidence shows that both regions experienced overall medieval warming and Little Ice Age cooling, but because of their paucity and sometimes poor data quality, it is very difficult to know from these sources alone if the medieval period was as warm as, or warmer than, the late 20th and early 21st centuries.
- Historical and archeological evidence can reveal how societies have responded to climate variability in the past. These show that societal responses could not have been predicted in advance and that successful adaptations to new climatic conditions depended on the good or bad choices that people made.

TYPES OF EVIDENCE

Historical observations, preserved mainly in documentary form, can provide valuable records about past climate states (Lamb 1982). For example, the schematic temperature curve for the last millennium included in the first Intergovernmental Panel on Climate Change report (IPCC 1990; see also Figure O-3) drew heavily on documentary evidence. In addition to systematic weather recordings, such as those used by Manley (1974) to compile his record of temperatures in central England, there is a wide range of direct and indirect

TABLE 3-1 Types of Documentary Evidence Used for Climate Reconstructions[a]

Direct data	*Descriptions*	*Direct measurements*	
	Weather diaries	Temperature	
	Natural disasters	Precipitation	
		Pressure	
Indirect (or proxy) data	*Organic*	*Inorganic*	*Material sources*
	Phenological data	Flood marks	Inscriptions
	Grape and crop harvests	Icing and breakups	Paintings
		Duration of snow cover	Photographs
			Maps and charts
			Rogation processions[b]

[a] Based on Pfister (1992). Reprinted with permission from Routledge; copyright 1992.
[b] Christian agricultural celebrations.

proxy climate information available (Table 3-1). In a classic early study, Ladurie (1972) used farming and phenological[1] records to document times of feast and famine in western Europe during the Little Ice Age (roughly 1500–1850). Logbooks and diaries, such as the diary kept by Benjamin Franklin when he was American ambassador in Paris during the 1780s, provide another, complementary source of data. Franklin reported a "constant dry fog on which the rays of the sun seemed to have little effect" along with severe late frosts, which we now attribute to the Laki volcanic fissure eruption in Iceland (Grattan and Brayshay 1995).

Many historical documents, rather than recording weather *per se*, provide indirect evidence of past climatic conditions. Historical paintings of alpine landscapes, for example, allow us to pinpoint the former extent of glaciers at precise moments in time, thus contributing to the temperature reconstructions derived from glacier length records discussed in Chapter 7. Similar, but potentially more continuous, time series of sea ice cover have been derived from Antarctic whaling records and from observations of drift ice around the coast of Iceland (e.g., Ogilvie 1992, de la Mare 1997). In the tropics and in dryland regions, periods of drought and flood are most frequently reported; Endfield et al. (2004), for instance, used archival sources to reconstruct rainfall fluctuations in Spanish colonial Mexico. To quantify long series of documentary data such as these in climatic terms, they, like other proxies, need to be calibrated against instrumental measurements. Brázdil et al. (2005) provide a comprehensive review of the methodological framework within which historical archives and documents are currently utilized.

LIMITATIONS AND BENEFITS OF HISTORICAL AND DOCUMENTARY SOURCES

All historical sources need to be evaluated critically, even for relatively recent times. For example, frost fairs were routinely held on the iced-over surface of the River

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[1] *Phenology* is the study of the annual cycles of plants and animals and how they respond to seasonal changes in their environment.

Thames in London during the cold winters of the Little Ice Age, with the last one occurring in 1814. It would be quite wrong, however, to attribute their absence since that time solely to a rise in Northern Hemisphere winter temperatures: As London has grown and developed, the "urban heat island" effect has reduced the likelihood of frosts in the city center, and the replacement of the old London Bridge in the 1830s allowed greater uptide incursion of saltwater, which freezes less easily. Manley's central England temperature series indicates that the winter of 1962–1963 was the third coldest since 1659, yet the Thames did not freeze below its tidal limit (Jones and Mann 2004b).

The problem of quality control becomes even more acute further back in time, so that—in contrast to natural archives such as ice cores or tree rings—historical records generally degrade in their utility as they become older. There are, for example, weather records preserved in Irish and Norse annals back to the middle of the first millennium A.D., but their dating is imprecise and descriptions of weather and climate often are exaggerated. Understandably, historical observations also tend to focus on extreme events rather than climatic averages. For example, it was major storm events that most concerned Venetian traders and mariners; their records were used by Grove (2004) to reconstruct the climate of Crete in the 16th and 17th centuries. Documentary evidence is one of the few kinds available that can register severe floods, hurricanes, and other natural disasters. Consequently, their analysis enables an investigation of the relationship between variations in climate and the frequency and severity of extreme events, a subject that is of major societal concern in relation to projected global warming.

Historical observations are typically discontinuous through time and, as such, one of their most valuable roles is in providing a cross-check on reconstructions based on other proxy records, such as tree rings, and on the validity of paleoclimate model simulations. For example, modeling experiments show marked warming in Siberia during the winters immediately following major explosive volcanic eruptions, such as that of Pinatubo (Shindell et al. 2003). The diaries of travelers passing through northern interior Asia in key years (e.g., 1815–1816, 1883–1884) would allow this prediction to be tested independently.

SYSTEMATIC CLIMATE RECONSTRUCTIONS DERIVED FROM HISTORICAL ARCHIVES

Europe and East Asia are the two regions of the world where long temperature series have been most successfully developed from documentary evidence in a repeatable and consistent way for periods of more than the last two centuries.

Europe

The documentary evidence for Europe as a whole has been reviewed by Brázdil et al. (2005) and for the Mediterranean region by Luterbacher et al. (2006). Seasonal temperature data have been compiled for most areas of central and western Europe back to 1500, and these show that the late 20th and early 21st centuries have been warmer, at high probability for three out of four seasons, than any time period in the last five centuries (Xoplaki et al. 2005) (Figure 3-1). By combining documentary evidence with other proxy data, Luterbacher et al. (2004) were able to map winter and summer temperature anomalies across Europe for individual years back to 1500, along

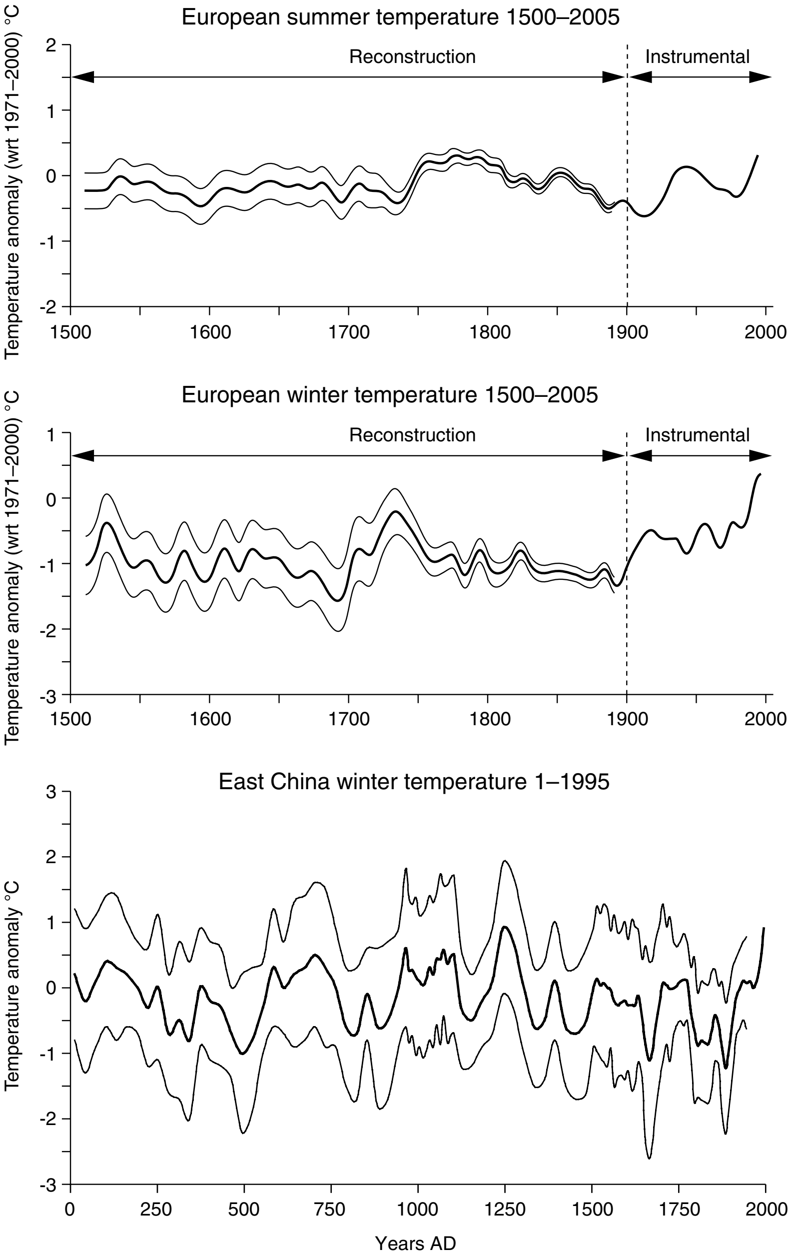

FIGURE 3-1 Seasonal temperature reconstructions based on historical evidence from Europe and China with standard errors (2 standard deviations for Europe, 1 standard deviation for China). Twentieth-century records (post-1950 for China) are based on instrumental data and do not show error bars. All data are subject to 30-year smoothing. SOURCES: Modified from Xoplaki et al. (2005), Luterbacher et al. (2004), and Ge et al. (2001). Reprinted with permission, Taylor & Francis Ltd. (http://tandf.co.uk/journals); copyright 2001.

with area-specific error estimates. This mapping permits a rigorous assessment of the spatial coherency of past annual to decadal climatic changes at a subcontinental scale, and also allowed Pauling et al. (2003) to calculate the best predictors of winter and summer temperatures from the available array of different proxy climate data for different parts of Europe and the North Atlantic Ocean. It shows, for example, tree rings to have been a good predictor of past summer temperatures across northern and central Europe, whereas documentary sources are more reliable for reconstructing wintertime temperatures.

Within Europe, only two continuous records currently extend back before 1500, namely, those from the Czech Republic (Brázdil 1996) and the Low Countries (Netherlands and Belgium; van Engelen et al. 2001), both of which have been incorporated into synthetic large-scale temperature reconstructions (e.g., Jones and Mann 2004b). They mark the 20th century as exceptionally warm but also indicate milder conditions prior to about 1400, while the Czech record also shows higher temperatures around the turn of the 19th century. It is not possible, however, to glean systematic, quantitative temperature data across Europe during the medieval period from historical documents alone. Although historical evidence provides important anecdotal evidence for this era, it is very difficult to know—from these limited and rather imprecise sources alone—if there were medieval time periods lasting a decade or more when the climate was as warm as, or warmer than, the late 20th and early 21st centuries.

East Asia

The second region for which there exist systematic temperature syntheses of several centuries' duration is East Asia. In Korea and Japan, for example, the date of the spring flowering of cherry trees has been recorded systematically every year for more than a thousand years (Aono and Omoto 1993). Wang et al. (2001) used documentary records to compile decadal average mean annual temperatures for East and North China back to 1380, and 50-year average temperatures for East China back to A.D. 800. In some cases (e.g., Yang et al. 2002), documentary data have been amalgamated with other proxy-climate data to generate regional composite temperature curves. Results from Ge et al. (2001) using phenological records supplemented by winter snow-day records from historical documents, reproduced in Figure 3-1, show temperatures above the long-term mean from A.D. 950 to 1300, and again after 1925, with Little Ice Age thermal minima in the 17th and 19th centuries. These data from the opposite ends of the Eurasian landmass give support to the idea that medieval warming and the Little Ice Age affected much if not all of the extratropical Northern Hemisphere landmasses, notwithstanding significant differences at annual to decadal timescales in the periods of warmth and cold.

Documentary evidence is generally limited to regions with long written traditions. The historical time depth is probably sufficient in a few other regions of the world to attempt systematic compilation of seasonal or annual temperature time series from documentary evidence. This potential exists, but has yet to be realized, in South and Southeast Asia and in the Middle East. An example of this capacity, albeit for African precipitation, is the Roda Nilometer, which has recorded annual data on the height of the Nile flood in Egypt from A.D. 645 to 1890 (Hassan 1981).

CONSEQUENCES OF CLIMATE CHANGE FOR PAST SOCIETIES

Historical documents, along with archeological and paleobiological evidence, can also reveal how societies and ecosystems have responded to climate variability in the past. This section provides a short illustrative summary of past human responses to climate change. However, it is important to note the danger of circular reasoning in this sphere, in the sense that the same evidence for cultural response cannot also be used to infer climatic causality. It is also clear that past societal responses have in general not been predictable or predetermined in advance. Although societies may have been required to adapt to new conditions, the outcome has depended on the success of the choices that were made (Diamond 2005, Rosen in press).

The implications of changing climatic conditions have often been most immediate for agrarian economies, particularly in environmentally marginal lands, and for long-distance communications. In the former case, there was a widespread contraction of rural settlement in upland regions of Europe to lower-lying terrain, associated with the overall climatic deterioration between the late 16th and mid-18th centuries (Parry 1978). In Iceland, an increase in storminess and in winter sea ice cover during the Little Ice Age hampered seaborne communications across the North Atlantic, on which the island's population was critically dependent. The 1780s brought not only the most severe pack ice of any decade since the 16th century (Ogilvie 1992) but also poisoning of livestock and humans by hydrogen fluoride gases released by the Laki fissure eruption. In combination, this killed more than 75 percent of Iceland's livestock and 25 percent of its human population and brought society close to collapse. Other examples where climate change may have played a part in societal collapse include the Classic Maya during the 9th century A.D. and the Anasazi of the American Southwest during the 12th and 13th centuries. Both of these cases were linked to periods of extended drought conditions (Hodell et al. 1995, Dean 1998). Climate-induced stress can also act as a stimulus to innovate; for example, declines in rainfall or shifts in temperature have sometimes been followed by technological developments, such as irrigation (Rosen in press).

It is also possible to find examples of climatic changes that were not accompanied by any obvious direct social consequences, and to find cases where the same climatic change had sharply contrasting consequences for different social groups in the same area. A clear example of contrasting adaptations and success/failure in the same environment is provided by the Inuit and the Vikings in western Greenland and the Arctic during the onset of the Little Ice Age. The Norse settlements of Greenland were always marginal, not only because climatic conditions were poorly suited for agriculture but also because of isolation from their parent cultures in northern Europe. In the face of increasingly harsh climatic conditions, populations declined, the western Viking settlement was abandoned around 1350, and the eastern settlement followed suit about a century later. The Norse perceived the adverse changes in climate as a function of cosmological disorder and built ever more impressive churches, rather than adopting new technologies or searching for new sources of food (Barlow et al. 1997, Buckland et al. 1996, McIntosh et al. 2000, Diamond 2005, Rosen in press).

During the same period of medieval warmth that had encouraged Norse expansion, retreating sea ice appears to have allowed an eastward migration of native Inuits along the Arctic shore from Alaska, and thence southward into the same areas of west Greenland being colonized by the Vikings. And like the Norse, these Thule Inuit cultures were challenged to adapt constantly in order to exploit the available resources; for example, their methods of whale hunting had to adjust depending on whether the sea ice was close to, or far removed from, the shore (Wohlforth 2004). There appears to have been little contact between the Norse and the Thule peoples and no cultural exchange, so that the Norse may not even have been aware of the successful Inuit adaptations for use of marine resources. During the period of the Little Ice Age, the Inuit peoples had to adapt to changing environmental conditions once again. For example, to continue whaling, their populations on Alaska's North Slope congregated in the few places on the coast where open water could still be reached, such as Nuvuk (Point Barrow). As a result of this and other choices, the Inuit—unlike the Norse—survived in the Arctic up to modern times.

4

Tree Rings

- Measurements of tree ring parameters from regions where temperature limits tree growth can be used to reconstruct surface temperature. These show that the 20th century warming was unusual since at least 1500.
- Tree rings have several features that make them well suited for climatic reconstruction, such as ease of replication, wide geographic availability, annual to seasonal resolution, and accurate, internally consistent dating.
- Tree ring records exist for the last two millennia, although spatial coverage decreases going back in time.
- Surface temperature reconstructions based on tree rings require attention to confounding factors; guidelines exist to identify and account for these factors.

DEFINITION AND PREMISES

Dendroclimatology is the application of tree ring science, or dendrochronology, to the study of climate (Fritts 1976). The online Bibliography of Dendrochronology (Dobbertin and Grissino-Mayer 2004) includes more than 10,000 references addressing questions in archeology, climatology, ecology, forestry, hydrology, geology, geomorphology, and other areas. A considerable portion of tree ring data collected on all inhabited continents is freely available online (Grissino-Mayer and Fritts 1997).

Dendroclimatic records are commonly derived from areas where wood growth is related to climate. For air temperature,[1] preferred locations are close to the treeline, which repre-

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[1] This chapter does not cover the other numerous climatic variables (e.g., precipitation and drought) that can be studied using tree ring records. It also does not consider other environmental factors (such as wildfires) that can be reconstructed from tree ring features.

sents the altitudinal or latitudinal limit to tree growth (Kullman 1998, Körner 1999). From a review of published data, Grace (1988) concluded that "a 1°C increase in a north temperate climate may be expected to increase plant productivity by about 10 percent, providing that other factors like water or nutrients do not become limiting." Controlled experiments dealing with the effect of temperature on plant growth are mostly performed on herbaceous species or seedlings (Junttila 1986, Loveys et al. 2002), and it is difficult to extrapolate those findings to the spatial and temporal scales considered by dendroclimatologists. For example, consider the evidence for treeline shifts in many areas of the world (MacDonald et al. 1998, Esper and Schweingruber 2004, Millar et al. in press). Such observations do not easily lend themselves to experimental testing of causal mechanisms. It has been argued that treeline position is not highly sensitive to interdecadal temperature change (Paulsen et al. 2000), but rather reflects environmental variability over several hundred years (Lloyd and Graumlich 1997, Körner 1999). Local disturbances, site conditions, and regional climatic regimes also influence the degree of sensitivity and rate of response of treelines to temperature changes (Kjällgren and Kullman 2002, Daniels and Veblen 2003).

The biological connection between temperature and tree ring variations on hourly to annual timescales has been investigated in the field using specialized instruments called dendrometers (Biondi et al. 2005), together with wood anatomy observations (Deslauriers et al. 2003a). For European and North American conifers living in cold environments, ring formation mostly occurs from May to the beginning of August, peaking around the time of maximum day length (Rossi et al. 2006 and references therein). By monitoring stem size of *Pinus cembra* and temperature during the growing season for two full years in the Alps, it was found that radial expansion ceased whenever air temperature fell below 5°C (Körner 1999). Night temperature was more important than day temperature for controlling radial growth of balsam fir at about 50°N latitude (Deslauriers et al. 2003b). At longer timescales (monthly to decadal), a number of dendroclimatic studies have identified a positive, linear relationship between mean July temperature and ring-width chronologies of *Pinus sylvestris* in northern Fennoscandia (Mikola 1962, Kalela-Brundin 1999, Helama et al. 2002).

In terms of causal mechanisms, tree ring records are likely to be the result of multivariate, and often nonlinear, biophysical processes. Models based on ecological or physiological concepts have been proposed to account for such processes (Fritts et al. 1991, Hunt Jr. et al. 1991, Scuderi et al. 1993, Berninger et al. 2004, Misson 2004). An intriguing hypothesis for the ability of treeline pine species to record slowly changing surface temperatures involves the fact that needles formed in one growing season remain alive and functioning for 10–30 years (LaMarche 1974). The mechanistic bases for the statistical models used to extract climate signals from tree ring data have been summarized in simulation models focusing on the activity of the tissue that forms wood, the vascular cambium (Vaganov et al. 2006). Also note that linear relationships between tree ring records and climate are at least equal to, and often exceed, those found for other proxies (Jones et al. 1998). Statistical techniques more responsive to nonlinear interactions have so far provided relatively small improvements for explaining climatic variance (Hughes 2002 and references therein).

All proxy records of climate are obtained from samples that are not randomly selected (Cronin 1999). Part of the researcher's ability consists of identifying sites where proxy records are as long, continuous, and representative of the target climatic variable as possible. Guidelines have been specified in the tree ring literature

(Schweingruber 1988, Fritts and Swetnam 1989) to ensure that sample (site, tree, and core) selection is based on *a priori* rather than *a posteriori* criteria. For instance, sites are selected in remote areas where tree density is low in order to minimize the impact of stand dynamics and intertree competition (Biondi et al. 1994). The influence of varying local conditions on dendroclimatic records has been studied for elevation, slope, and exposure (Kienast and Schweingruber 1986, Villalba et al. 1994, Buckley et al. 1997, Tardif et al. 2003, Piovesan et al. 2005), topographic convergence and potential relative radiation (Bunn et al. 2005), and flooding patterns (Tardif and Bergeron 1997). Sampled trees should not show signs of disturbance factors such as insect infestation, grazing, fire damage, human utilization, fungal infestation, or mistletoe attack (Schweingruber 1988, Fritts and Swetnam 1989). Overall, as in any other field-based investigation of environmental change, defining the research question is the premise to a proper selection of materials and methods (Bräker 2002).

FIELD AND LABORATORY METHODS

To ensure reliable results, tree ring science places great emphasis on replication (Wigley et al. 1984, Fritts and Swetnam 1989). At least 10–20 trees per species are sampled at a site, mostly by taking increment cores, and each tree is cored following specific guidelines (Grissino-Mayer 2003). All collected samples are transported back to the laboratory, where they are compared to one another. The method of crossdating (or pattern matching) is used to assign calendar years to the individual rings (Baillie and Pilcher 1973, Wigley et al. 1987, Yamaguchi 1991). Initially based on a visual comparison (Stokes and Smiley 1996), crossdating is quality controlled by means of numerical techniques once the ring widths are measured (Holmes 1983, Grissino-Mayer 1997). The precision and accuracy of crossdating have allowed the refinement of radiocarbon dating techniques (LaMarche and Harlan 1973, Friedrich et al. 2004). Tree ring chronology development follows rules that are common to all applications of tree ring science, and is completely independent of any climatic data. Samples or portions of samples that cannot be crossdated with the rest of the specimens are not included in the final chronology. Recommendations to archive all collected materials, so that they remain available for future study, have been published (Eckstein et al. 1984). The Laboratory of Tree-Ring Research at the University of Arizona still has wood samples, field notes, and measurements that were taken a century ago by A.E. Douglass, the Tucson astronomer who proposed many of the dendrochronological methods still in use today (Webb 1983).

After crossdating, tree ring parameters other than width (such as density, stable isotopic composition, cell size and wall thickness, resin duct density, and trace metal concentrations) can be measured. Dendroclimatic studies of past surface temperature are mostly based on ring width or maximum latewood density; the latter usually has a higher correlation with temperature, especially during the summer (Conkey 1986, Briffa et al. 2002). Maximum latewood density is also correlated with ring anatomy as measured by cell number, cell diameter, and cell wall thickness (Wang et al. 2002). Measurements made on crossdated wood samples from the same species and site are typically combined into a master chronology (Fritts 1976, Cook and Kairiukstis 1990). This process is aimed at increasing the climatic signal by reducing the importance of individual sample noise. In general, the number of specimens required to obtain a robust chronology increases as the common variance among specimens decreases (Fritts and Swetnam 1989). Although all crossdated samples are entered into the final chronology, standardization removes any difference in mean growth rate between specimens, so that faster-growing trees do not dominate the record. Any criteria used to form a chronology out of a subset of the crossdated specimens need to be clearly reported and justified.

The identification of year-to-year (high-frequency) climate signals in tree ring records is relatively straightforward since it is based on the elimination of time series autocorrelation using autoregressive models (Biondi and Swetnam 1987, Cook and Kairiukstis 1990). If adequately long instrumental records are available, it is even possible to explore the stationarity of statistical relationships between climatic variables and tree ring parameters by considering multiple time intervals (Biondi and Waikul 2004).

With regard to low-frequency temperature patterns, the length of the individual tree ring records used to produce a master chronology (rather than the length of the chronology itself) can influence the reconstruction (Cook et al. 1995). It is also difficult to distinguish the amount of temporal autocorrelation in tree ring records that is linked to biological processes instead of climatic ones (Fritts 1976). One way to resolve these issues is to compute the expected value of the tree ring parameter (width, density, etc.) as a function of biological age (i.e., time since ring formation), and use the resulting growth curve to standardize the individual tree ring series. This method, which is now called Regional Curve Standardization (RCS), was first proposed in the 1930s (Grudd et al. 2002), later described by Fritts (1976), and made popular by Briffa et al. (1992). In addition to its theoretical appeal, the RCS method is suitable for retrieving low-frequency signals in tree ring records (Esper et al. 2003, Bunn et al. 2004) and is widely employed in dendroclimatic reconstructions of surface temperature (Esper et al. 2002a, Gunnarson and Linderholm 2002, Naurzbaev et al. 2002).

TEMPERATURE RECONSTRUCTIONS

To prevent the risk that a single tree ring chronology could reflect the influence of localized nonclimatic influences (Fritts 1976, Trotter et al. 2002), dendroclimatic reconstructions often rely on networks of site chronologies. Regional tree ring networks typically have strong intersite correlations (e.g., Hughes et al. 1984, Figure 2), and continental-to-hemispheric-scale networks are able to reproduce synoptic-scale climatological patterns (Fritts 1991, Briffa et al. 2002). When based on a number of sites in the Northern Hemisphere, dendroclimatic reconstructions of surface temperatures show that the 20th century warming was unusual since at least 1500 (D'Arrigo et al. 2006; Figures 4-1 and 4-2), in agreement with independent reconstructions derived from written documents (Xoplaki et al. 2005), borehole temperatures (Pollack and Smerdon 2004), and glacier lengths (Oerlemans 2005a). When records are sought for the last two millennia, the number of available tree ring chronologies declines markedly (Hughes 2002), so confidence in reconstructed patterns is reduced.

All paleoclimatic reconstructions rely on the "uniformity principle" (Camardi 1999), which assumes that modern natural processes have acted similarly in the past, and is also discussed as the "stationarity" assumption in Chapter 9. Although limiting factors controlled tree ring parameters in the past just as they do today, it is possible that the role of different factors at a single location or over an entire region could change over time. This possibility has been raised to explain the "divergence" (i.e.,

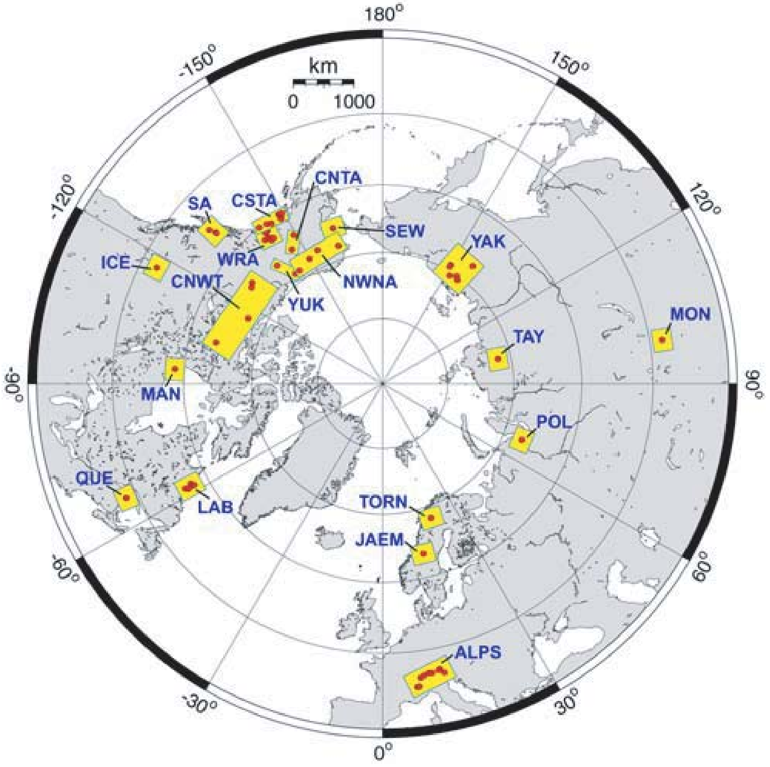
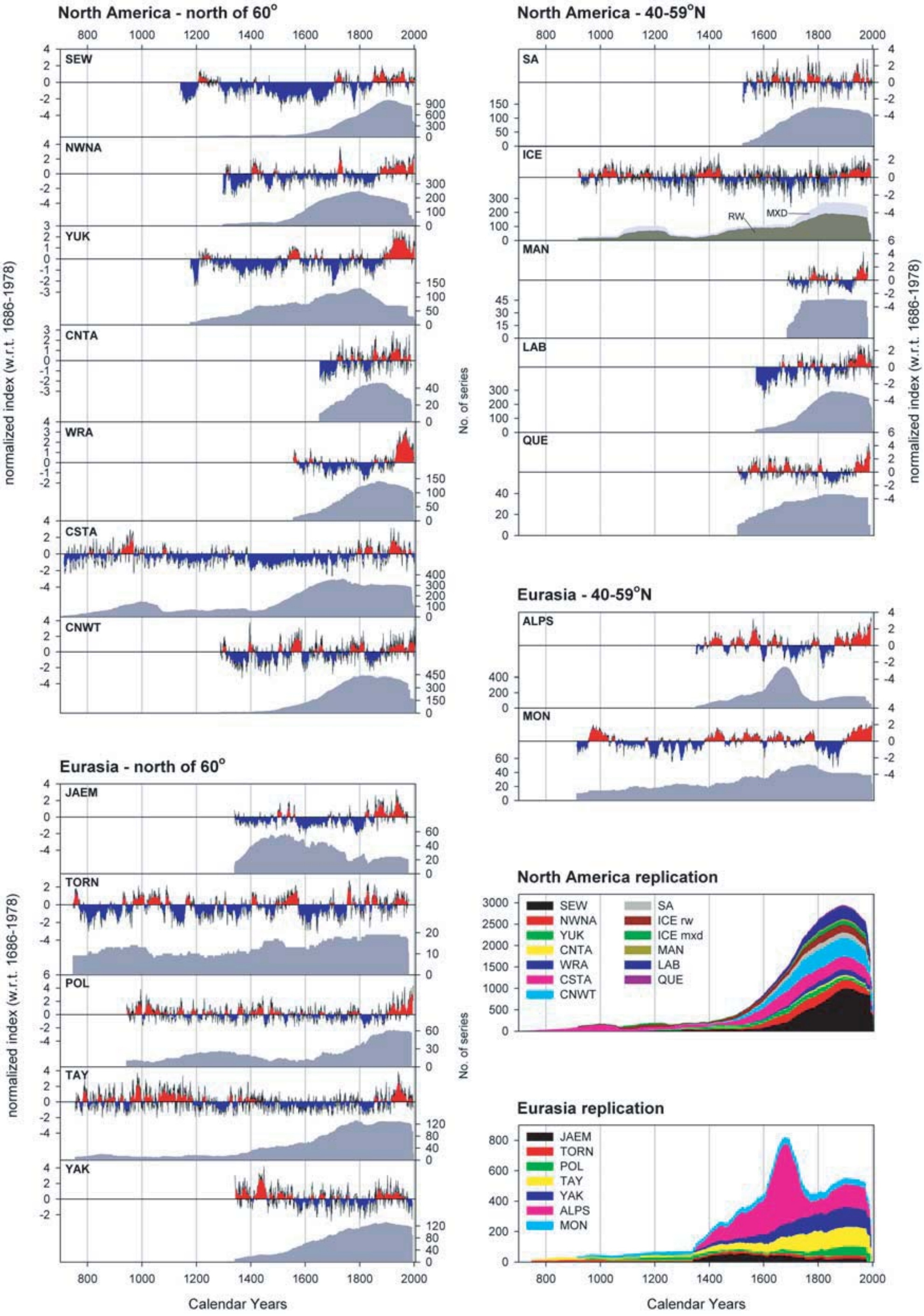


FIGURE 4-1 Location map of individual sites (red) and regional composites (yellow boxes) used to reconstruct Northern Hemisphere surface temperatures for the past millennium. SOURCE: D'Arrigo et al. (2006). Reproduced by permission of American Geophysical Union; copyright 2006. NOTE: ALPS = Alps, CNTA = Central Alaska, CNWT = Central Northwest Territory, CSTA = Coastal Alaska, ICE = Icefields, JAEM = Jaemtland, LAB = Labrador, MAN = Manitoba, MON = Mongolia, NWNA = Northwest North Alaska, POL = Polar Urals, QUE = Quebec, SA = Southern Alaska, SEW = Seward, TAY = Taymir, TORN = Tornetraesk, WRA = Wrangells, YAK = Yaktutia, YUK = Yukon.

reduced correlation) between temperature and ring parameters (width and maximum latewood density) during the late 20th century (Jacoby and D'Arrigo 1995, Briffa et al. 1998). In Alaska, it appears that increasing air temperature over the past decades is not reflected in increasing tree ring records because water (i.e., drought stress) has become the limiting factor (Barber et al. 2000, Lloyd and Fastie 2002, Wilmking and Juday 2005). In Siberia, on the other hand, reduced correlation of tree ring chronologies with summer temperature has been attributed to increasing winter precipitation, which leads to delayed snowmelt in permafrost environments, thus shortening the tree growing season (Vaganov et al. 1999). Other hypotheses have been formulated for the reduced correlation between temperature and tree ring chronologies, such as a negative effect on tree growth due to greater ultraviolet radiation reaching the ground as a


North America - north of 60°
SEW
NWNA
YUK
CNTA
WRA
CSTA
CNWT
North America - 40-59°N
SA
ICE
RW
MXD
MAN
LAB
QUE
Eurasia - north of 60°
JAEM
TORN
POL
TAY
YAK
Eurasia - 40-59°N
ALPS
MON
North America replication
SEW
NWNA
YUK
CNTA
WRA
CSTA
CNWT
SA
ICE rw
ICE mxd
MAN
LAB
QUE
Eurasia replication
JAEM
TORN
POL
TAY
YAK
ALPS
MON
normalized index (w.r.t. 1686-1978)
No. of series
800
1000
1200
1400
1600
1800
2000
Calendar Years

result of thinning stratospheric ozone (Briffa et al. 2004), or the possibility that surface instrumental temperatures are affected by an upward bias (Hoyt 2006). Elevational treeline sites in Mongolia (D'Arrigo et al. 2001) and the European Alps (Büntgen et al. 2005) are not affected by "divergence." This geographic separation was confirmed by Cook et al. (2004), who subdivided long tree ring records for the Northern Hemisphere into latitudinal bands and found not only that "divergence" is unique to areas north of 55°N but also that the difference between northern and southern sites found after about 1950 is unprecedented since at least A.D. 900.

An especially suitable strategy to minimize confounding effects is to sample sites along ecological gradients, such as elevation or latitude (Fritts and Swetnam 1989, Bugmann 1996). For example, Naurzbaev et al. (2004) selected sites along latitudinal (from 55 to 72°N) and elevational (from 1120 to 2350 meters above sea level) transects and used the parameters of the Regional Curve Standardization to infer climatic influences and past temperature variability. Other strategies are available to improve tree ring reconstructions of surface temperature. Some of these strategies involve using maximum temperature instead of mean temperature (Luckman and Wilson 2005), combining multiple tree ring parameters related to temperature (Helle and Schleser 2004), sampling species with opposing responses to temperature (Biondi et al. 1999), and applying mechanistic models to tree ring records (Anchukaitis et al. 2006).

The possibility that increasing tree ring widths in modern times might be driven by increasing atmospheric carbon dioxide (CO_2) concentrations, rather than increasing temperatures, was first proposed by LaMarche et al. (1984) for bristlecone pines (*Pinus longaeva*) in the White Mountains of California. In old age these trees can assume a "strip-bark" form, characterized by a band of trunk that remains alive and continues to grow after the rest of the stem has died. Such trees are sensitive to higher atmospheric CO_2 concentrations (Graybill and Idso 1993), possibly because of greater water-use efficiency (Knapp et al. 2001, Bunn et al. 2003) or different carbon partitioning among tree parts (Tang et al. 1999). Support for a direct CO_2 influence on tree ring records extracted from "full-bark" trees is less conclusive. Increasing mean ring width was reported for *Pinus cembra* from the central Alps growing well below treeline (Nicolussi et al. 1995). Free-Air CO_2 Enrichment (FACE) data for conifer plantations in the Duke Forest (Hamilton et al. 2002) and at the alpine treeline (Hättenschwiler et al. 2002) also showed increased tree growth after exposure to atmospheric CO_2 concentrations about 50 percent greater than present. On the other hand, no convincing evidence for such effect was found in conifer tree ring records from the Sierra Nevada in California (Graumlich 1991) or the Rocky Mountains in Colorado (Kienast and

FIGURE 4-2 Results for individual regional composite chronologies for the sites shown in Figure 4-1. The time series have been loosely grouped according to latitude bands and normalized to the common period. The bottom two panels in the right column show grouped replication plots for both North America and Eurasia. For definitions of abbreviations, see Figure 4-1. SOURCE: D'Arrigo et al. (2006). Reproduced by permission of American Geophysical Union; copyright 2006.

Luxmoore 1988). Further evidence comes from a recent review of data for mature trees in four climatic zones, which concluded that pine growth at the treeline is limited by factors other than carbon (Körner 2003). While "strip-bark" samples should be avoided for temperature reconstructions, attention should also be paid to the confounding effects of anthropogenic nitrogen deposition (Vitousek et al. 1997), since the nutrient conditions of the soil determine wood growth response to increased atmospheric CO_2 (Kostiainen et al. 2004). However, in forest areas below the treeline where modern nitrogen input could be expected to influence dendroclimatic records, such as Scotland (Hughes et al. 1984) and Maine (Conkey 1986), the relationship between temperature and tree ring parameters was stable over time.

In conclusion, tree ring science provides useful insights into past temperature variability. Promising areas of current and future research can be summarized as:

- updating site chronologies that were collected 20–30 years ago,
- increasing the number and geographic coverage of temperature-sensitive tree ring chronologies longer than 1,000 years,
- quantifying the precision and accuracy of low-frequency temperature signals,
- performing experimental studies on biophysical relationships between temperature and tree ring parameters, and
- refining mechanistic models of temperature effects on tree ring parameters at multiple spatial and temporal scales.

5

Marine, Lake, and Cave Proxies

- Annual coral records indicate a warming and/or freshening of surface seawater over the last century at most tropical locations, as well as shifts toward warmer and/or fresher waters during the mid-1800s and between 1920 and 1940.
- North Atlantic sediment records from the Labrador Sea, Bermuda Rise, and the coast of Africa show a medieval warming and cooling during the Little Ice Age.
- Corals and marine sediments provide information about surface temperature in otherwise undersampled ocean regions. Peat and lake muds, which contain microfossils of climate-sensitive organisms, and cave calcite deposits provide information on climate events impacting land areas.
- Although records from marine, lake, and cave proxies can be annually banded, many of the proxies discussed in this chapter have only interannual to decadal resolution and thus mainly contribute to describing the low-frequency variability of past climate.
- Many of the records discussed in this chapter are more sensitive to variations in hydrologic factors than variations in surface temperature. Variations in precipitation often coincide with wider changes in climate, although there is no consistent global relationship between cold/wet and warm/dry conditions, or vice versa. The quantity used as a proxy for temperature in most coral studies to date is also influenced by changes in isotope ratios of seawater, although newer techniques address this limitation.

CORALS

Massive corals that live near the sea surface produce annual density bands of aragonite (calcium carbonate) that can be sampled and used to reconstruct monthly climate records by examining their geochemical composition. In particular, the ratio of ^{18}O to ^{16}O (commonly referred to as $\delta^{18}O$)[1] in coralline aragonite decreases with increasing seawater temperature and with decreasing $\delta^{18}O$ in water at the time of formation. The $\delta^{18}O$ of water is often strongly correlated with salinity. Hence, $\delta^{18}O$ values from a coral that grew in an open-ocean location can be used to reconstruct a combined signal of sea surface temperature (SST) and salinity for that oceanic region.

Sites for coral sampling are selected on the basis of proximity to open ocean and generally well-flushed locations. The largest corals are usually found in leeward locations that are minimally influenced by storms and silt. The morphology of the coral head should show a rounded shape with minimal erosion at the base caused by boring organisms or physical damage. In most cases, more than one coral is sampled from each site to obtain the longest record. Ideally, coral-based reconstructions would be based on multiple cores from the same site, but in practice few sites have been studied in this detail (for an exception, see Hendy et al. 2002). More commonly, coral reconstructions are calibrated closely with instrumental data, and high correlation coefficients lend confidence to the reconstruction of past conditions (for reviews, see Gagan et al. 2000, Cole 2003). The primary limitation of using coral $\delta^{18}O$ for SST reconstruction is the added variable of water $\delta^{18}O$, which is important in areas of high rainfall, evaporation, or river input, such as the western Pacific warm pool. Recently, it has been discovered that this limitation can be overcome by simultaneously measuring the elemental ratio of strontium to calcium (denoted Sr/Ca) in coral bands, because the Sr/Ca ratio changes mainly as a function of SST. Sr/Ca ratios have been shown to track SST quantitatively with a high degree of precision (Beck et al. 1992), yielding an uncertainty in SST reconstructions of less than 0.3°C. There are several long-term reconstructions of SSTs available using coral Sr/Ca ratios including the Great Barrier Reef (Hendy et al. 2002), Rarotonga and Fiji (Linsley et al. 2004), Madagascar (Zinke et al. 2004), and Hawaii (Druffel et al. 2001). A few studies have also used uranium/calcium (U/Ca) ratios to reconstruct SSTs (e.g., Hendy et al. 2002).

Results of Coral-Based Reconstructions

Continuous coral $\delta^{18}O$ records for the last 100–400 years are available for regions in the tropical and subtropical Pacific, Indian, and Atlantic oceans (see summary papers: Cole 2003, Lough 2004, Gagan et al. 2000). Corals from most of these sites display an overall decrease in $\delta^{18}O$ values toward the 20th century, which indicates surface seawater that is warmer, fresher (lower salinity), or both. Most of these records also show abrupt shifts toward warmer/fresher waters during the mid-

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[1] The $\delta^{18}O$ of a sample is defined as follows:

$$\delta^{18}O = ((R_{samp} - R_{std})/R_{std}) \times 1{,}000$$

where R_{samp} is the $^{18}O/^{16}O$ ratio in a sample and R_{std} is the $^{18}O/^{16}O$ ratio in a reference standard.

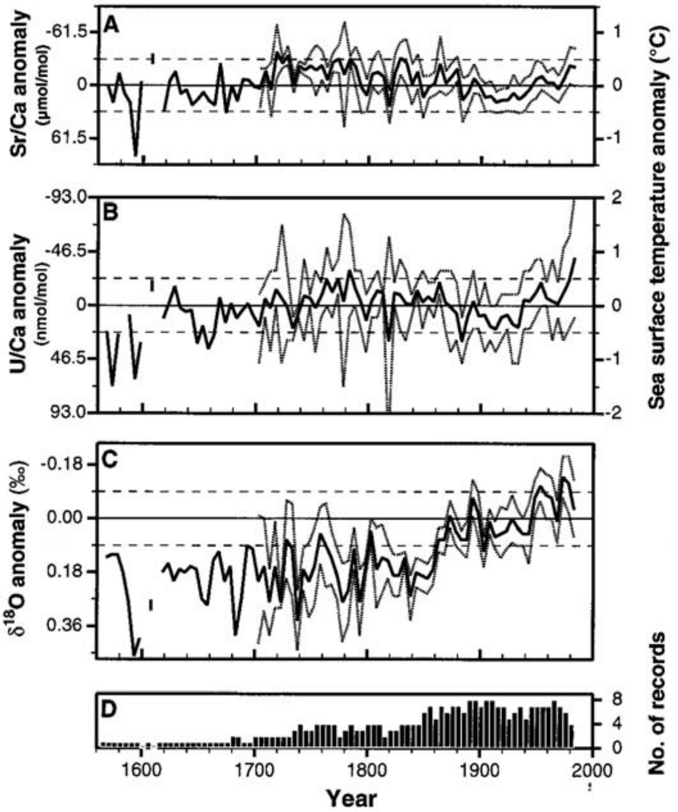

FIGURE 5-1 Sr/Ca, U/Ca, and δ^{18}O anomalies from Great Barrier Reef composites; the Sr/Ca and U/Ca anomalies have been used to reconstruct local SST records for five-year averages, with 95 percent statistical confidence intervals indicated by dotted lines. SOURCE: Hendy et al. (2002). Reprinted with permission from AAAS; copyright 2002.

1800s and from 1920 to 1940, the latter of which agrees with instrumental records (Gagan et al. 2000). Superimposed on the recent oceanic warming, some locations show distinct patterns of decadal variability, with repeated shifts of several tenths of a degree Celsius.

Figures 5-1 and 5-2 show examples of isotopic and elemental records derived from corals. Using Sr/Ca and U/Ca ratios in eight coral cores from the Great Barrier Reef, Hendy et al. (2002) (Figure 5-1) revealed that above-average SSTs were present in the 18th and 19th centuries, with cooling in the early 20th century and warming until the 1980s (more so for the U/Ca results). Other coral records from the southwestern Pacific (Figure 5-2) display interdecadal changes in the δ^{18}O and Sr/Ca values that reflect both SSTs and changes in the circulation near the South Pacific Convergence Zone (Linsley et al. 2004). These authors conclude that the degree of cross-

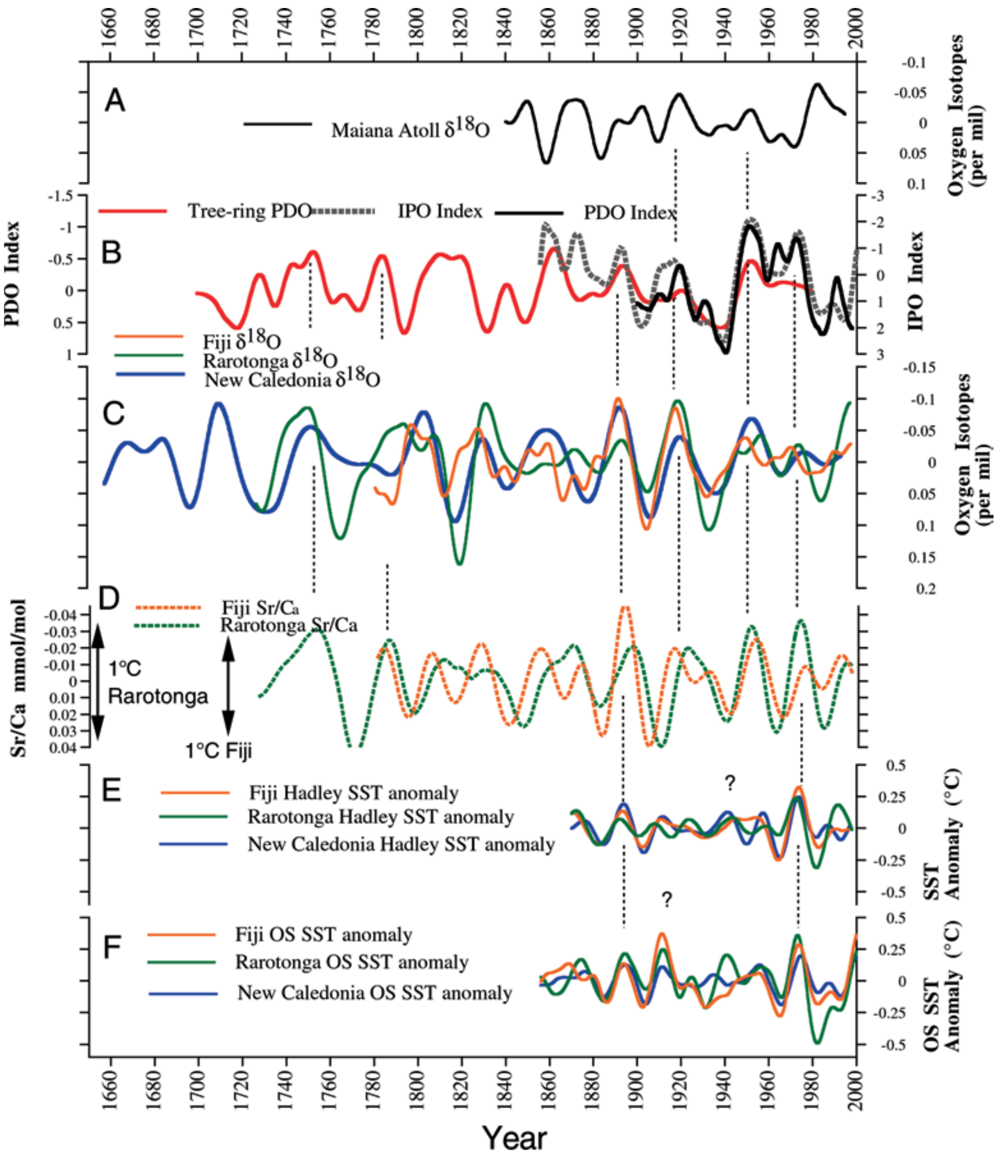

FIGURE 5-2 (A–F) Comparison of interdecadal variability in geochemical records from *Porites* corals from Rarotonga (Linsley et al. 2000), Fiji and New Caledonia (Quinn et al. 1998), and Maiana Atoll (Urban et al. 2000). The long-term trend has been removed from all data; thus, the warming during the 20th century cannot be seen. Also shown are instrumentally based indices of the Interdecadal Pacific Oscillation (IPO) (Folland et al. 2002) and Pacific Decadal Oscillation (PDO) (Mantua et al. 1997) indices, along with the North American tree-ring-based PDO index of D'Arrigo et al. (2001) and SST data from Rarotonga, Fiji, and New Caledonia from two different datasets (HADISST1 and Kaplan et al. [1998]). SOURCE: Linsley et al. (2004). Reprinted with kind permission of Springer Science and Business Media; copyright 2004.

hemispheric symmetry of interdecadal oceanographic variability has varied over time, with a lower correlation between the North and South Pacific during the mid-18th century.

In the eastern tropical Pacific, where El Niño–Southern Oscillation (ENSO) events dominate the climatology, coral records primarily reflect variability of SSTs, and there is no shift toward lower $\delta^{18}O$ (warmer SSTs) by 1954 (Dunbar et al. 1994). Other isotopic and elemental records from corals in this region also demonstrate incidences of these events (Shen et al. 1992, Guilderson and Schrag 1998, Druffel 1981). In the western Indian Ocean, coral $\delta^{18}O$ from the Seychelles (Charles et al. 1997) and Malindi, Kenya (Cole et al. 2000) demonstrate an SST increase of 0.6°C from the mid-1800s to 1980; discontinuous records from Madagascar indicate cool conditions from 1675 to 1760 and warm conditions from 1880 to 1900 and from 1973 to 1995 (Zinke et al. 2004). The impact and nature of ENSO cycles in this region appear to have changed during this most recent warm period. In the southeast Indian Ocean, the coral $\delta^{18}O$ record suggests a rise in SST by 0.6°C since 1944 and an additional half degree rise since 1795 (Kuhnert et al. 1999). Finally, $\delta^{18}O$ data from Bermuda corals indicate a slight shift toward higher SSTs, whereas data from other isotope ratios ($^{13}C/^{12}C$ and $^{14}C/^{12}C$) show that mixing in the upper ocean was variable during the 19th and 20th centuries (Nozaki et al. 1978; Druffel 1989, 1997). Coral records from Florida and the Caribbean Sea show $\delta^{18}O$ variations that reflect some combination of SST and hydrologic changes (Druffel 1981, Winter et al. 2000, Swart et al. 1996).

Prospects for Improving and Extending Coral Records

To obtain large-scale, multicentury reconstructions of SSTs based on Sr/Ca ratios, it is necessary to obtain long records of Sr/Ca ratios in corals for a much larger number of locations than is currently available. Uranium-thorium measurements make it possible to obtain windows of shorter records within the last few millennia to shed light on tropical and subtropical ocean climate variability. Cobb et al. (2003) reported a $\delta^{18}O$ record for portions of the last 1,100 years from fossil corals at Palmyra atoll in the mid-tropical Pacific. As shown in Figure 5-3, they find relatively cool and dry climate conditions during the 10th century to increasingly warmer and wetter climate in the 20th century. ENSO activity was found to be most intense during the mid-17th century than during other periods examined. Although not a problem with these data, the possibility of diagenetic alteration of fossil segments must be considered in coral studies.

Sclerosponges and Molluscs

Sclerosponges inhabit shallow tropical caves and secrete aragonite at very low growth rates (0.1–0.2 millimeters per year); relatively small specimens can be over 1,000 years old. Sr/Ca ratios measured in sclerosponge layers demonstrate correlation with SST (Rosenheim et al. 2004). Long-lived shells such as the clam *Arctica islandica* live in cold surface waters and put on annual growth bands. Although promising (Forsythe et al. 2003), mollusc $\delta^{18}O$ and geochemical records available so far are too short to be used for long-term reconstruction of SSTs.

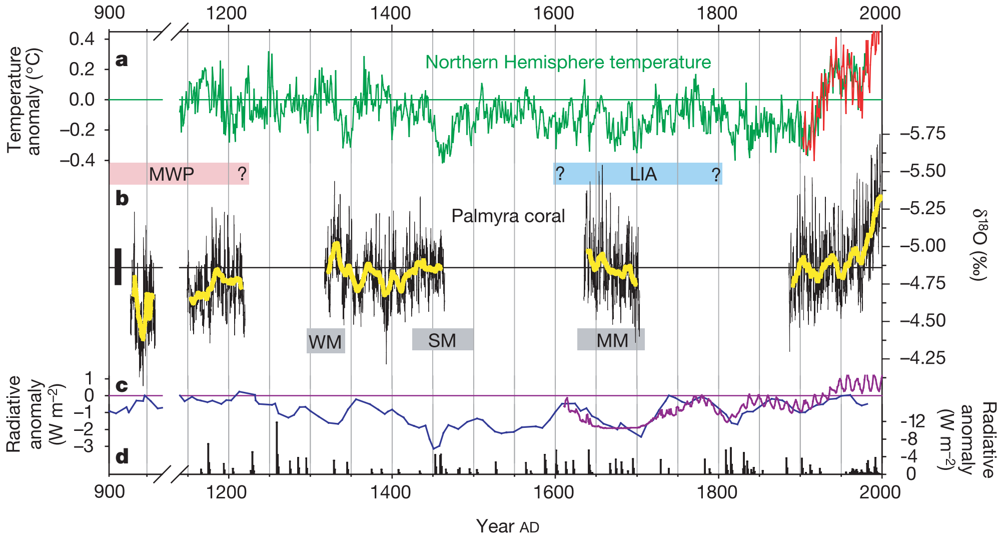

FIGURE 5-3 Composite from Cobb et al. (2003) showing Northern Hemisphere reconstructed temperature anomalies (Mann et al. 1999), $\delta^{18}O$ values derived from fossil corals in Palmyra, solar radiance anomalies (Lean et al. 1995, Bard et al. 2000), and one estimate of radiative forcing anomaly (Crowley 2000). SOURCE: Cobb et al. (2003). Reprinted with permission from Macmillan Publishers Ltd.; copyright 2003.

MARINE SEDIMENTS

The utility of marine sediments in recording climate change during the Holocene depends either on sufficiently rapid sediment accumulation to overcome the mixing effects of bioturbation[2] (usually up to 8 centimeters) or deposition under anoxic or suboxic oceanic conditions to retain annual layers. Both types of depositional environments have been exploited in attempts to infer oceanic and atmospheric conditions affecting the record in the sediments.

Several studies of marine sediments have provided insight into past climate on a regional basis. The Cariaco Basin off Venezuela is an anoxic basin with annual layers reflecting changes in atmospheric conditions that accompany shifts in the location of the Intertropical Convergence Zone (ITCZ), in particular the location and intensity of precipitation. Haug et al. (2003) have studied the titanium concentration changes in the Cariaco Basin annual sediment layers to infer the variations in the ITCZ, which impacted rainfall on the Yucatan Peninsula. The record is somewhat ambiguous in defining the Little Ice Age or a warm period during medieval times, but the authors believe it indicates several epochs of severe drought at the beginning of medieval times

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[2] Bioturbation is the mixing of sediments by bottom-dwelling organisms (see, e.g., Turekian et al. 1978).

that caused the collapse of the Classic Mayan civilization. Black et al. (1999) demonstrated that decadal-to-multicentury variations in wind-driven upwelling in the Cariaco Basin, and by inference the mean position of the ITCZ, were closely linked to North Atlantic SSTs over the past eight centuries. Other records from upwelling areas off Pakistan (e.g., von Rad et al. 1999) and zones of layered sediment deposited under anoxic conditions—such as fjords along the coast of British Columbia, Canada—also possess marine sediments with distinct seasonal layers that offer high-resolution histories of late Holocene climate.

Records from rapidly accumulating sediments in the Atlantic Ocean also provide information about temperature changes over the last 2,000 years. The temperature proxies derived from benthic and planktic foraminifera in the northwestern Atlantic Ocean (Keigwin and Pickart 1999, Marchitto and deMenocal 2003), the Bermuda Rise (Keigwin 1996, Keigwin and Boyle 2000), and off the west coast of Africa (deMenocal et al. 2000), as well as from marine diatoms (silica-shelled algae; Jiang et al. 2002), all reveal changes in surface ocean temperatures or surface ocean temperatures transmitted to depth by sinking water masses. To varying degrees, both the Little Ice Age and the warm period around medieval times are revealed by these records (Figures 5-4 and 5-5). It has been suggested that Holocene climate variations indicated by peaks in ice-

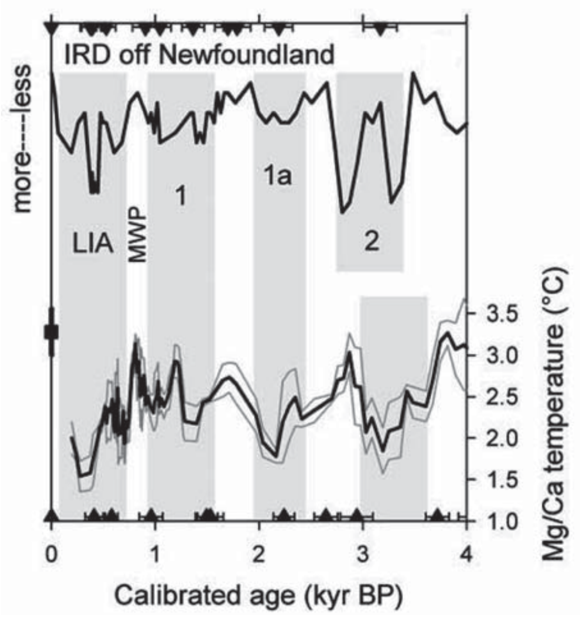

FIGURE 5-4 Variation of bottom temperature on the Labrador current inferred from Mg/Ca ratios in forams and the relation to the measure of ice-rafted debris (IRD) showing variations in North Atlantic temperature changes as reflected in deep-sea sediments. SOURCE: Marchitto and deMenocal (2003). Reproduced by permission of American Geophysical Union; copyright 2003.

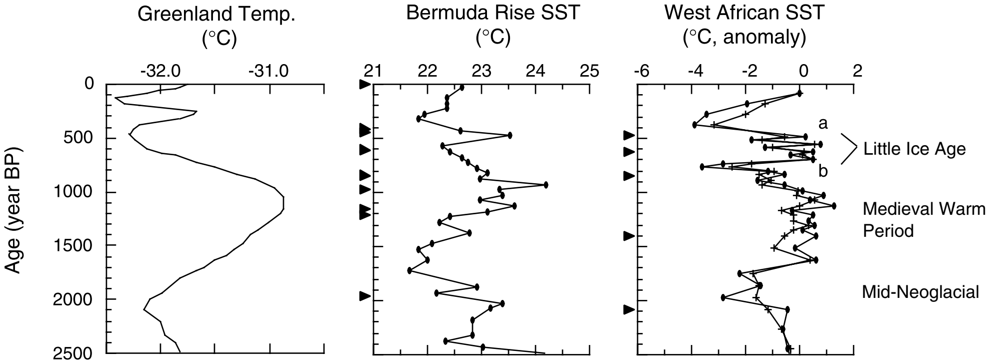

FIGURE 5-5 Greenland temperature (Dahl-Jensen et al. 1998), Bermuda Rise SST (Keigwin 1996), and West African SST for the last 2,500 years. SOURCE: deMenocal et al. (2000). Reprinted with permission from AAAS; copyright 2000.

rafted lithic grain abundances in several North Atlantic cores were paced by variations in solar irradiance (Bond et al. 1997, 2001) (Figure 5-6).

In addition, sedimentation rates are fast enough in some estuarine and coastal settings to allow climate reconstruction for the last 2,000 years. Cronin et al. (2003) used Mg/Ca paleothermometry on microfossil shells to show temperature shifts of 2–4°C in the Chesapeake Bay, including cold excursions during the Little Ice Age and warmer periods during medieval times (about A.D. 800 to 1300). Because of estuarine pollution linked to land clearance from the mid-19th century, the most recent part of this record may reflect factors other than water temperature.

LAKE AND PEAT SEDIMENTS

In many lakes, sediments contain distinct seasonal layers, or varves, that are either biogenic (e.g., carbonate, diatom silica, and organic matter) or minerogenic (alternating coarse and fine-grained particles) in origin. Both sediment types potentially allow annual dating for sequences that span many millennia, although typically with chronological errors of a few percent (Zolitschka 2003). Lake water biology and chemistry are often sensitive to temperature, but they are also influenced by other factors such as precipitation, watershed land use, and atmospheric pollution. To obtain unambiguous climate signals from lake records, researchers often choose sites in remote locations, such as the High Arctic. The summer ice-free period in Arctic Canadian lakes is highly sensitive to temperature, for example, and this in turn has been recorded in the thickness and nature of seasonal varves (Lamoureux and Bradley 1996).

Lakes in tropical and dryland regions are usually more sensitive to water balance than they are to temperature *per se*. Consequently, lake sediment records provide one of the key natural archives for reconstructing histories of drought and flood in regions such as the U.S. Midwest (Laird et al. 1998), as well as long-term changes in ENSO activity (Rodbell et al. 1999). Stable isotope analysis of a varved lake sequence by

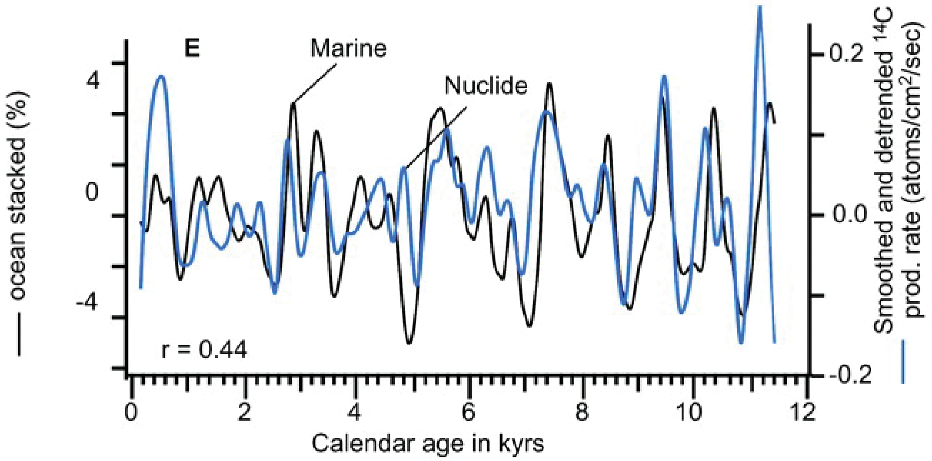

FIGURE 5-6 Relationship between the concentration of ice-rafted debris (as inferred from iron [Fe] concentration) and the flux of cosmogenic ^{14}C. SOURCE: Bond et al. (2001). Reprinted with permission from AAAS; copyright 2001.

Jones et al. (2006) showed increased (i.e., more positive) δ^{18}O values corresponding to the Little Ice Age along with decreased (i.e., more negative) δ^{18}O values before about 1400 (Figure 5-7). However, the primary control on this and similar lake records was not temperature *per se* but the intensity of drought—linked in this case to the intensity of the summer monsoon over South Asia—and precipitation, determined here by winter atmospheric circulation over the North Atlantic. Although the East Mediterranean was relatively dry during the Little Ice Age, low lake levels in East Africa and North America indicate that droughts in these regions were more extreme in medieval times than during the 20th century, possibly linked to changes in solar activity (Hodell et al. 2001, Verschuren et al. 2000).

Biological Remains

Fossil remains from terrestrial sediments also offer indications of past surface temperatures. Nonbiting midge larvae (chironomids) and some species of beetles are highly sensitive to temperature, and the hard parts of both organisms are preserved in lake and peat sediments. However, the main application of these records to date has been on timescales longer than the last 2,000 years. In peat bogs, testate-forming amoebae species are sensitive to water table depths, which in turn are generally controlled by both rainfall and temperature. Charman et al. (2006) have used reconstructed water table changes to build up decadal-resolution climate histories for the last 4,000 years in northern Britain. Pollen analysis is a key technique for longer term climatic and vegetation history, but does not provide climatic data of sufficient time precision or reliability to assist directly in temperature reconstruction for the last two

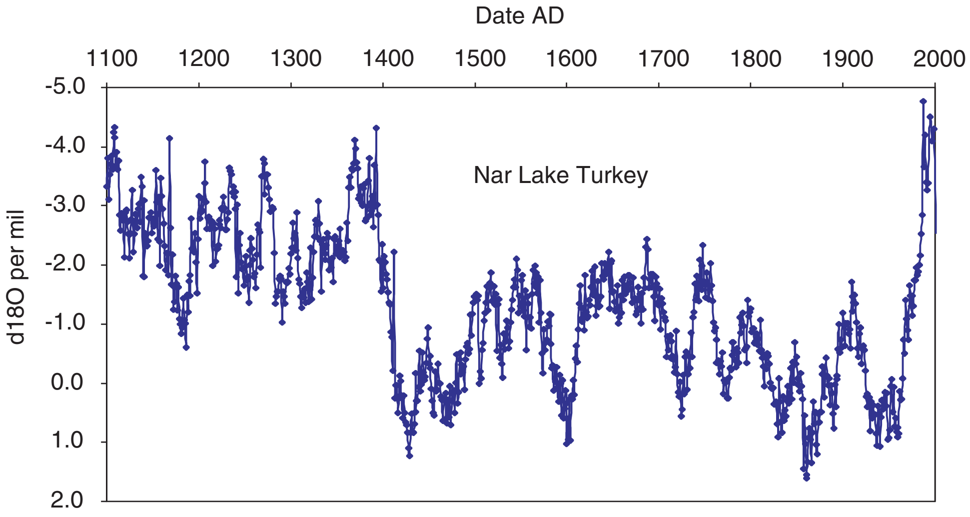

FIGURE 5-7 Annually resolved oxygen isotope record for the last 900 years from varved crater lake carbonates in the East Mediterranean. SOURCE: Modified from Jones et al. (2006). Reprinted with permission; copyright 2006.

millennia, partly because the vegetation that produces pollen lags in its response to climatic forcing.

The calibration approach used for all of these organisms is based on modern training sets rather than matching them against past temperature changes in the instrumental record. A minimum of about 30 sites are analyzed along a climatic gradient for their contemporary species mix (e.g., diatoms in surface muds) and for a range of environmental measurements (pH, salinity, water, air temperature, etc.). These modern training sets are then used to calibrate past species assemblages preserved in sediment cores using regression-based multivariate statistical techniques (Birks 1998). Using this approach, freshwater diatoms from Alpine lakes were found to track lakewater pH, which in turn has followed 20th century temperatures (Koinig et al. 1998).

SPELEOTHEMS

Speleothems are cave deposits such as stalagmites. They record changes in the external climate via a range of different proxies, including luminescence intensity, growth rate, and elemental and isotope chemistry (McDermott et al. 1999, Lauritzen 2003). Speleothem calcium carbonate registers the changing isotopic composition of cave groundwater along with cave temperature. Calcium carbonate deposits grow radially as well as upward in a stalagmite, and records of annual isotopic changes such as $\delta^{18}O$ can be evaluated chronologically by accurate dating techniques (e.g., uranium-thorium ratio) and then converted to a climate signal. Such records represent a com-

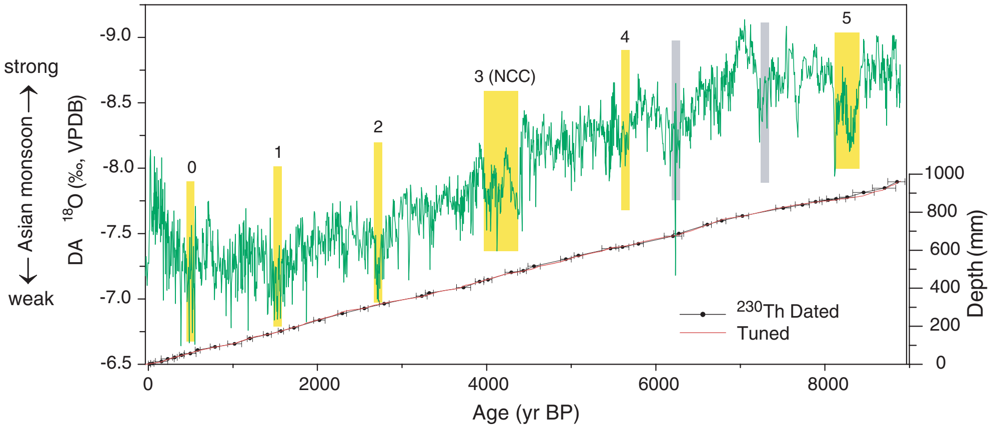

FIGURE 5-8 $\delta^{18}O$ over the Holocene derived from a cave in eastern Asia. The yellow numbered bands correspond to times of ice-rafted debris in the North Atlantic shown in Figure 5-6 (Bond et al. 2001). SOURCE: Wang et al. (2005b). Reprinted with permission from AAAS; copyright 2005.

bined signal of temperature and precipitation—along with source area changes—but each of these signals may be dominant in different settings. In tropical and dryland regions, rainfall amount is usually the main determinant of the $\delta^{18}O$ content of cave carbonates (Bar-Matthews et al. 2003). Thus, oxygen isotope records obtained from caves in southern China (Wang et al. 2005b) (Figure 5-8) and Oman (Fleitmann et al. 2003) suggest that strong climatological changes have occurred in Asian monsoon intensity over the last several thousand years. Episodic submillennial variations within these Holocene records generally match the North Atlantic ice-rafted debris pattern of Bond et al. (2001). The correlation of speleothem records from cave sites associated with the Asian monsoons to a marine record of ice advance and retreat in the North Atlantic provides a suggestion of hemisphere-wide century-scale climate changes resulting in different local manifestations.

In some cool and wet regions, the cave temperature signal may be dominant in controlling the $\delta^{18}O$ and other measurements, and this is especially valuable because cave temperature is stable throughout the year and represents the mean annual temperature of the outside environment. Modern speleothem properties have been used to calibrate cave sequences from northern Scandinavia in terms of Holocene temperature variability (Lauritzen and Lundberg 1999). In addition, some speleothems contain annual bands much like lake varves or tree growth rings, and these have allowed very high resolution measurements of cave isotopic changes during the last 2,000 years. Proctor et al. (2000, 2002) used one such record from northern Scotland to reconstruct annual-to-decadal climatic changes in the North Atlantic during the last three millennia.

SUMMARY

A key advantage of the records described in this chapter is the ability to carry out many different types of laboratory analyses on the same profiles. These multiple proxies—physical, biological, or chemical—can have different and independent bases for climatic calibration; they include the use of modern training sets, sediment trap studies, and historic calibration. Some, but not all, marine, lake, peat, and cave records have annual time resolution. Those that do not have annual dating may nonetheless be able to capture low-frequency climate fluctuations (Moberg et al. 2005b). A major challenge in these cases is to ensure that records are accurately dated and correlated because, if they are not, composite records will tend to smooth out the true temperature variability.

6

Ice Isotopes

- Analyses of stable isotopes in glacial ice provide records of climate changes at high resolution over long time periods. In the low latitudes, this signal is a combination of temperature and hydrologic variables. In the polar ice sheets, the signal is primarily driven by temperature.
- Isotope records from Tibet and the Andes show that the climate of the 20th century was unusual with respect to the preceding 2,000 years. Current understanding does not allow us to separate the temperature part of this signal rigorously, but all evidence indicates Tibet warmed over the last century. Andean climate changes have patterns over space and time that are not yet understood.
- Greenland had a pronounced period of warmth around A.D. 1000, a cool period from 1600 through 1900, and a modest 20th century warming. Some coastal sites in Antarctica show 20th century warming but interior sites do not. No Antarctic sites show a warming during medieval times.

Measurements of oxygen and hydrogen isotopic ratios in ice cores, or ice isotopic ratios, are an important temperature proxy, providing high-resolution continuous records of climatic temperature change at locations with persistent snow accumulation and low temperatures.[1] The isotopic record provides information about climate because atmospheric moisture transported onto cold glaciers is distilled by the precipitation process as the air mass cools. This distillation combines with the temperature dependence of isotopic separations

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[1] In this context, ice isotopic ratio refers to the oxygen and hydrogen stable isotopic composition of water molecules composing the ice itself.

during snow formation to generate an ice isotopic ratio signal. Both of these factors increase in strength as temperature is reduced and, consequently, the correlation of the ice isotopic ratio with temperature is very strong in the cold interiors of the polar ice sheets. Ice isotopic ratio records are geographically limited to locations of significant ice thickness, namely, polar regions and high-altitude mountain ranges elsewhere. It is remarkably fortuitous that the high Andes, the Tibetan and Himalayan ranges, and the great volcanoes of eastern equatorial Africa offer any ice records at all for Earth's low latitudes.

PHYSICAL BASIS FOR DERIVING CLIMATE SIGNALS FROM ICE ISOTOPIC RATIO RECORDS

The temperature dependence of the ice isotopic ratio arises from fundamental physics at the molecular scale combined with geophysical processes at the planetary scale (Dansgaard 1964, Kavanaugh and Cuffey 2003). However, additional influences on ice isotopic ratio can be significant (Dansgaard 1964, Pierrehumbert 1999, Alley and Cuffey 2001, Kavanaugh and Cuffey 2003, Jouzel et al. 1997), and, consequently, ice isotopic ratio measurements must be calibrated against independent temperature information in order to be used as a quantitatively accurate thermometer (Cuffey et al. 1995). Such calibrations have been applied for long-timescale records from the polar ice sheets, but not for low-latitude high-altitude ice cores (from the Andes, Kilimanjaro, and Tibet), where it is more difficult to isolate and quantify the temperature component of the signal. In general, the ice isotopic ratio records from the interior regions of polar ice sheets yield good temperature reconstructions (Alley and Cuffey 2001, Cuffey et al. 1995). The low-latitude ice isotopic ratios yield a climate signal that depends on a variety of hydrologic and thermal influences in the broad geographic region that supplies moisture to the high glaciated mountains (Pierrehumbert 1999, Tian et al. 2003, Vuille et al. 2003a, Hoffmann et al. 2003, Thompson and Davis 2005, Alley and Cuffey 2001, Jouzel et al. 1997). The connection of ice isotopic ratio to temperature becomes stronger at lower temperatures (e.g., Kavanaugh and Cuffey 2003, Jouzel et al. 1997).

All glacial sites in the low latitudes are cold enough that this temperature influence will have some reflection in the ice isotopic ratio (Pierrehumbert 1999, Tian et al. 2003). Ambiguity results from significant residual influences of warmer regions upwind and local processes related to snowfall timing and preservation (Hardy et al. 2003). Precipitation amount is the effect of greatest importance (Dansgaard 1964). Near sea level at low latitudes the isotopic ratios in precipitation are demonstrably not reflective of temperature changes at ground level—the water distillation process primarily happens in the vertical dimension in large storm clouds, resulting in a correlation between precipitation amount and isotopes at ground level, rather than a correlation between temperature and isotopes. The high-altitude low-latitude ice core sites are in a transition zone where both temperature and this precipitation effect have influence (Pierrehumbert 1999).

In Tibet, ice isotopic ratios in the south appear to be dominantly influenced by monsoonal precipitation, whereas in the north, temperature dominates (Yao et al. 1996, Tian et al. 2003). In the equatorial Andes, ice isotopic ratios retain a strong influence of precipitation over the Amazon lowlands and partly correlate with both Pacific sea surface temperatures and Amazonian temperatures (Henderson et al. 1999, Hardy et al. 2003, Vuille et al. 2003a). The local warming observed at the Quelccaya ice cap (Thompson et al. 2000a, Mark and Seltzer 2005) does correlate with the ice isotopic ratio there. In both Tibet and the Andes, there is no clear relationship between ice isotopic ratio and local accumulation on the ice caps. Thus, the ice isotopic ratios in these locations are not heavily influenced by local precipitation, but hydrologic influences retained from the lowland regions upwind may still be very important. Controls on ice isotopic ratio in equatorial Africa are not known.

CALIBRATION AND RESOLUTION

The correlation of the ice isotopic ratio with temperature is very strong in the cold interiors of the polar ice sheets. Calibration is nonetheless necessary because factors like the seasonal timing of precipitation, the warm-weather bias of storms, and the atmospheric mixing of air masses may change with time. Calibration of the ice isotopic ratio thermometer is achieved over a range of timescales (Alley and Cuffey 2001 and references therein) by using weather station and satellite records for annual cycles, by using gas isotopic ratios for decadal-scale rapid climate changes, and by using borehole temperatures for centennial-to-millennial-scale climate changes. Such studies have shown polar ice isotopic ratios to be reliable thermometers. Before calibration, temperature changes inferred from ice isotopic ratio changes are accurate to within a multiple of approximately 2. Temperatures recorded by ice isotopic ratio in the polar ice sheets are representative of a broad region in the ice sheet interior and also include an imprint of temperature at much larger scales.

The time resolution of ice isotopic ratio temperature reconstructions varies from place to place. Many sites from Greenland, the Canadian Arctic, and the tropics have nearly annual resolution, whereas sites from the very dry interior of East Antarctica have only decadal resolution. Diffusional smoothing reduces the resolution from annual to a few years or more in most places, and this reduction of resolution increases backward in time. The time span covered by ice isotopic ratio records is greatest where snowfall rates are small and glacier thicknesses are greatest, and varies from several hundred thousand years in central East Antarctica to 100,000 years in central Greenland to 10,000 years in the high-altitude tropics and coastal Antarctica and Greenland. Most glaciers in the midlatitude mountains cannot provide long records of this sort because the ice mass is too rapidly removed by flow.

RESULTS FROM ICE ISOTOPIC RATIO RECORDS

The four available ice cores from Tibet (Figures 6-1 and 6-2) together show that 20th century climate is anomalous relative to the preceding 1,900 years for this region (Thompson et al. 1989, 1997, 2000a, 2003, 2006, in press).[2] The anomaly is some combination of apparent warm conditions and weak monsoon precipitation. That a warming is part of this signal is clear, given that the anomaly is seen in the northern Tibetan records and that the monsoon-dominated southern records correlate with instrumental trends in the region (Thompson et al. 2000a; the Dasuopu core). A

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[2] Evidence is from Dunde, Guliya, Dasuopu, and Puruogangri cores.

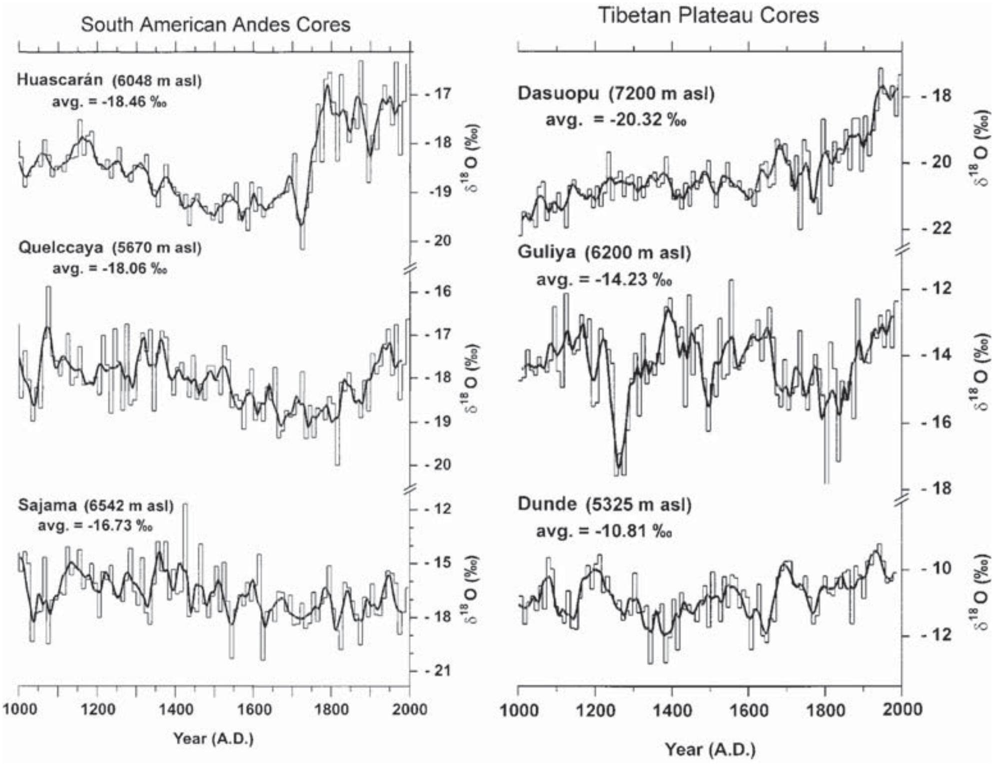

FIGURE 6-1 Isotopic records from high-altitude ice cores from the equatorial Andes (left) and the Tibetan Plateau (right). Higher isotopic values generally indicate warmer conditions, but the records from the Andes may be dominated by hydrologic factors such as precipitation in Amazonia. SOURCE: Thompson et al. (2003). Reprinted with kind permission of Springer Science and Business Media; copyright 2003.

quantitative assessment of temperature change from the north Tibetan cores, using typical isotopic sensitivity, is preliminary, but both suggest warming over the last 150 years of at least 1°C.[3]

The ice isotopic ratio records available from three sites in the high Andes (Figures 6-1 and 6-2) together suggest warm conditions and weak Amazonian precipitation over the last two centuries, relatively cold and wet from 1400 to 1800, and relatively warm and dry before then (Thompson et al. 1986, 1995, 1998, 2000b, 2003, 2006). The current warm/dry period is a 20th century phenomenon at Quelccaya, but clearly began around 1750 at Huascaran (to the north) and is absent from Sajama (to the south). This latitudinal gradient is interesting but not yet understood. Ice isotopic

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[3] This also matches trends in instrumental records on the Tibetan Plateau (Liu and Chen 2000).

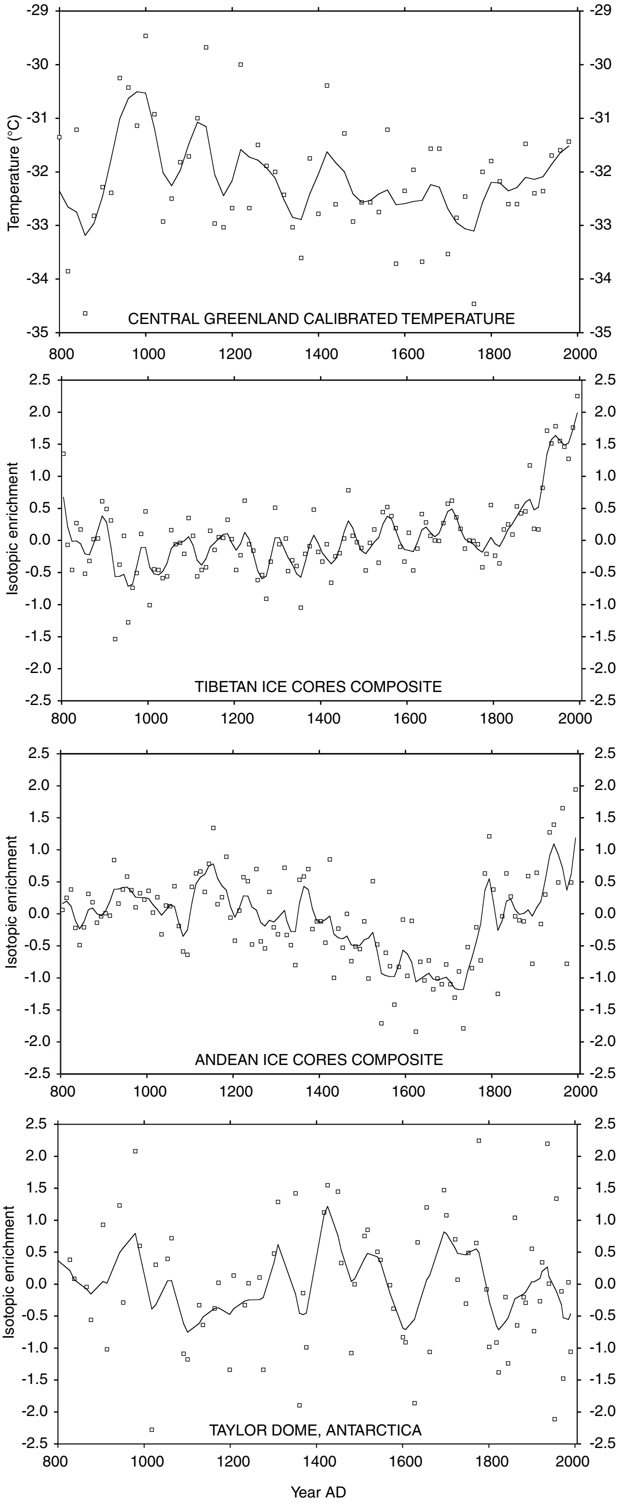

FIGURE 6-2 Two composite isotopic records from low latitudes and two isotopic records from single locations on the polar ice sheets. Top: Record for central Greenland (GISP2 site), converted to temperature by calibration against borehole temperatures. Second from top: Composite record (normalized to mean and standard deviation) for four ice cores from Tibet. Third from top: Composite record (normalized to mean and standard deviation) for three ice cores from the equatorial Andes. Bottom: Normalized record (deuterium) from Taylor Dome, Antarctica. In each plot, data are shown as point measurements and a smoothed version is superimposed for clarity of trends. The central Greenland and Taylor Dome series are smoothed using a 100-year triangular filter, while the composite series uses a 50-year triangular filter. SOURCES: Data from Cuffey and Clow (1997), Thompson et al. (2003, 2006), and Steig et al. (2000).

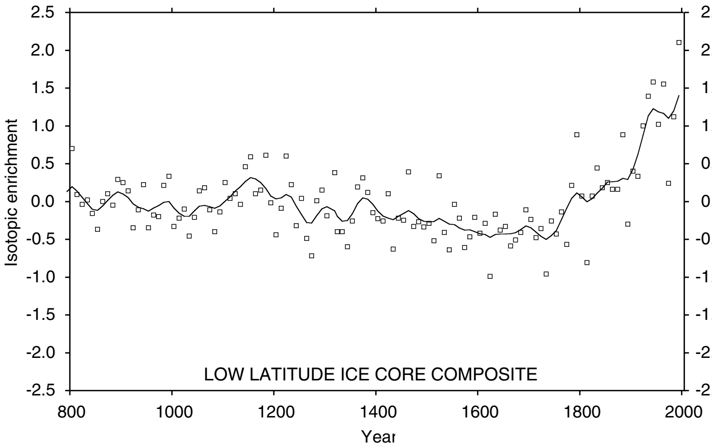

FIGURE 6-3 Composite isotopic record from low latitudes, including four ice cores from Tibet and three from the Andes. The isotope records have been normalized to mean and standard deviation and averaged. The solid line is a smoothed version of the composite record created using a 50-year triangular filter. SOURCE: Data from Thompson et al. (2006). Reprinted with permission; copyright 2006.

ratios from Kilimanjaro reveal no consistent trend over the last two millennia (Thompson et al. 2002).

The combined isotopic signal from all available ice cores in Tibet and the Andes shows that the climate of the 20th century was unusual with respect to the preceding 1900 years (Figure 6-3).

In Greenland (Figure 6-2) and coastal Antarctica, ice isotopic ratio records clearly shows 20th century warming, a Little Ice Age, and earlier warmth. In Greenland, this earlier warmth is centered at about A.D. 1000, whereas in Antarctica it was much earlier. Borehole temperature analyses yield the same pattern (see Chapter 8). In Greenland, the 20th century warmth is not higher than that during medieval times (11th century). In the Canadian Arctic, ice isotopic ratio records from the Agassiz Ice Cap on Ellesmere Island show warming over the last 150 years, which is unprecedented for the last millennium (Fisher et al. 1995). As a group, the ice cores from interior Antarctica (Figure 6-2) show nothing anomalous about the 20th century (Masson et al. 2000).

7

Glacier Length and Mass Balance Records

- Records of glacier length can be used to infer temperature history. These records show global warming of approximately 0.6°C from 1850 to 1990 and cooler conditions for the prior few centuries.
- The majority of glaciers in high mountain ranges outside the polar regions have retreated during the last 150 years, primarily as a consequence of warming. Other evidence from glaciers suggests that the recent warmth is unprecedented on millennial timescales, including melt and retreat of Andean glaciers and disintegration of Antarctic ice shelves.
- Glacier length is also influenced by changes in precipitation, but snowfall on mountain glaciers is currently increasing on average, so the retreat pattern is not due to climatic drying.
- Glacier lengths provide temperature information that is independent of other temperature reconstruction methods, including the instrumental record.
- Glacier length records need to be updated to extend temperature reconstructions from 1990 to the present.

Outside of the very cold polar regions, the majority of glaciers in mountain ranges worldwide retreated substantially during the 20th century (Oerlemans 1994, 2005a; Dyurgerov and Meier 1997a,b, 2000; Sapiano et al. 1998; Kaser 1999; Warren and Aniya 1999; Francou et al. 2000; Arendt et al. 2002; Dyurgerov 2003; Khromova et al. 2003; Thompson et al. in press). The reduction in ice cover is pronounced in nearly every major high glaciated mountain range examined, including the Alaska Range and Alaska's Southeastern Ranges, the Canadian Rockies, the Washington Cascades, the equatorial and Patagonian Andes, the European Alps, the New Zealand Alps, the Tien-Shan, and the Himalayas. In the mid- and high latitudes, this glacier retreat was caused primarily by widespread climatic warming, which increased ice loss by melt (Oerlemans 2001, 2005a; Dyurgerov and Meier 2000; Oerlemans et al. 1998; Zuo and Oerlemans 1997; Oerlemans and Fortuin 1992). In the tropics, glacier retreat was apparently caused by both temperature changes and moisture changes, depending on the time and region (Kaser 1999, Francou et al. 2000, Mölg et al. 2003, Vuille et al. 2003b, Kaser et al. 2004, Mark and Seltzer 2005). Warming is the dominant factor in the tropical Andes (Thompson et al. 2000b, Vuille et al. 2003b, Mark and Seltzer 2005), whereas moisture change has an influence in equatorial Africa (Mölg et al. 2003, Kaser et al. 2004). On average, snowfall rates increased modestly on these glaciers during the latter half of the 20th century (Dyurgerov and Meier 2000), providing strong evidence against drying as a cause of retreat for this time period.

RECONSTRUCTING TEMPERATURE RECORDS FROM GLACIER RECORDS

Records of glacier length changes during the 20th century and earlier have been analyzed to reconstruct past temperature changes (Oerlemans 1994, 2005a; Oerlemans et al. 1998). These analyses are based on glacier physics (Paterson 1994, Van der Veen 1999, Oerlemans 2001) and provide temperature information that is independent of other temperature reconstruction methods. In particular, the temperature reconstruction from glacier retreat is not calibrated against the instrumental record. Instead, it is based on glacier dynamics models that are highly generalized but calibrated against a small number of extensively studied glacier systems (Oerlemans et al. 1998, Oerlemans 2001) for which realistic glacier dynamics and energy balance modeling has been completed. Glacier-length-based temperature reconstructions are further significant because the influences of urban heat islands and land use changes are likely to be small.

Oerlemans (2005a) showed that temperatures increased by about 0.6°C from the late 19th to the mid-20th century and were persistently cool in the three centuries before this (Figure 7-1). Results also show a small cooling from 1950 to 1980, followed by renewed warming until the record ends in 1990. Data on recent and ongoing retreats have not yet been extensively compiled. It is known, however, that mass loss from mountain glaciers increased strongly in the 1990s due primarily to accelerated warming (Dyurgerov 2003, Meier et al. 2003, Dyurgerov and Meier 2005).

During their period of overlap (1850–1990) the glacier length reconstruction and the instrumental record are very similar in magnitude and pattern (Oerlemans 2005a). The glacier length record thus validates the quantitative accuracy of the instrumental composite for this period as a large-scale average. Reconstructed temperatures from the glacier length record are similar for low- and high-altitude glaciers (Oerlemans 2005a). The dominant pattern of cool climate for a few centuries followed by warming beginning in the late 19th century is seen in all geographic regions examined, though significant differences in details exist.

MORE DETAILED BACKGROUND ON GLACIER-LENGTH-BASED RECONSTRUCTIONS

The most recent and comprehensive temperature reconstruction (Oerlemans 2005a) uses glacier length records for a large number of glaciers (Oerlemans et al. 1998, Oerlemans 2001). The information needed for detailed individual modeling for most of these glaciers does not exist, so the analysis instead uses an approximate and

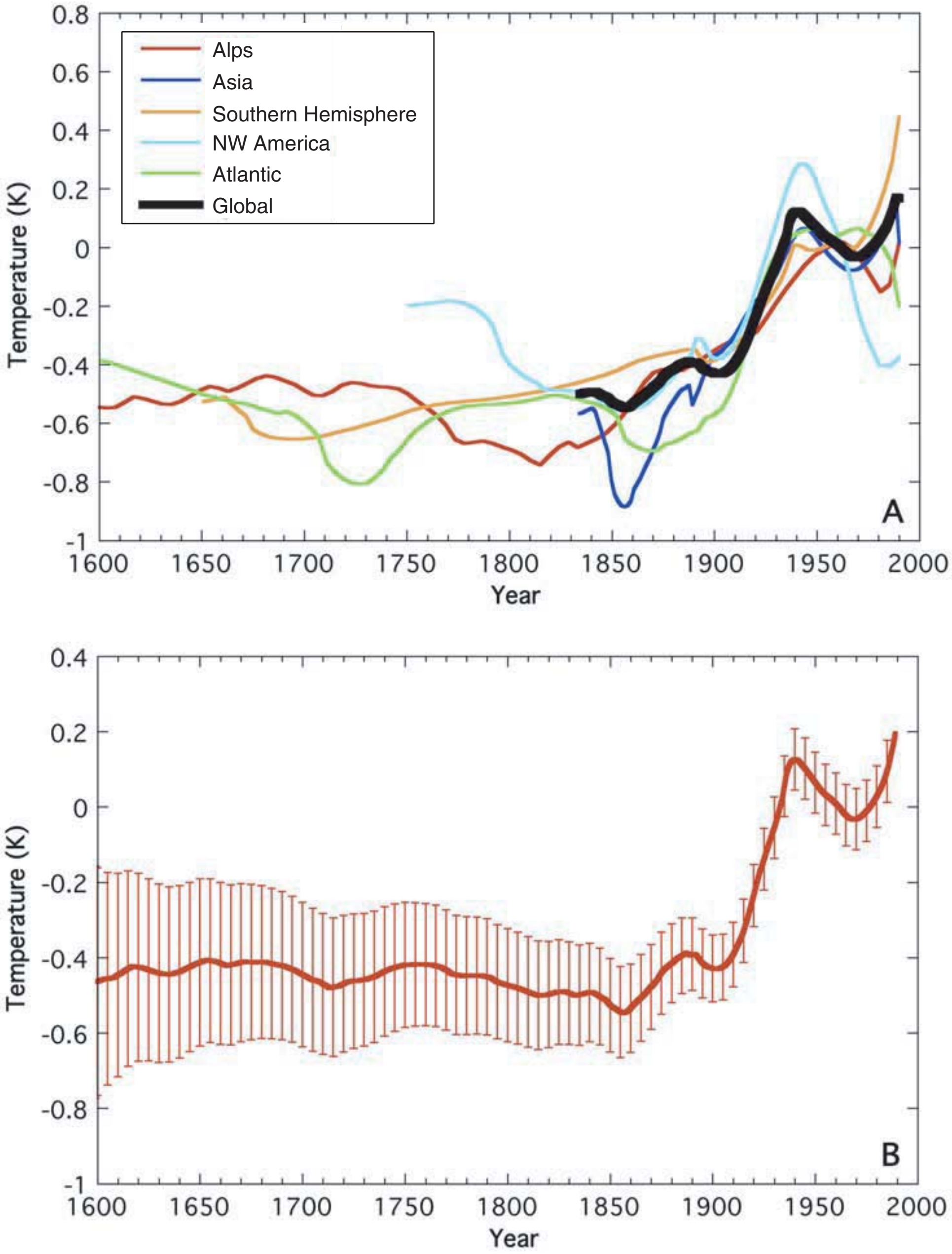

FIGURE 7-1 (A) Glacier-length-based temperature reconstruction for various regions. The black curve shows an estimated global mean value, obtained by giving weights of 0.5 to the Southern Hemisphere, 0.1 to Northwest America, 0.15 to the Atlantic sector, 0.1 to the Alps, and 0.15 to Asia. (B) Best estimate of the global mean temperature, obtained by combining the weighted global mean temperature for 1834–1990 with the average of temperature records at earlier times. The band indicates the estimated standard deviation. SOURCE: Oerlemans (2005a). Reprinted with permission from AAAS; copyright 2005.

generalized approach. Both the sensitivity of glacier length to temperature and the lag time for the glacier response are parameterized in terms of the dominant physical controls or correlates, which are topographic slope, annual precipitation, and glacier length itself. The connection of these parameterizations to the underlying physics is supported in the technical literature, including detailed analyses of specific glaciers (Oerlemans et al. 1998, Oerlemans 2001). However, these parameterizations are only expected to be accurate as an average for a large number of glaciers.

The sensitivity of glacier length to temperature arises from a fundamental aspect of glacial systems (Paterson 1994, Van der Veen 1999, Oerlemans 2001)[1]: A glacier forming at high altitude will advance downward, extending its front into a region of net melt until all ice mass flux supplied from the high-altitude regions is removed by melt in the lower region. Glaciers will always tend toward such a balance between mass inputs to the system and mass outflow, and this balance will be achieved with the glacier straddling the boundary between regions of net melt and net snowfall. Any climate change will affect this delicate balance and cause some adjustment of the glacier system.

The dominant climatic influences are temperature and snowfall rate, though other variables such as cloud cover can be important in some situations. A temperature increase in the overlying atmosphere increases the energy input to a melting glacier surface through increased downward longwave radiation and increased sensible heat transfer, increasing the rate of melt. An increase in temperature also causes more of the precipitation to reach the glacier surface as rain instead of snowfall. Snowfall is the supply of new ice mass that sustains the glacier. A reduction or increase of the snowfall rate will cause the glacier to shrink or grow, respectively.

Considering individual glaciers, snowfall changes can cause glaciers to advance and retreat, and this effect dominates in some situations (e.g., western Norway before the late 1990s). Temperature is a more powerful influence on average, however, because the melt process only acts over a small fraction of the annual cycle and uses a small fraction of the total energy flux, so its capacity to change is large. A typical quantitative estimate for the leverage of temperature versus snowfall on mountain glaciers is that a 1°C temperature increase is equivalent to a 25 percent reduction of snowfall (Oerlemans and Fortuin 1992, Oerlemans et al. 1998, Oerlemans 2001). As a consequence, glaciers on Earth exist in precipitation regimes extending from the very wet temperate and tropical highlands down to the driest polar deserts, but are completely absent from environments spanning a large range of medium to high mean annual temperatures.

In principle, it would be possible for the global population of glaciers to have shrunk over the past century due to a global-scale precipitation reduction. However, there is no evidence of such a global drying (Folland et al. 2001a), which would require an unprecedented spatial coherence. Furthermore, focused studies of individual glaciers demonstrate the dominant role of temperature change in 20th century retreats (Oerlemans et al. 1998, Oerlemans 2001), and mass balance studies for the later 20th century show that, on average, for studied glaciers, snowfall has been increasing

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[1] Here we are discussing only glaciers that terminate on land and are in warm enough environments to lose mass primarily by melt rather than iceberg production or sublimation.

(Dyurgerov and Meier 2000, Dyurgerov 2003). Hence, it is reasonable to assume that precipitation changes induce variability (or noise) in the glacier length record but do not control its global mean pattern. Regional patterns, on the other hand, are in some cases dominated by precipitation or other variables. For example, in the late 20th century, increased snowfall caused glaciers in western Scandinavia to advance (Dyurgerov and Meier 1997a,b, 2000), whereas combinations of precipitation and temperature changes have induced retreat of the glaciers in equatorial Africa (Mölg et al. 2003, Kaser et al. 2004, Hastenrath 2005). Although warming in recent decades is an important factor driving glacier recession on Mt. Kenya and the Ruwenzori summits, the much higher altitude glaciers on Kilimanjaro may be shrinking primarily as a continuing response to precipitation changes earlier in the century. The magnitude and importance of recent warming are still being researched.

Temperature reconstructions based on glacier length and mass balance records are limited in their temporal and spatial resolution. They do not provide a year-to-year view of temperature change, but only averages over several years to decades (depending on the resolution of the length measurements and on the accuracy of assumptions in the physics). They do not provide any information about most of the globe prior to the 19th century. Only the North Atlantic and European Alpine regions have glacier records back to around A.D. 1600, and even in these regions there is little information prior to the 17th century. The time required for data collection, compilation, and reporting has so far prevented the most recent 15 years from being included in the analysis. In North America, many of the glacier records end between the mid-1970s and 1990 (Oerlemans 2005a), so for this region the late 20th century reconstruction is not yet reliable. Geographic limits arise from the obvious fact that glaciers do not exist everywhere, so the low and middle elevations of the low latitudes are entirely absent. There is also a paucity of data for the Southern Hemisphere. Finally, these reconstructions cannot be done for mountain glaciers in Antarctica because it is so cold there that melt is not the dominant mass loss process (it is iceberg production), so the connection to temperature is different.

OTHER INFORMATION AVAILABLE FROM GLACIERS

Though not suitable for reconstructing temperature time series, other glacier indicators—such as melting on ice caps, organic material uncovered when glaciers melt, and disintegration of ice shelves—provide temperature information. An increase of summertime warmth over the last 150 years caused increased melt on Ellesmere Island's major ice cap in the Canadian Arctic. This extent of melt had not occurred in the previous 1,500 years (Fisher et al. 1995).

The recent retreat of glaciers has exposed organic material that would have decomposed if not covered by ice, including a human body (the now famous "Ice Man" of the Alps) and plant material (Thompson et al. in press). Three of these finds have been dated (from the Alps, from Washington State, and from Peru) and all have ages greater than 5,000 years before present. This suggests rather strongly that the current deglaciation is unprecedented in the last few millennia at these widespread sites. Nonetheless, it is known from dating of organic material transported to the fronts of glaciers in the Alps that glacier recessions more extensive than the present one have occurred at some sites in Europe (Hormes et al. 2001), with dates ranging from A.D. 800 to

8000 B.C. Such recession has thus occurred in the past due to natural variability, but has been rare in the most recent few millennia.

In the Andes, at the same glacier where the dated plant material was exposed (Quelccaya), melting in the 1980s was strong enough to destroy the geochemical signature of annual layers in the ice beneath (Alley 2006; Thompson et al. 2003, in press). An ice core taken from Quelccaya in the late 1970s showed that such melt had not happened in at least the previous millennium. This strongly suggests anomalous warmth in the late 20th century. The Quelccaya ice cap has existed without interruption for more than 1,000 years. If its present rate of shrinkage continues, it will disappear entirely within a few decades.

Over the last few decades, the floating ice shelves along the Antarctic Peninsula have been disintegrating, following a progressively southward pattern (Vaughan and Doake 1996, Cook et al. 2005). This is primarily a result of higher temperatures inducing surface melt (van den Broeke 2005). Analysis of sediment cores from the seafloor (Domack et al. 2005) beneath one of the largest former shelves (the Larsen B, which disintegrated in the late 1990s) indicates that this ice shelf had persisted throughout the previous 10,000 years, providing further evidence that recent decades have been anomalously warm.

8

Boreholes

- Measurements of temperature beneath the ground surface show widespread warming during the most recent century and cooler conditions for the four prior centuries.
- The magnitude of warming from 1850 to 1990 is estimated to have been approximately 0.7°C ±0.2°C, consistent with the instrumental record.
- Temperatures inferred from borehole data are not calibrated against the instrumental temperature record, thereby providing an independent measurement of past temperature.
- For the period 1600–1900, borehole-based temperature reconstructions have century-scale resolution and thus provide information about long-term temperature trends, but not about decadal or annual variations.

When the temperature at the ground surface changes, the temperature of the underlying substrate (soil, rock, or ice) will also change in response, as heat diffuses and advects vertically. For example, a sustained increase of ground surface temperature will cause a wave of warming to propagate downward. The vertical distribution of temperature below the surface thus contains information about past temperatures at the surface (Lachenbruch and Marshall 1986, Paterson 1994). Temperature-depth profiles of this sort are measured in boreholes, and analyses of these data can be used to generate reconstructions of near-surface air temperature (Lachenbruch and Marshall 1986, Huang et al. 2000, Pollack and Huang 2000, Harris and Chapman 2001, Pollack and Smerdon 2004, Majorowicz et al. 2006), provided that the ground surface temperature and the climatic temperature at the borehole site are closely connected.

BOREHOLES IN ROCK AND PERMAFROST

Analyses of a large number of continental boreholes have yielded temperature reconstructions for the last 500 years (Lachenbruch and Marshall 1986, Pollack and Huang 2000, Harris and Chapman 2001, Majorowicz et al. 2006). These reconstructions have particular value because they do not have to be calibrated against the instrumental record and because temperature itself is being measured, not a proxy for temperature. Important quantitative uncertainties exist, but general trends in these reconstructions are likely robust.

Borehole-based temperature reconstructions averaged for broad regions (including eastern North America, western North America, Europe, Australia, and South Africa) show warming from the 19th century to the present and persistently cool conditions for the preceding few centuries (Gosnold et al. 1997, Pollack and Huang 2000 and references therein, Huang et al. 2000, Harris and Chapman 2001, Pollack and Smerdon 2004, Majorowicz et al. 2006). Temperature changes for earlier times are not resolvable. Estimates of the magnitude of recent warming as a global (continental) average, or an average over the middle latitudes, are approximately 0.7–0.9°C, from the mid-19th century to the late 20th century (Huang et al. 2000, Pollack and Huang 2000, Harris and Chapman 2001), which is similar to the temperature increase estimated from the instrumental record discussed in Chapter 2 (Figures 8-1 and 8-2). Some

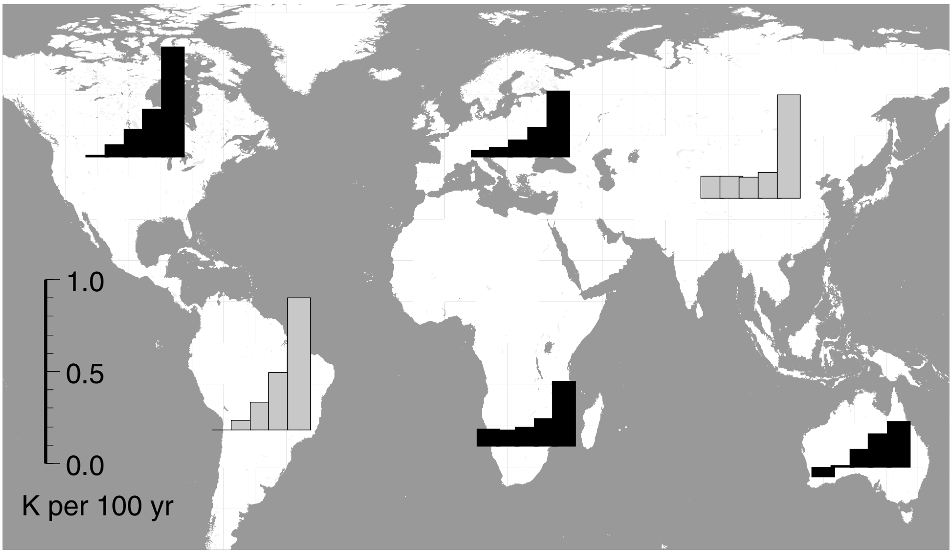

FIGURE 8-1 Summary of borehole-based reconstructions of continental century-long ground surface temperature trends. In each bar plot, the five columns from left to right represent, respectively, the magnitude of temperature increase in the 16th, 17th, 18th, 19th, and 20th centuries. Magnitude of the temperature change is shown as the height of the column. The reconstructions for South America and Asia are lightly shaded to indicate the larger uncertainties in these two continents because of the low spatial density of observations. SOURCE: Huang et al. (2000). Reprinted by permission from Macmillan Publishers Ltd.; copyright 2000.

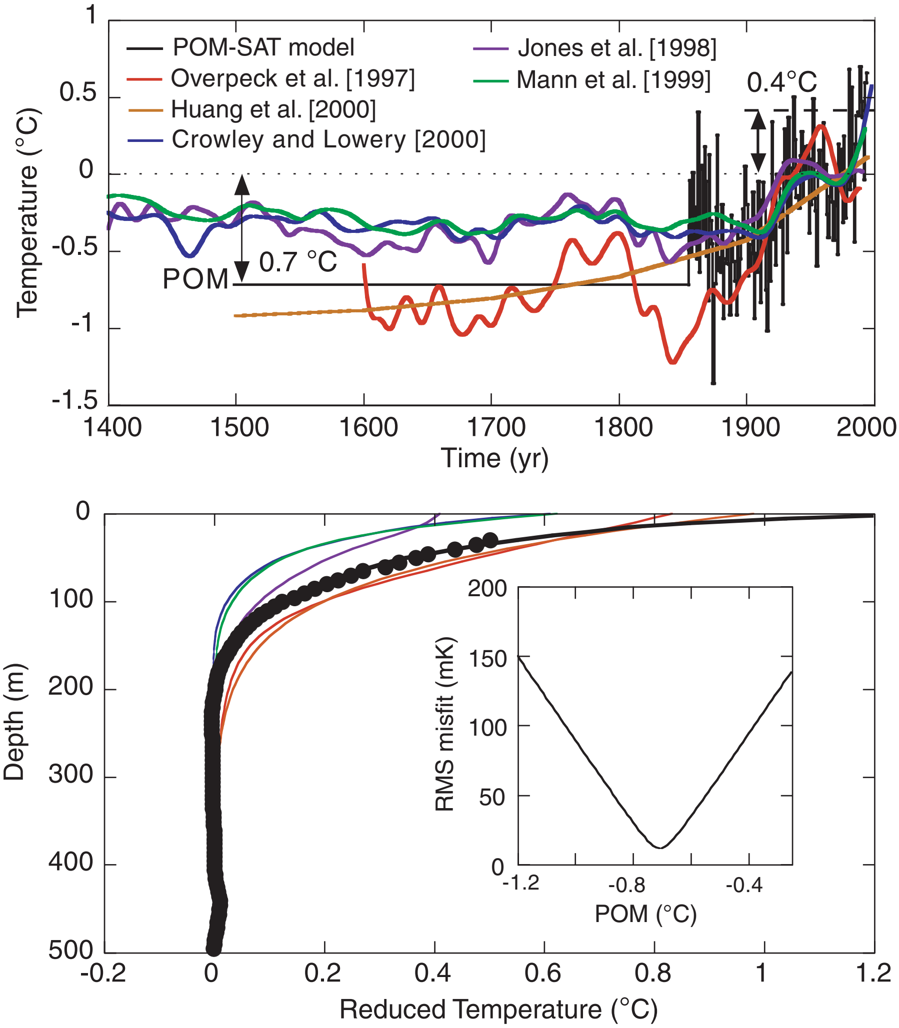

FIGURE 8-2 Here, six climate reconstructions have been used to predict ground subsurface temperature. For each curve in the upper panel, the temperature reconstruction is used as the surface temperature for a thermal model to predict the temperature at depth. The top panel shows the six reconstructions, with zero defined as the 1961–1990 mean. The reconstruction shown in black (labeled POM-SAT) uses the borehole temperatures to constrain the Pre-Observational Mean (POM) and uses the instrumental temperature record from 1856 onward. The measured subsurface temperature pattern (bottom panel, black circles) is explained almost perfectly by the instrumental record and preceding cool centuries (black curve in the top panel). SOURCE: Harris and Chapman (2001). Reproduced by permission of American Geophysical Union; copyright 2001.

borehole-based reconstructions also indicate an earlier persistent smaller warming of roughly 0.3°C from 1500 to 1850 (Pollack and Huang 2000, Huang et al. 2000) (Figure 8-1). Regional estimates for the warming of the last 150 years range from 2–4°C for northern Alaska (Lachenbruch and Marshall 1986, Pollack and Huang 2000) to 0.5°C for Australia (Pollack and Huang 2000). Estimates for the western and eastern sectors of North America are rather different, 0.4–0.6°C and 1.0–1.3°C, respectively (Pollack and Huang 2000).

LIMITS ON BOREHOLE-BASED RECONSTRUCTIONS

The time resolution and length of borehole-based surface temperature reconstructions are severely limited by the physics of the heat transfer process (Clow 1992). A surface temperature signal is irrecoverably smeared as it is transferred to depth. The time resolution of the reconstruction thus decreases backward in time. For rock and permafrost boreholes, this resolution is a few decades at the start of the 20th century and a few centuries at 1500. Borehole temperatures thus only reveal long-term temperature averages and trends prior to the period of instrumental records; they tell us nothing about decadal variations or specific years, except for the most recent ones. For rock and permafrost boreholes, the thermal smearing is strong enough to prevent recovery of clear temperature signals prior to about 1500. The spatial distribution of borehole temperature records is also strongly weighted toward North America, Europe, South Africa, East Asia, and Australia (Pollack and Smerdon 2004), with almost no information from South America and North or Central Africa and spotty coverage in Asia. Furthermore, the usable boreholes are mostly a legacy of mining exploration, so the spatial coverage has not been chosen to optimize climate reconstruction.

Important quantitative uncertainties in borehole-based reconstructions could arise from two separate sources. First, borehole temperatures respond to the ground surface temperature and not the temperature in the overlying air (Gosnold et al. 1997, Smerdon et al. 2004, Pollack et al. 2005). It is possible that these two temperatures will vary differently over time, for example, due to changes in snow cover and soil moisture. Thus, a key question is whether long-term trends in air and ground temperature are similar. Although there are clear exceptions (Gosnold et al. 1997), the majority of evidence indicates that this similarity is generally strong: As a large-scale geographic average, measured ground temperatures match those predicted directly from air temperature changes (Harris and Chapman 2001), and air versus ground temperature trends are similar at some specific sites (Baker and Ruschy 1993, Majorowicz and Safanda 2005, Majorowicz et al. 2006).

The second important potential source of error in rock borehole-based temperature reconstructions is the downward percolation of groundwater, which can reduce the temperature at depth and be misinterpreted as a warming of the surface over time (Chisholm and Chapman 1992, Harris and Chapman 1995, Ferguson and Woodbury 2005, Majorowicz et al. 2006). This may introduce a "warming" bias to reconstructions based on continental boreholes, the magnitude of which has not been addressed systematically. However, the similarity between measured ground temperatures and ground temperatures calculated using air temperatures (Harris and Chapman 2001) suggests that the average bias must be small over the middle latitudes. In general, groundwater bias can only be a problem in humid climates and in rock that readily conducts groundwater (including all highly fractured rock and many sandstones and basalts). The groundwater bias cannot be responsible for the strong reconstructed warming in permafrost regions of northern Alaska (Lachenbruch and Marshall 1986) and in the semiarid U.S. and Canadian plains (Gosnold et al. 1997), although it may be partly responsible for the stronger reconstructed warming in eastern versus western North America (Pollack and Huang 2000). A comparison of borehole-based and instrumental 20th century warming trends for specific regions (Pollack and Smerdon 2004) shows no consistent offset related to precipitation: borehole-inferred warming exceeds instrumental warming in the wet regions of North America but is less than instrumental warming in the wet regions of Europe and Southeast Asia. This is further evidence that the groundwater bias is quantitatively small in borehole-based temperature reconstructions on larger scales. The borehole temperature database has been screened to eliminate other sorts of groundwater influences that are more readily apparent (Huang and Pollack 1998).

A separate issue from the uncertainty of reconstructions is that air temperature itself can change for many local reasons, including deforestation and urban expansion (Skinner and Majorowicz 1999, Majorowicz et al. 2006), as discussed in Chapter 2. Borehole temperatures do record such changes, which are real changes of local climate. The borehole temperature database has been screened to eliminate sites with urban influence. Effects of rural land use change are not eliminated and represent part of the human influence on climate in rural regions.

BOREHOLES IN GLACIAL ICE

A small number of boreholes in the ice sheets have also been analyzed in conjunction with ice core studies (Cuffey et al. 1994, 1995; Cuffey and Clow 1997; Dahl-Jensen et al. 1998, 1999). Ice sheet boreholes permit longer timescale temperature reconstructions because of the purity of ice, the great depth of the boreholes, and the opportunity for combination with isotopic information from the ice core itself. These analyses can only be conducted in dry cold ice, and so are limited to the polar ice sheets and some high-altitude sites. As with the continental boreholes, the time resolution of reconstructions is strongly limited by the heat flow process; ice boreholes can only be used to reconstruct long-term averaged temperatures. Ice borehole reconstructions have used several different methods, yielding similar results (Cuffey et al. 1995, Dahl-Jensen et al. 1998, Clow and Waddington 1999). The main assumption of these analyses is that the physical process of heat transfer in the ice is well understood.

As with continental boreholes, the ice boreholes give a temperature history that is the local surface temperature. For central Greenland (Cuffey et al. 1995, Cuffey and Clow 1997, Dahl-Jensen et al. 1998), results show a warming over the last 150 years of approximately 1°C ± 0.2°C preceded by a few centuries of cool conditions. Preceding this was a warm period centered around A.D. 1000, which was warmer than the late 20th century by approximately 1°C. An analysis for south-central Greenland (Dahl-Jensen et al. 1998) shows the same pattern of warming and cooling but with larger magnitude changes. Uncertainties on these earlier numbers are a few tenths of a degree Celsius for averages over a few centuries.

A borehole from Law Dome (Dahl-Jensen et al. 1999), in coastal East Antarctica, reveals a warming of approximately 0.7°C from the middle 19th century to present (uncertainty of approximately 0.2°C). This was preceded by a period of comparable warmth centered on 1500–1600, a 1°C cooler period centered on 1300, and consistently warmer conditions prior to this (with temperature at A.D. 1 being approximately 1°C warmer than the late 20th century). There was no apparent warming during medieval times at this site. Uncertainties on these results for earlier time periods are on the order of a few tenths of a degree Celsius for averages over a few centuries.

9

Statistical Background

- The standard proxy reconstructions based on linear regression are generally reasonable statistical methods for estimating past temperatures but may be associated with substantial uncertainty.
- There is a need for more rigorous statistical error characterization for proxy reconstructions of temperature that includes accounting for temporal correlation and the choice of principal components.
- The variability of proxy reconstructed temperatures will be less than the variability of the actual temperatures and may not reproduce the actual temperature pattern at particular timescales.
- Examining the prediction of the reconstruction in a validation period is important, but the length of this period sets limits on a statistical appraisal of the uncertainty in the reconstruction. Most critically, the relatively short instrumental temperature record provides very few degrees of freedom[1] for verifying the low-frequency content of a reconstruction.
- The differences among a collection of proxy reconstructions that have not been deliberately created as a representative statistical sample may not reveal the full uncertainty in any one of them.

The process of reconstructing climate records from most proxy data is essentially a statistical one, and all efforts to estimate regional or global climate history from multiple

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[1] "Degrees of freedom" measures the amount of information for estimating a variance; specifically, it is the equivalent number of independent observations.

proxies require statistical analyses. The first step is typically to separate the period of instrumental measurements into two segments: a calibration period and a validation period. The statistical relationship between proxy data (e.g., tree ring width or a multiproxy assemblage) and instrumental measurements of a climate variable (e.g., surface temperature) is determined over the calibration period. Past variations in the climate variable, including those during the validation period, are then reconstructed by using this statistical relationship to predict the variable from the proxy data. Before the proxy reconstruction is accepted as valid, the relationship between the reconstruction and the instrumental measurements during the validation period is examined to test the accuracy of the reconstruction. In a complete statistical analysis, the validation step should also include the calculation of measures of uncertainty, which gives an idea of the confidence one should place in the reconstructed record.

This chapter outlines and discusses some key elements of the statistical process described in the preceding paragraph and alluded to in other chapters of this report. Viewing the statistical analysis from a more fundamental level will help to clarify some of the methodologies used in surface temperature reconstruction and highlight the different types of uncertainties associated with these various methods. Resolving the numerous methodological differences and criticisms of proxy reconstruction is beyond the scope of this chapter, but we will address some key issues related to temporal correlation, the use of principal components, and the interpretation of validation statistics. As a concrete example, the chapter focuses on the Northern Hemisphere annual mean surface temperature reconstructed from annually resolved proxies such as tree rings. However, the basic principles can be generalized to other climate proxies and other meteorological variables. Spatially resolved reconstructions can also be reproduced using these methods, but a discussion of this application is not possible within the length of this chapter.

LINEAR REGRESSION AND PROXY RECONSTRUCTION

The most common form of proxy reconstruction depends on the use of a multivariate linear regression. This methodology requires two key assumptions:

1. *Linearity*: There is a linear statistical relationship between the proxies and the expected value of the climate variable.
2. *Stationarity*: The statistical relationship between the proxies and the climate variable is the same throughout the calibration period, validation period, and reconstruction period. Note that the stationarity of the relationship does not require stationarity of the series themselves, which would imply constant means, constant variances, and time-homogeneous correlations.

These two assumptions have precise mathematical formulations and address the two key questions concerning climate reconstructions: (1) How is the proxy related to the climate variable? (2) Is this relationship consistent across both the instrumental period and at earlier times? In statistical terminology, these assumptions comprise a statistical model because they define a statistical relationship among the data.

An Illustration

Figure 9-1 is a simple illustration using a single proxy to predict temperature. Plotted are 100 pairs of points that may be thought of as a hypothetical annual series of proxy data and corresponding instrumental surface temperature measurements over a 100-year calibration period. The solid black line is the linear fit to these data, or the calibration, which forms the basis for predictions of temperatures during other time periods. Here the prediction of temperature based on a proxy with value A is T_A and the proxy with value B predicts the temperature T_B.

The curved blue lines in Figure 9-1 present the calibration error, or the uncertainty in predictions based on the calibration (technically the 95 percent prediction interval, which has probability 0.95 of covering the unknown temperature), which is a standard component of a regression analysis. In this illustration, the uncertainty associated with temperature predictions based on proxy data is greater at point A than it is at point B. This is because the calibration errors are magnified for predictions based on proxy

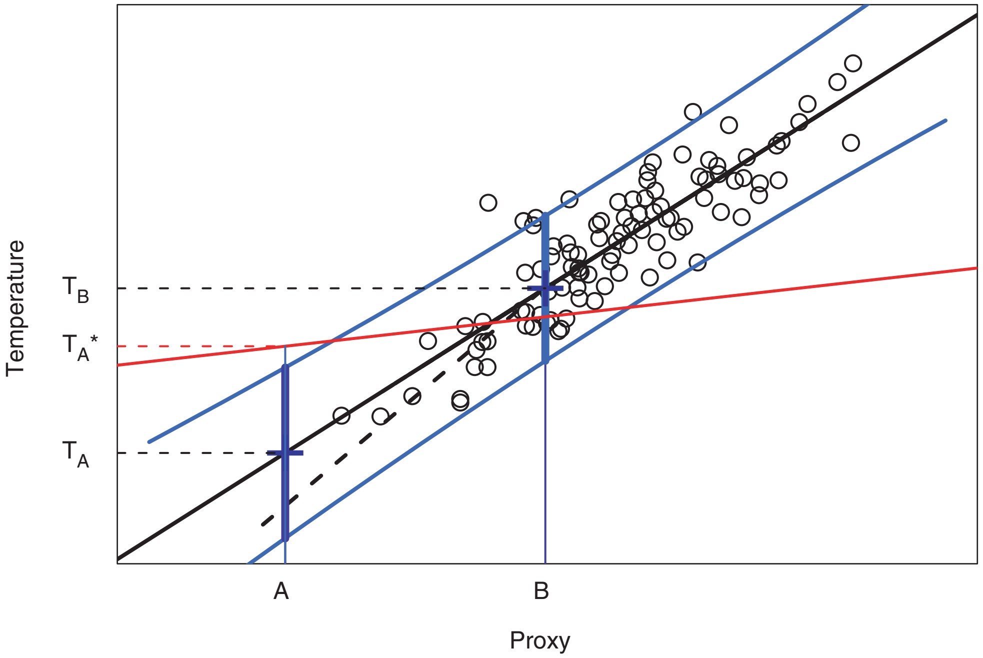

FIGURE 9-1 An illustration of using linear regression to predict temperature from proxy values. Plotted are 100 pairs of points corresponding to a hypothetical dataset of proxy observations and temperature measurements. The solid black line is the least-squares fitted line and the blue lines indicate 95 percent prediction intervals for temperature using this linear relationship. The dashed line and the red line indicate possible departures from a linear relationship between the proxy data and the temperature data. The figure also illustrates predictions made at proxy values A and B and the corresponding prediction intervals (wide blue lines) for the temperature.

values that are outside the range of proxy data used to estimate the linear relationship. In the case of multiple proxies used to predict temperature, it is not possible to use a two-dimensional graph to illustrate the fitted statistical model and the uncertainties. However, as in the single-proxy case, the prediction errors using several proxies will increase as the values deviate from those observed in the calibration period.

Variability in the Regression Predictions

Strictly speaking, assumption 1 posits a straight-line relationship between the average value of the climate variable, given the proxy, and the value of the proxy. This detail has the practical significance of potentially reducing the variability in the reconstructed series, which can also be illustrated using Figure 9-1. For example, note that there is some variability in the instrumental temperature measurements at the proxy value B (i.e., near point B, there are multiple temperature readings, most of which do not fall on the calibration line). However, estimates of past temperatures using proxy data near B will always yield the same temperature, namely T_B, rather than a corresponding scatter of temperatures. This difference is entirely appropriate because T_B is the most likely temperature value for each proxy measurement that yields B. In general, the predictions from regression will have less variability than the actual values, so time series of reconstructed temperatures will not fully reproduce the variability observed in the instrumental record.

One way to assess methods of reconstructing temperatures is to apply them to a synthetic history in which all temperatures are known. Zorita and von Storch (2005) and von Storch et al. (2004) carried out such an exercise using temperature output from the ECHO-G climate model. These authors constructed pseudoproxies by sampling the temperature field at locations used by Mann et al. (1998) and corrupted them with increasing levels of white noise. They then reconstructed the Northern Hemisphere average temperature using both regression methods and the related Mann et al. method and found that in both cases the variance of the reconstruction was attenuated relative to the "true" temperature time series with the attenuation increasing as the noise variance was increased.

This phenomenon, identified by Zorita and von Storch (2005) and others, is not unexpected. Within the calibration period, the fraction of variance of temperature that is explained by the proxies naturally decreases as the noise level of the proxies increases. If the regression equation is then used to reconstruct temperatures for another period during which the proxies are statistically similar to those in the calibration period, it would be expected to capture a similar fraction of the variance.

Some other approaches to reconstruction (e.g., Moberg et al. 2005b) yield a reconstructed series that has variability similar to the observed temperature series. These approaches include alternatives to ordinary regression methods such as inverse regression and total least-squares regression (Hegerl 2006) that are not subject to attenuation. Such methods may avoid the misleading impression that a graph of an attenuated temperature signal might give, but they do so at a price: Direct regression gives the most precise reconstruction, in the sense of mean squared error, so these other methods give up accuracy. Referring back to the example in Figure 9-1, using the straight-line relationship is the best prediction to make from these data, and any inflation of the variability will degrade the accuracy of the reconstruction.

Departures from the Assumptions

The dashed line in Figure 9-1 represents a hypothetical departure from the strict linear relationship between the proxy data and temperature. This illustrates a violation of the linearity assumption because, for lower values of the proxy, the relationship is not the same as given by the (straight) least-squares best-fit line. If the dashed line describes a more accurate representation of the relationship between the proxy values and temperature measurements at lower proxy values, then using the dashed line will result in different reconstructed temperature series.

The linear relationship among the temperature and proxy variables can also be influenced by whether the variables are detrended. If a temperature and a proxy time series share a common trend but are uncorrelated once the trends are removed, the regression analysis can give markedly different results. The regression performed without first removing a trend could exhibit a strong relationship, while the detrended regression could be weak. Whether to include a trend or not should be based on scientific understanding of the similarities or differences of the relationship over longer and shorter timescales.

A departure from the stationarity assumption is illustrated by the red line in Figure 9-1. Suppose that in a period other than the calibration period, the proxy and the temperature are related on average by the red line, that is, a different linear relationship from the one in the calibration period. For an accurate reconstruction, one would want to use this red line and the estimate for a temperature at the proxy value A is indicated by T_A^* in the figure.

Both the linearity and stationarity assumptions may be checked using the training and validation periods of the instrumental record. If the relationship is not linear over the training period, a variety of objective statistical approaches can be used to describe a more complicated relationship than a linear one. Moreover, one can contrast the effect of using detrended versus raw variables. Stationarity can also be tested for the validation period, although in most cases the use of the proxy relationship will involve extrapolation beyond the range of observed values, such as in the case of point A in the illustration given above. In cases such as this, the extrapolation must also rely on the scientific context for its validity; that is, one must provide a scientific basis for the assumed relationship.

The distinction between the assumptions used to reconstruct temperatures and the additional assumptions required to generate statistical measures of the uncertainty of such reconstructions is critical. For example, the error bounds in Figure 9-1 are based on statistical assumptions on how the temperature departs from an exact linear relationship. These assumptions can also be checked using the training and calibration periods, and often more complicated regression methods can be used to adjust for particular features in the data that violate the assumptions. One example is temporal correlation among data points, which is discussed in the next section.

Inverse Regression and Statistical Calibration

Reconstructing temperature or another climate variable from a proxy such as a tree ring parameter has a formal resemblance to the statistical calibration of a measurement instrument. A statistical calibration exercise consists of a sequence of experiments in which a single factor (e.g., the temperature) is set to precise, known levels, and one or more measurements are made on a response (e.g., the proxy). Subsequently, in a second controlled experiment under identical conditions, the response is measured for an unknown level of the factor, and the regression relationship is used to infer the value of the factor. This approach is known as inverse regression (Eisenhart 1939) because the roles of the response and factor are reversed from the more direct prediction illustrated in Figure 9-1. Attaching an uncertainty to the result is nontrivial, but conservative approximations are known (Fieller 1954). There remains some debate in the statistical literature concerning the circumstances when inverse or direct methods are better (Osborne 1991).

The temperature reconstruction problem does not fit into this framework because both temperature and proxy values are not controlled. A more useful model is to consider the proxy and the target climate variable as a bivariate observation on a complex system. Now the statistical solution to the reconstruction problem is to state the conditional distribution of the unobserved part of the pair, temperature, given the value of the observed part, the proxy. This is also termed the random calibration problem by Brown (1982). If the bivariate distribution is Gaussian, then the conditional distribution is itself Gaussian, with a mean that is a linear function of the proxy and a constant variance. From a sample of completely observed pairs, the regression methods outlined above give unbiased estimates of the intercept and slope in that linear function. In reality, the bivariate distribution is not expected to follow the Gaussian exactly. In this case the linear function is only an approximation; however, the adequacy of these approximations can be checked based on the data using standard regression diagnostic methods. With multiple proxies, the dimension of the joint distribution increases, but the calculation of the conditional distribution is a direct generalization from the bivariate (single-proxy) case.

Regression with Correlated Data

In most cases, calibrations are based on proxy and temperature data that are sequential in time. However, geophysical data are often autocorrelated, which has the effect of reducing the effective sample size of the data. This reduction in sample size decreases the accuracy of the estimated regression coefficients and causes the standard error to be underestimated during the calibration period. To avoid these problems and form a credible measure of uncertainty, the autocorrelation of the input data must be taken into account.

The statistical strategy for accommodating correlation in the data used in a regression model is two-pronged. The first part is to specify a model for the correlation structure and to use modified regression estimates (generalized least squares) that achieve better precision. The correctness of the specification can be tested using, for example, the Durbin-Watson statistic (Durbin and Watson 1950, 1951, 1971). The second part of the strategy is to recognize that correlation structure is usually too complex to be captured with parsimonious models. This structure may be revealed by a significant Durbin-Watson statistic or some other test, or it may be suspected on other grounds. In this case, the model-based standard errors of estimated coefficients may be replaced by more robust versions, discussed for instance by Hinkley and Wang (1991). For time series data, Andrews (1991) describes estimates of standard errors that are consistent in the presence of autocorrelated errors with changing variances. For time series data, the correlations are usually modeled as *stationary*; parsimonious models for stationary time series, such as ARMA, were popularized by Box and Jenkins (Box et al. 1994). Note that this approach does *not* require either the temperature or the proxy to be stationary, only the errors in the regression equation.

Reconstruction Uncertainty and Temporal Correlation

An indication of the uncertainty of a reconstruction is an important part of any display of the reconstruction itself. Usually this is in the form:

$$\text{Reconstruction} \pm 2 \times \text{standard error},$$

and the standard error is given by conventional regression calculations.

The prediction mean squared error is the square of the standard error and is the sum of two terms. One is the variance of the errors in the regression equation, which is estimated from calibration data, and may be modified in the light of differences between the calibration errors and the validation errors. This term is the same for all reconstruction dates. The other term is the variance of the estimation error in the regression parameters, and this varies in magnitude depending on the values of the proxies and also the degree of autocorrelation in the errors. This second term is usually small for a date when the proxies are well within the range represented by the calibration data, but may become large when the equation is used to extrapolate to proxy values outside that range.

Smoothed Reconstructions

Reconstructions are often shown in a smoothed form, both because the main features are brought out by smoothing and because the reconstruction of low-frequency features may be more precise than short-term behavior. The two parts of the prediction variance are both affected by smoothing but in different ways. The effect on the first depends on the correlation structure of the errors, which may require some further modeling, but is always a reduction in size. The second term depends on the smoothed values of the proxies and may become either larger or smaller but typically becomes a more important part of the resulting standard error, especially when extrapolating.

PRINCIPAL COMPONENT REGRESSION

The basic idea behind principal component regression is to replace the predictors (i.e., individual proxies) with a smaller number of objectively determined variables that are linear combinations of the original proxies. The new variables are designed to contain as much information as possible from the original proxies. As the number of principal components becomes large, the principal component regression becomes close to the regression on the full set of proxies. However, in practice the number of principal components is usually kept small, to avoid overfitting and the consequent loss of prediction skill. No known statistical theory suggests that limiting the number of principal components used in regression leads to good predictions, although this practice has been found to work well in many applications. Fritts et al. (1971) introduced the idea to dendroclimatology, and it was discussed by Briffa and Cook (1990).

Jolliffe (2002) describes many issues in the use of principal component analysis, including principal component regression, as it is used in many areas of science.

The principal components contain maximum information in the sense that the full set of proxies can be reproduced as closely as possible, given only the values of the new variables (Johnson and Wichern 2002, Suppl. 8A). In general, one should judge the set of principal components taken together as a group because they are used together to form a reconstruction. Comparing just single principal components between two different approaches may be misleading. For example, each of the two *groups* of principal components may give equally valid approximations to the full set of proxies. This equivalence can occur without being able to match on a one-to-one basis the principal components in one group with those in a second group.

Spurious Principal Components

McIntyre and McKitrick (2003) demonstrated that under some conditions the leading principal component can exhibit a spurious trendlike appearance, which could then lead to a spurious trend in the proxy-based reconstruction. To see how this can happen, suppose that instead of proxy climate data, one simply used a random sample of autocorrelated time series that did not contain a coherent signal. If these simulated proxies are standardized as anomalies with respect to a calibration period and used to form principal components, the first component tends to exhibit a trend, even though the proxies themselves have no common trend. Essentially, the first component tends to capture those proxies that, by chance, show different values between the calibration period and the remainder of the data. If this component is used by itself or in conjunction with a small number of unaffected components to perform reconstruction, the resulting temperature reconstruction may exhibit a trend, even though the individual proxies do not. Figure 9-2 shows the result of a simple simulation along the lines of McIntyre and McKitrick (2003) (the computer code appears in Appendix B). In each simulation, 50 autocorrelated time series of length 600 were constructed, with no coherent signal. Each was centered at the mean of its last 100 values, and the first principal component was found. The figure shows the first components from five such simulations overlaid. Principal components have an arbitrary sign, which was chosen here to make the last 100 values higher on average than the remainder.

Principal components of sample data reflect the shape of the corresponding eigenvectors of the population covariance matrix. The first eigenvector of the covariance matrix for this simulation is the red curve in Figure 9-2, showing the precise form of the spurious trend that the principal component would introduce into the fitted model in this case.

This exercise demonstrates that the baseline with respect to which anomalies are calculated can influence principal components in unanticipated ways. Huybers (2005), commenting on McIntyre and McKitrick (2005a), points out that normalization also affects results, a point that is reinforced by McIntyre and McKitrick (2005b) in their response to Huybers. Principal component calculations are often carried out on a correlation matrix obtained by normalizing each variable by its sample standard deviation. Variables in different physical units clearly require some kind of normalization to bring them to a common scale, but even variables that are physically equivalent or

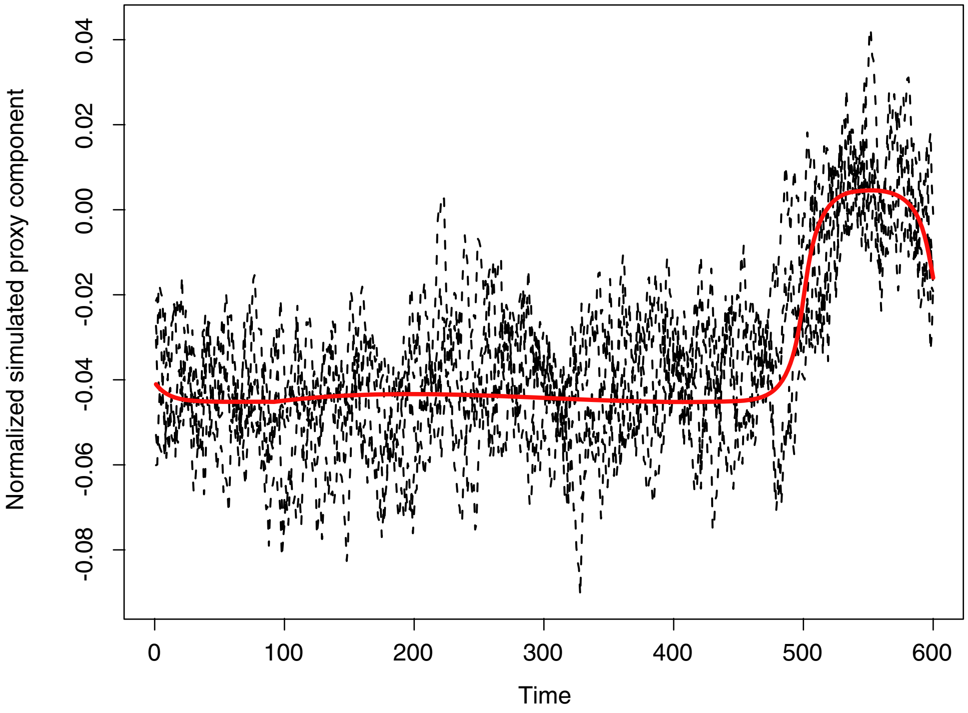

FIGURE 9-2 Five simulated principal components and the corresponding population eigenvector. See text for details.

normalized to a common scale may have widely different variances. Huybers comments on tree ring densities, which have much lower variances than widths, even after conversion to dimensionless "standardized" form. In this case, an argument can be made for using the variables without further normalization. However, the higher-variance variables tend to make correspondingly higher contributions to the principal components, so the decision whether to equalize variances or not should be based on the scientific considerations of the climate information represented in each of the proxies.

Each principal component is a weighted combination of the individual proxy series. When those series consist of a common signal plus incoherent noise, the best estimate of the common signal has weights proportional to the sensitivity of the proxy divided by its noise variance. These weights in general are not the same as the weights in the principal component, as calculated from either raw or standardized proxies, either of which is therefore suboptimal. In any case, the principal components should be constructed to achieve a low-dimensional representation of the entire set of proxy variables that incorporates most of the climate information contained therein.

VALIDATION AND THE PREDICTION SKILL OF THE PROXY RECONSTRUCTION

The role of a validation period is to provide an independent assessment of the accuracy of the reconstruction method. As discussed above, it is possible to overfit the statistical model during the calibration period, which has the effect of underestimating the prediction error. Reserving a subset of the data for validation is a natural way to offset this problem. If the validation period is independent of the calibration period, any skill measures used to assess the quality of the reconstruction will not be biased by the potential overfit during the calibration period. An inherent difficulty in validating a climate reconstruction is that the validation period is limited to the historical instrumental record, so it is not possible to obtain a direct estimate of the reconstruction skill at earlier periods. Because of the autocorrelation in most geophysical time series, a validation period adjacent to the calibration period cannot be truly independent; if the autocorrelation is short term, the lack of independence does not seriously bias the validation results.

Measures of Prediction Skill

Some common measures used to assess the accuracy of statistical predictions are the mean squared error (MSE), reduction of error (RE), coefficient of efficiency (CE), and the squared correlation (r^2). The mathematical definitions of these quantities are given in Box 9.1. MSE is a measure of how close a set of predictions are to the actual values and is widely used throughout the geosciences and statistics. It is usually normalized and presented in the form of either the RE statistic (Fritts 1976) or the CE statistic (Cook et al. 1994). The RE statistic compares the MSE of the reconstruction to the MSE of a reconstruction that is constant in time with a value equivalent to the sample mean for the *calibration* data. If the reconstruction has any predictive value, one would expect it to do better than just the sample average over the calibration period; that is, one would expect RE to be greater than zero.

The CE, on the other hand, compares the MSE to the performance of a reconstruction that is constant in time with a value equivalent to the sample mean for the *validation* data. This second constant reconstruction depends on the validation data, which are withheld from the calibration process, and therefore presents a more demanding comparison. In fact, CE will always be less than RE, and the difference increases as the difference between the sample means for the validation and the calibration periods increases.

If the calibration has any predictive value, one would expect it to do better than just the sample average over the validation period and, for this reason, CE is a particularly useful measure. The squared correlation statistic, denoted as r^2, is usually adopted as a measure of association between two variables. Specifically, r^2 measures the strength of a linear relationship between two variables when the linear fit is determined by regression. For example, the correlation between the variables in Figure 9-1 is 0.88, which means that the regression line explains $100 \times 0.88^2 = 77.4$ percent of the variability in the temperature values. However, r^2 measures how well some linear function of the predictions matches the data, not how well the predictions themselves perform. The coefficients in that linear function cannot be calculated without knowing the values being predicted, so it is not in itself a useful indication of merit. A high CE

BOX 9.1
Measures of Reconstruction Accuracy

Let y_t denote a temperature at time t and $\hat{y}_t$ the prediction based on a proxy reconstruction.

Mean squared error (MSE)

$$\mathrm{MSE}(\hat{y}) = \frac{1}{N}\sum\left(y_t - \hat{y}_t\right)^2,$$

where the sum on the right-hand side of the equation is over times of interest (either the calibration or validation period) and N is the number of time points.

Reduction of error statistic (RE)

$$\mathrm{RE} = 1 - \frac{\mathrm{MSE}(\hat{y})}{\mathrm{MSE}(\bar{y}_c)},$$

where $\mathrm{MSE}(\bar{y}_c)$ is the mean squared error of using the sample average temperature *over the calibration period* (a constant, $\bar{y}_c$) to predict temperatures during the period of interest:

$$\mathrm{MSE}(\bar{y}_c) = \frac{1}{N}\sum\left(y_t - \bar{y}_c\right)^2$$

Coefficient of efficiency (CE)

$$\mathrm{CE} = 1 - \frac{\mathrm{MSE}(\hat{y})}{\mathrm{MSE}(\bar{y}_i)},$$

where $\mathrm{MSE}(\bar{y}_i)$ is the mean squared error of using the sample average *over the period of interest* ($\bar{y}_i$) as a predictor of temperatures during the period of interest:

$$\mathrm{MSE}(\bar{y}_i) = \frac{1}{N}\sum\left(y_t - \bar{y}_i\right)^2$$

Squared correlation (r^2)

$$r^2 = \frac{\left[\sum\left(y_t - \bar{y}_i\right)\left(\hat{y}_t - \bar{\hat{y}}\right)\right]^2}{\sum\left(y_t - \bar{y}_i\right)^2\left(\hat{y}_t - \bar{\hat{y}}\right)^2}$$

If $\hat{y}_t$ are the predictions from a linear regression of y_t on the proxies, and the period of interest is the calibration period, then RE, CE, and r^2 are all equal. Otherwise, CE is less than both RE and r^2.

value, however, will always have a high r^2, and this is another justification for considering the CE.

Illustration of CE and r^2

Figure 9-3 gives some examples of a hypothetical temperature series and several reconstruction series, where the black line is the actual temperatures and the colored lines are various reconstructions. The red line has an r^2 of 1 but a CE of –18.9 and is

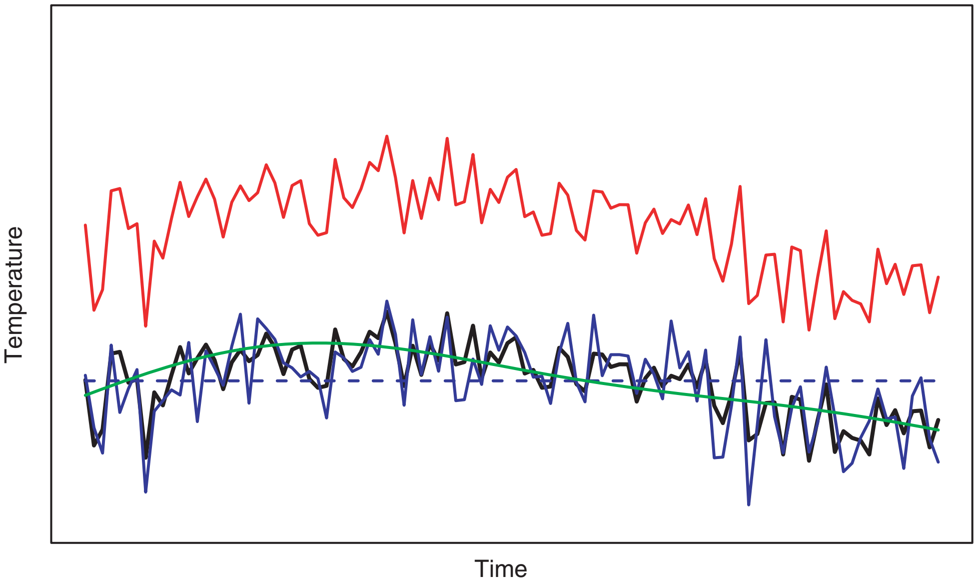

FIGURE 9-3 A hypothetical temperature series (black line) and four possible reconstructions.

an example of a perfectly correlated reconstruction with no skill at prediction. The dashed blue line is level at the mean temperature and has an r^2 and a CE that are both zero. The blue and green reconstructed lines both have a CE of 0.50. For either of these reconstructions to be better than just the mean, they must exhibit some degree of correlation with the temperatures. In this case, r^2 is 0.68 for the blue line and 0.51 for the green line.

Despite a common CE, these two reconstructions match the temperature series in different ways. The blue curve is more highly correlated with the short-term fluctuations, and the green curve tracks the longer term variations of the temperature series. The difference between the blue and green lines illustrates that the CE statistic alone does not contain all the useful information about the reconstruction error.

Distinguishing Between RE and CE and the Validation Period

The combination of a high RE and a low CE or r^2 means that the reconstruction identified the change in mean levels between the calibration and validation periods reasonably well but failed to track the variations within the validation period. One way that this discrepancy can occur is for the proxies and the temperatures to be related by a common trend in the calibration period. When the trend is large this can result in a high RE. If the validation period does not have as strong a trend and the proxies are not skillful at predicting shorter timescale fluctuations in temperature, then the CE can be substantially lower. For example, the reconstructions may only do as well as the mean level in the validation period, in which case CE will be close to zero. An ideal validation procedure would measure skill at different timescales, or in different frequency bands using wavelet or power spectrum calculations. Unfortunately, the paucity of validation data places severe limits on their sensitivity. For instance, a focus on variations of decadal or longer timescales with the 45 years of validation data used by Mann et al. (1998) would give statistics with just (2 × 45 ÷ 10) = 9 degrees of freedom, too few to adequately quantify skill. This discussion also motivates the choice of a validation period that exhibits the same kind of variability as the calibration period. Simply using the earliest part of the instrumental series may not be the best choice for validation.

Determining Uncertainty and Selecting Among Statistical Methods

Besides supplying an unbiased appraisal of the accuracy of the reconstruction, the validation period can also be used to adjust the uncertainty measures for the reconstruction. For example, the MSE calculated for the validation period provides a useful measure of the accuracy of the reconstruction; the square root of MSE can be used as an estimate of the reconstruction standard error. Reconstructions that have poor validation statistics (i.e., low CE) will have correspondingly wide uncertainty bounds, and so can be seen to be unreliable in an objective way. Moreover, a CE statistic close to zero or negative suggests that the reconstruction is no better than the mean, and so its skill for time averages shorter than the validation period will be low. Some recent results reported in Table 1S of Wahl and Ammann (in press) indicate that their reconstruction, which uses the same procedure and full set of proxies used by Mann et al. (1999), gives CE values ranging from 0.103 to –0.215, depending on how far back in time the reconstruction is carried. Although some debate has focused on when a validation statistic, such as CE or RE, is significant, a more meaningful approach may be to concentrate on the implied prediction intervals for a given reconstruction. Even a low CE value may still provide prediction intervals that are useful for drawing particular scientific conclusions.

The work of Bürger and Cubasch (2005) considers different variations on the reconstruction method to arrive at 64 different analyses. Although they do not report CE, examination of Figure 1 in their paper suggests that many of the variant reconstructions will have low CE and that selecting a reconstruction based on its CE value could be a useful way to winnow the choices for the reconstruction. Using CE to judge the merits of a reconstruction is known as cross-validation and is a common statistical technique for selecting among competing models and subsets of data. When the validation period is independent of the calibration period, cross-validation avoids many of the issues of overfitting if models were simply selected on the basis of RE.

QUANTIFYING THE FULL UNCERTAINTY OF A RECONSTRUCTION

The statistical framework based on regression provides a basis for attaching uncertainty estimates to the reconstructions. It should be emphasized, however, that this is only the statistical uncertainty and that other sources of error need to be addressed from a scientific perspective. These sources of error are specific to each proxy and are discussed in detail in Chapters 3–8 of this report. The quantification of statistical uncertainty depends on the stationarity and linearity assumptions cited above, the adjustment for temporal correlation in the proxy calibration, and the sensible use of principal components or other methods for data reduction. On the basis of these assumptions and an approximate Gaussian distribution for the noise in the relationship between temperature and the proxies, one can derive prediction intervals for the reconstructed temperatures using standard techniques (see, e.g., Draper and Smith 1981). This calculation will also provide a theoretical MSE for the validation period, which can be compared to the actual mean squared validation error as a check on the method.

One useful adjustment is to inflate the estimated prediction standard error (but not the reconstruction itself) in the predictions so that they agree with the observed CE or other measures of skill during the validation period. This will account for the additional uncertainty in the predictions that cannot be deduced directly from the statistical model. Another adjustment is to use Monte Carlo simulation techniques to account for uncertainty in the choice of principal components. Often, 10-, 30-, or 50-year running means are applied to temperature reconstructions to estimate long-term temperature averages. A slightly more elaborate computation, but still a standard technique in regression analysis, would be to derive a covariance matrix of the uncertainties in the reconstructions over a sequence of years. This would make it possible to provide a statistically rigorous standard error when proxy-based reconstructions are smoothed.

Interpreting Confidence Intervals

A common way of reporting the uncertainty in a reconstruction is graphing the reconstructed temperature for a given year with the upper and lower limits of a 95 percent confidence interval to quantify the uncertainty. Usually, the reconstructed curve is plotted with the confidence intervals forming a band about the estimate. The fraction of variance that is *not* explained by the proxies is associated with the residuals, and their variance is one part of the mean squared prediction error, which determines the width of the error band.

Although this way of illustrating uncertainty ranges is correct, it can easily be misinterpreted. The confusion arises because the uncertainty for the reconstruction is shown as a curve, rather than as a collection of points. For example, the 95 percent confidence intervals, when combined over the time of the reconstruction, do not form an envelope that has 95 percent probability of containing the true temperature series. To form such an envelope, the intervals would have to be inflated further with a factor computed from a statistical model for the autocorrelation, typically using Monte Carlo techniques. Such inflated intervals would be a valid description of the uncertainty in the maximum or minimum of the reconstructed temperature series.

Other issues also arise in interpreting the shape of a temperature reconstruction curve. Most temperature reconstructions exhibit a characteristic variability over time. However, the characteristics of the unknown temperature series may be quite different from those of the reconstruction, which must always be borne in mind when interpreting a reconstruction. For example, one might observe some decadal variability in the reconstruction and attribute similar variability to the real temperature series. However, this inference is not justified without further statistical assumptions, such as the probability of a particular pattern appearing due to chance in a temporally correlated series. Given the attenuation in variability associated with the regression method and the temporal correlations within the proxy record that may not be related to temperature, quantifying how the shape of the reconstructed temperature curve is related to the actual temperature series is difficult.

Ensembles of Reconstructions

One approach to depicting the uncertainty in the reconstructed temperature series is already done informally by considering a sample, or *ensemble*, of possible reconstructions. By graphing different approaches or variants of a reconstruction on the same axes, such as Figure S-1 of this report, differences in variability and trends can be appreciated. The problem with this approach is that the collection of curves cannot be interpreted as a representative sample of some population of reconstructions. This is also true of the 64 variants in Bürger and Cubasch (2005). The differences in methodology and datasets supporting these reconstructions make them distinct, but whether they represent a deliberate sample from the range of possible temperature reconstructions is not clear. As an alternative, statistical methods exist for generating an ensemble of temperature reconstructions that can be interpreted in the more traditional way as a random sample. Although this requires additional statistical assumptions on the joint distribution of the proxies and temperatures, it simplifies the interpretation of the reconstruction. For example, to draw inferences about the maximum values in past temperatures, one would just form a histogram of the maxima in the different ensemble members. The spread in the histogram is a rigorous way to quantify the uncertainty in the maximum of a temperature reconstruction.

10

Climate Forcings and Climate Models

- The main external climate forcings experienced over the last 2,000 years are volcanic eruptions, changes in solar radiation reaching the Earth, and increases in atmospheric greenhouse gases and aerosols due to human activities
- Proxy records are available for reconstructing climate forcings over the last 2,000 years, but these climate forcing reconstructions are associated with as much uncertainty as surface temperature reconstructions.
- Greenhouse gases and tropospheric aerosols varied little from A.D. 1 to around 1850. Volcanic eruptions and solar fluctuations were likely the most strongly varying external forcings during this period, but it is currently estimated that the temperature variations caused by these forcings were much less pronounced than the warming due to greenhouse gas forcing since the mid-19th century.
- Climate model simulations indicate that solar and volcanic forcings together could have produced periods of relative warmth and cold during the preindustrial portion of the last 1,000 years. However, anthropogenic greenhouse gas increases are needed to simulate late 20th century warmth.

As described in Chapter 1, global mean surface temperature varies in response to forcings external to the climate system that affect the global energy balance. For the last 2,000 years, the dominant forcings have been the natural changes in solar irradiance and volcanic eruptions, along with the more recent anthropogenic influences from greenhouse gases, tropospheric aerosols, and land use changes. This chapter largely focuses on the natural forcings during the preindustrial period, data for which come from some of the same sources as the proxy evidence for surface temperature variations, namely, historical records, ice cores, and tree rings. These reconstructions are typically associated with as much uncertainty as reconstructions of surface temperature.

Climate models are often used to simulate the response of climate to variations in external forcing, including those indicated by proxy evidence. A variety of models have been used to estimate the surface temperature variations implied by the available proxy data for the last 2,000 years. Climate models can also be used to study the feedbacks that determine the response of the global mean surface temperature to external forcings and also to estimate the natural internal variability of the climate system.

CLIMATE FORCINGS

The temperature of the Earth is determined by a balance of the energy entering the Earth–atmosphere system and the energy leaving the system. An energy imbalance imposed on the climate system either externally or by human activities is termed a *climate forcing* (NRC 2005); persistent climate forcings cause the temperature of the Earth to change until an energy balance is restored. The amount of change is determined by the magnitudes of the climate forcings and the feedbacks within the climate system that amplify or diminish the effect of the forcings (NRC 2003b). Climate forcings that directly affect the radiative balance of the Earth are termed radiative forcings and are typically measured in watts per square meter ($W \cdot m^{-2}$) (NRC 2005). Positive global mean radiative forcings result in warming of global mean surface temperatures. Volcanic eruptions, changes in the Sun's radiative output, and the mostly anthropogenic changes in greenhouse gases, tropospheric aerosols, and land use are the main climate forcings for surface temperatures over the last 2,000 years.

Greenhouse Gases

The primary natural greenhouse gases are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Water vapor is also a greenhouse gas that contributes the largest warming, but it is treated as a feedback because its concentration is controlled by the temperature of the atmosphere rather than by human activities. Continuous atmospheric measurements of carbon dioxide have been available since the mid-20th century from the Mauna Loa Observatory, and all of the significant greenhouse gases have been monitored since 1980 by the National Oceanic and Atmospheric Administration's global air sampling network (Keeling and Whorf 2005). For previous decades and centuries, greenhouse gas concentrations are obtained by analyzing air bubbles trapped in cores and firn of ice in Antarctica and Greenland.

Over the glacial–interglacial cycles of the last 650,000 years, carbon dioxide varied between about 300 ppm (parts per million by volume) during warm interglacial periods and about 180 ppm during cold glacial periods (Siegenthaler et al. 2005a). Methane and nitrous oxide atmospheric concentrations during interglacial periods did not exceed 790 ppb (parts per billion by volume) and 290 ppb, respectively (Spahni et al. 2005). Carbon dioxide, methane, and nitrous oxide varied little over the past 2,000 years prior to the industrial era (Figure 10-1). Ice core measurements indicate that carbon dioxide and nitrous oxide remained within a few ppm and ppb, respectively, of their mean concentrations and within the uncertainties of the data (Raynaud et al. 2003, Gerber et al. 2003). Methane fluctuated between 600 and 750 ppb, changing with the climate and likely resulting from fluctuations in natural and early anthropo-

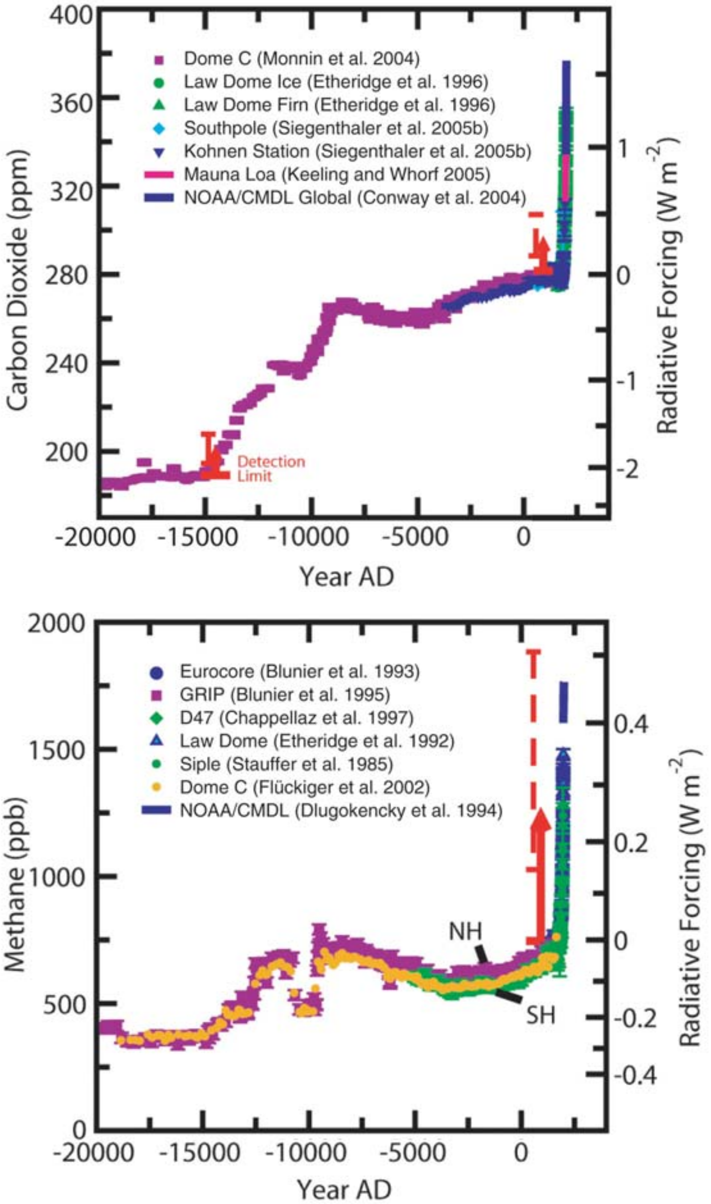

FIGURE 10-1 Evolution of atmospheric carbon dioxide and methane over the last 22,000 years. Left-hand axes show atmospheric concentrations (note the carbon dioxide scale does not start from zero), and right-hand axes show the radiative forcing relative to 1750 as calculated using the formulas given by Myhre et al. (1998) and Ramaswamy et al. (2001). Red arrows indicate the theoretical detection limit of a forcing (relative to Last Glacial Maximum and preindustrial conditions) within a climate system model, assuming an internal climate variability or detection threshold of 0.2°C, climate equilibrium, and a midrange climate sensitivity of 3°C for a carbon dioxide doubling. Dashed red lines indicate the uncertainty of the detection threshold associated with the climate sensitivity range of 1.5 to 4.5°C. SOURCE: Joos (2005). Reprinted with permission; copyright 2005.

genic sources (Blunier et al. 1993, Ruddiman and Thomson 2001, Raynaud et al. 2003, Keppler et al. 2006). Since the beginning of the Industrial Revolution (ca. 1750), the concentrations of these greenhouse gases in the atmosphere have increased considerably. Currently, they are appreciably outside the envelope of glacial–interglacial variations of the last 650,000 years. Carbon dioxide has increased from about 280 ppm during preindustrial times to current values of around 380 ppm. Methane has more than doubled from preindustrial levels, with more moderate but significant increases of nitrous oxide. The radiative forcing due to the increases of these and other long-lived greenhouse gases (relative to A.D. 1750) is about 2.5 $W{\cdot}m^{-2}$ (Joos 2005) (Figure 10-1). This is significantly larger than any variations or trends in the natural forcings, as we understand them over the last 2,000 years.

Orbital Changes in Incoming Solar Radiation

The amount of energy received by the Earth from the Sun varies on many different timescales. Over the last two millennia, two mechanisms mainly have affected the amount of solar energy reaching the top of Earth's atmosphere. The first mechanism is tied to changes in the Earth's orbital parameters caused by the gravitational pull of the Sun, Moon, and other planets. These effects combine to change the tilt of Earth's axis of rotation, the eccentricity of Earth's orbit, and the orientation of the eccentric orbit with respect to the vernal equinox, with timescales ranging from 20,000 to 400,000 years (Berger 1978). Over the limited period of the last 2,000 years, changes in the Earth's orbit have led to small changes in the amount of solar radiation arriving at the top of the Earth's atmosphere by latitude and by season. These orbital effects should have resulted in only a small trend in seasonal surface temperatures over the last 2,000 years, making Northern Hemisphere summers slightly cooler and Northern Hemisphere winters slightly warmer today than they were 2,000 years ago. Because of the seasonal nature of these effects, the incoming global average, annual mean solar radiation has remained essentially unchanged.

Solar Variability

The Sun's emission of radiation also varies in association with the frequency of occurrence of dark sunspots, bright faculae, and other solar phenomena. Estimates of *total solar irradiance* over the last two millennia come from several measures. Direct space-based radiometer measurements available since 1978 indicate that the total irradiance has varied by only about 0.1 percent over the last two 11-year solar cycles (Fröhlich and Lean 2004). These direct measurements showed a good correlation of sunspot number and irradiance during cycles 21 and 22. For the most recent cycle, the irradiance is as high as during the last two cycles, but the sunspot number is 20–30 percent lower (Fröhlich and Lean 2004, Lean 2005b).

Different solar indices, such as sunspot number, length of the solar cycle, and cosmogenic isotopes of carbon and beryllium, have been proposed as proxies for total solar irradiance during the past two millennia (Figure 10-2). Visual recordings of sunspots with telescopes have been available since 1610, but as noted above, the correlation of sunspots with irradiance has not been the same for the last three cycles. Measurements of beryllium isotopes in ice cores and carbon isotopes in tree rings are available for the past 1,000 to 2,000 years. The production of these isotopes is from

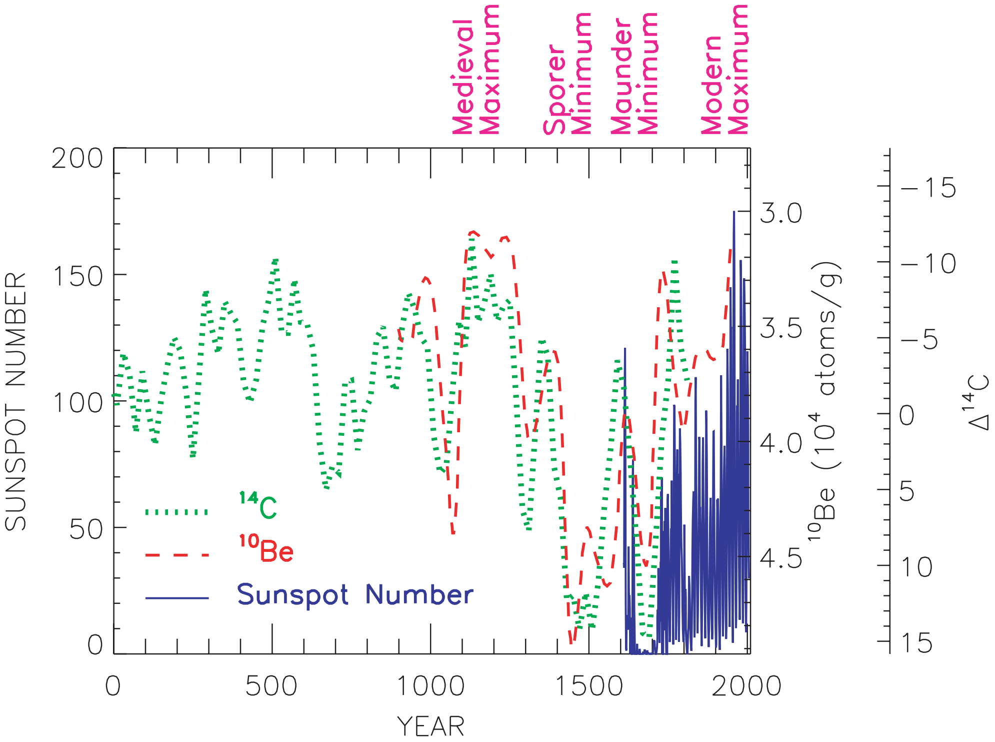

FIGURE 10-2 Records of sunspot number and cosmogenic isotope fluctuations in tree rings and ice cores associated with solar activity over the past 2,000 years. SOURCE: Updated from Fröhlich and Lean (2004). Reprinted with permission; copyright 2004.

galactic cosmic rays that are pushed away from Earth by the solar wind during times of strong solar activity. The relation between irradiance and cosmogenic isotopes, though, is complex and is not necessarily linear (Wang et al. 2005b).

Proxy records of solar irradiance have been used, often in combination with recent satellite measurements and solar modeling experiments, to obtain reconstructions of total solar irradiance over the last two millennia. Early reconstructions adopted a long-term trend in solar irradiance based on cosmogenic isotope records and comparisons to Sun-like stars, yielding a solar irradiance estimate for the Maunder Minimum (1645–1715) of about 0.2–0.4 percent below contemporary solar minima (Hoyt and Schatten 1993, Lean et al. 1995). The mechanisms proposed to explain this trend have been questioned recently, and newer reconstructions assume that solar output during the Maunder Minimum was closer to that of the present-day solar minima (Foukal et al. 2004). The most recent reconstructions (Fröhlich and Lean 2004, Wang et al. 2005a) indicate that solar irradiance has varied by about 0.1 percent over the last 2,000 years, which is equivalent to variations in radiative forcing of 0.1–0.2 W·m^{-2} between periods of low and high solar activity (Figure 10-2). Extended intervals of low solar activity, marked by an absence of sunspots, include the periods from 1645 to 1715 (the Maunder Minimum) and from 1450 to 1550 (the Sporer Minimum). These solar minima occurred within the Little Ice Age (which extended from around 1500 to 1850). Some studies have suggested that solar activity during medieval times may have been comparable to the modern solar maximum. Significant uncertainties exist in all of these records because of the shortness of the calibration record and our incomplete physical understanding of solar activity and its influence on irradiance. Additionally, indirect effects associated with ozone and stratospheric changes may alter the atmospheric circulation and response (Shindell et al. 2001).

Volcanic Eruptions

The radiative effect of a volcanic eruption depends on its magnitude and location, the time of year, the vertical orientation of the eruption, and the types and sizes of the ejecta (Robock 2000). Explosive volcanic eruptions add large amounts of ash and sulfur gases to the atmosphere, which diminish the amount of solar radiation reaching the surface, thereby cooling the Earth. Larger ash particles settle rapidly to the surface and generally only cool the surface temperature over a small region for several days to a few weeks. The sulfur gases combine with water vapor to form sulfate aerosols. In large explosive eruptions, the smaller sulfate aerosols are injected high into the atmosphere where they remain for up to several years. Sulfate aerosols from tropical eruptions are transported globally by high-altitude winds, whereas sulfate aerosols from high-latitude eruptions are more spatially restricted and have less effect on global temperature. Although large eruptions can lead to significant cooling immediately after the eruption, such as “the year without a summer” after the 1815 eruption of Mount Tambora in Indonesia, the effect is isolated to a few years. Accumulation of sulfate aerosols from several volcanoes closely spaced in time can lead to more extended global cooling.

Satellite instruments provided aerosol measurements for the large Mount Pinatubo eruption of 1991 in the Philippines. Historical records have been used to document past large eruptions in populated regions, notably Tambora in 1815 and Krakatau in 1883. Farther back, polar ice cores in Greenland and Antarctica recorded the acidity and sulfate in annual ice layers from the settling of volcanic sulfate aerosols (Crowley 2000, Hegerl 2006). Disentangling whether the volcanic debris were from a high-latitude volcano nearby or a large tropical volcano requires using records from multiple ice cores located at both poles and is sensitive to which ice cores are used. Reconstructions of volcanic activity over the last two millennia all distinguish the large eruptions of 1258 or 1259, 1453, and 1815, along with periods of more active volcanism in the late 13th century, the 17th century, and the early 19th century, although the various reconstructions differ with respect to some of the details (Figure 10-3).

Land Use

Although humans have been changing the natural vegetation for thousands of years by clearing forests and planting crops (Ruddiman 2003), the largest regional changes in continental vegetation cover have occurred since the mid-19th century in the Northern Hemisphere and early 20th century in the Southern Hemisphere (Bertrand et al. 2002). Changing land cover affects climate by modifying the surface reflectivity

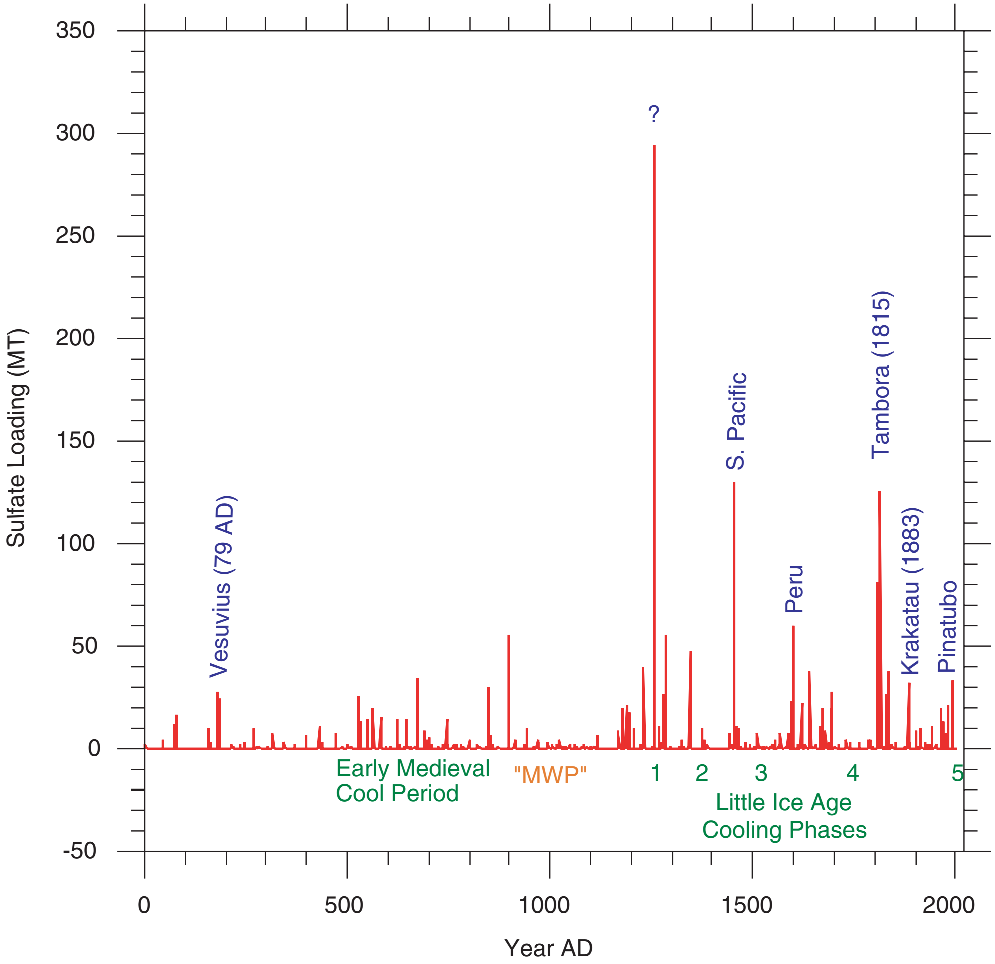

FIGURE 10-3 Ice core estimates of global stratospheric sulfate loading from volcanoes (A.D. 1–2005). SOURCE: T. Crowley, Duke University, 2006, unpublished material. Reprinted with permission; copyright 2006.

and the hydrological cycle. At present, estimates of the temperature change due to land use change are model and dataset dependent and cannot be independently verified with proxy data. One study estimates a global cooling as large as 0.4°C over the last 1,000 years (Bauer et al. 2003). Another suggests significant regional warming in the 20th century (Christy et al. 2006).

In addition to these direct radiative effects, land cover changes can affect the sources and sinks of greenhouse gases and the amount of dust lifted into the atmosphere by the wind. For instance, atmospheric carbon dioxide concentrations are increased by clearing of forests and decreased by reforestation, methane concentrations are increased by the cultivation of rice, and nitrous oxide concentrations are increased by the use of nitrogen fertilizers in agricultural activity.

Tropospheric Aerosols

Natural concentrations of tropospheric aerosols remained relatively constant before the industrial period. Concentrations increased over the 20th century due to human activities (Ramaswamy et al. 2001). The radiative forcings of tropospheric aerosols have large ranges associated with uncertainties in aerosol sources, composition, and properties and their interactions with clouds (NRC 2005). Observations and models indicate that, in total, the direct effects of aerosols and the indirect effect associated with aerosol–cloud interactions likely lead to a reduction of solar radiative flux at the Earth's surface, although separate aerosol species, such as black carbon, may have a positive radiative forcing (Ramaswamy et al. 2001). Tropospheric aerosols persist in the atmosphere for days to weeks and have significant regional variation; uncertainties in their forcing effects are large, especially at smaller spatial scales (NRC 2005).

CLIMATE MODEL SIMULATIONS

Computer models can be used to simulate the behavior of the climate system, taking into account both temporal and geographic variability, to understand both the natural variability of the climate system and the response of the climate system to changes in climate forcings (NRC 2001). These simulations can also be used to interpret proxy-based climate reconstructions (Trenberth and Otto-Bliesner 2003). A hierarchy of models have been used to simulate the climate variability of the last 1,000 years. These models range from simpler energy balance models to much more detailed and computer-intensive models of the Earth system. Climate models have been used to test various aspects of surface temperature reconstructions. In addition, they can be used to estimate the sensitivity of the surface temperature and other climatic variables to the estimated climate forcings over this period and the uncertainties inherent in those estimates. Using model simulations with several temperature reconstructions and instrumental data over the past seven centuries and accounting for uncertainties in the reconstructions and forcings, Hegerl et al. (2006) give an estimate of climate sensitivity of 1.5–6.2°C.

Climate simulations of the last 1,000 years have been performed with a variety of models (Jones and Mann 2004b and references therein). These simulations generally indicate that surface temperatures in the Northern Hemisphere were cooler prior to the 20th century than during the reference period from 1961 to 1990, with the second half of the 20th century being warmer than any part of the preceding millennium (Figure 10-4). Simulated Northern Hemisphere surface temperatures decrease from A.D. 1000 to a broad minimum extending from 1500 to 1700, and they warm substantially after 1900. Coolings associated with volcanoes are evident in the simulated surface temperatures. The average response of a climate model to volcanic forcing exhibits an e-folding time of cooling consistent with that inferred from large-scale tree-ring- and multiproxy-based reconstructions of Northern Hemisphere summer surface temperature (Hegerl et al. 2003; Figure 10-5). The model simulations are consistent with published surface temperature reconstructions.

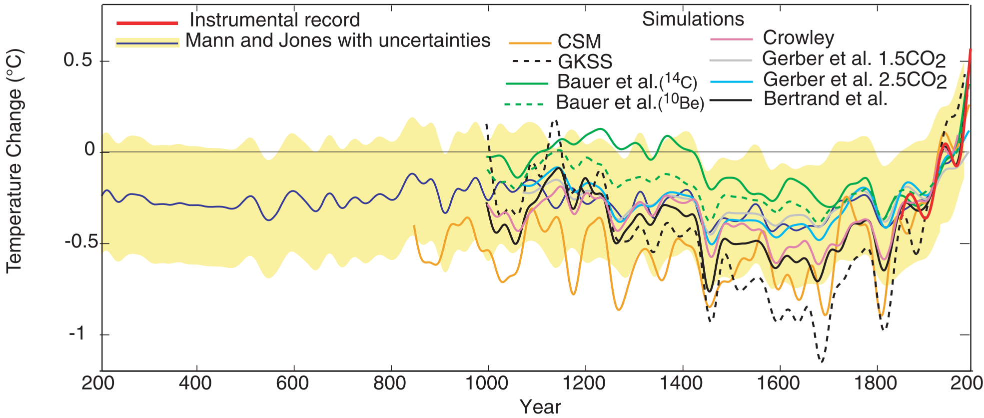

FIGURE 10-4 Estimates of Northern Hemisphere surface temperature variations over the last two millennia. Shown are 40-year smoothed series. Models have been aligned to have the same mean over the common 1856–1980 period as the instrumental series (which is assigned zero mean during the 1961–1990 reference period). The model simulations are based on varying radiative forcing histories and employ a hierarchy of models. SOURCE: Jones and Mann (2004b). Reproduced by permission of American Geophysical Union; copyright 2004.

Differences among the model simulations of the last millennium are related to several factors. The volcanic and solar forcing reconstructions used by the models differ as do their geographic and seasonal implementation. Most climate model simulations published to date used one of the earlier reconstructions of solar irradiance that included an increase in solar irradiance from the Maunder Minimum to present of around 0.2–0.4 percent. None of the long transient simulations have included wavelength-dependent changes in solar irradiance, although this effect has been investigated with shorter sensitivity simulations and has been shown to impact regional surface climate (Shindell et al. 2001). Volcanic reconstructions used in the various climate model simulations show similar timing of major volcanic eruptions and temporal clusters of eruptions. The models differ in the conversion of volcanic sulfate loading into optical depth and in the seasonally dependent horizontal and vertical dispersion of the aerosol cloud. The models also vary with respect to the specifics of the radiative transfer calculations included for volcanic aerosols. For example, in some energy balance models and intermediate complexity models, volcanoes are represented as a negative deviation of the solar irradiance.

Differences between the various model simulations can also be related to differences in the sensitivity of the models (Goosse et al. 2005). Two of the models, CSM and GKSS, are full three-dimensional climate models and have equilibrium climate sensitivities of 2°C and 3.2°C, respectively, for doubling of atmospheric CO_2. Some simpler models have an adjustable climate sensitivity (i.e., the Gerber 1.5 × CO_2 and 2.5 × CO_2 simulations). Different models also exhibit different sensitivities to different external forcings. The full three-dimensional climate models, which include parameterizations for the size distribution and transport of volcanic aerosols, show

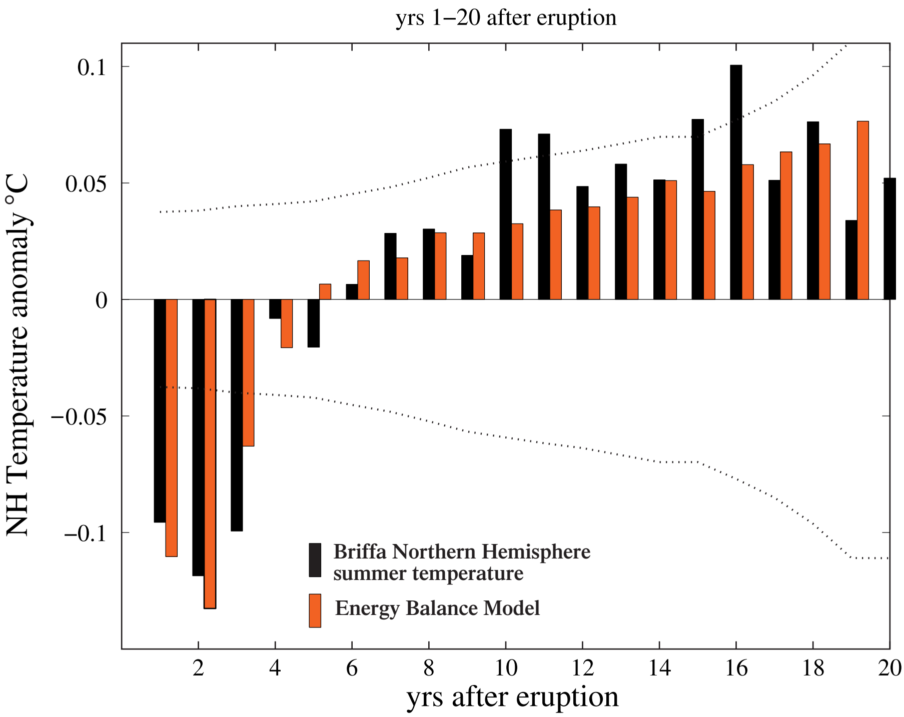

FIGURE 10-5 Comparison of the average response to volcanic eruptions in an energy balance model and the Briffa et al. (2001) reconstruction for the year of the eruption (year 1) to the next major eruption. Dotted lines represent 9–95 percent uncertainty ranges for the observed response (note the sample size decreases with time). SOURCE: Hegerl et al. (2003). Reproduced by permission of American Geophysical Union; copyright 2003.

stronger cooling than the models that prescribe the volcanic forcing in terms of a reduction in the Sun's emission.

ANTHROPOGENIC FORCING AND RECENT CLIMATE CHANGE

Based on current estimates, variations in natural climate forcings over the last 2,000 years were much less than the increase in current greenhouse forcing due to human activities. Over the 27-year period in which it has been monitored with satellite-borne instruments, the solar radiative forcing has varied only by 0.1–0.2 $W{\cdot}m^{-2}$ (Foukal et al. 2004). Volcanic activity has not been anomalous as compared to the last 1,000 years and cannot be used to explain the late 20th century warmth. Concentrations of the greenhouse gases in the atmosphere increased substantially over the 20th century and are appreciably above their preindustrial levels. The radiative forcing due to the increases of long-lived greenhouse gases from 1750 to 2000 is about 2.5 $W{\cdot}m^{-2}$ (Ramaswamy et al. 2001). Tropospheric aerosols and land use have also changed due to human activities, but the magnitudes of these forcings are not as well

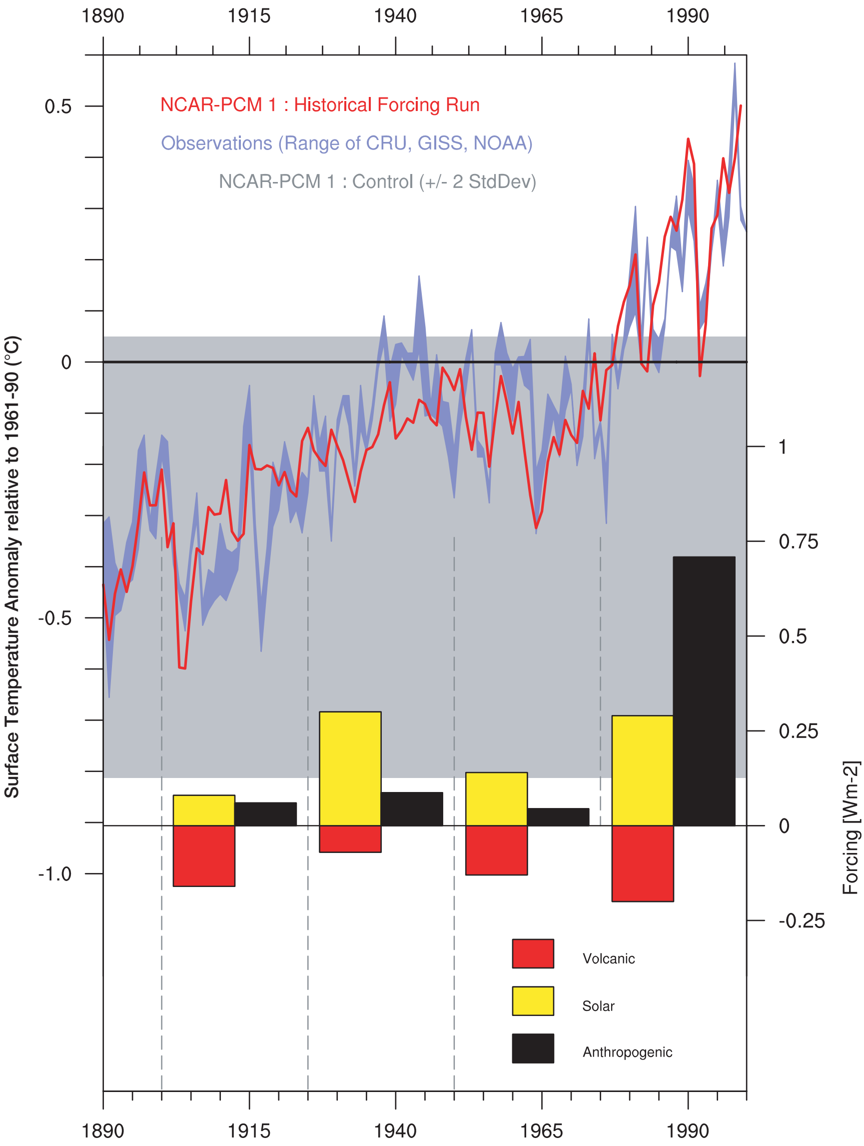

FIGURE 10-6 Model-based estimates of global surface temperature (blue line) compared to observational estimates (red line) with contributions of natural and anthropogenic forcings for 25-year periods shown as color bars. SOURCE: Ammann et al. (2003). Reproduced by permission of American Geophysical Union; copyright 2003.

constrained (Ramaswamy et al. 2001, NRC 2005). Results using a Monte Carlo approach, climate model simulations, and observations of atmospheric and oceanic warming suggest a total radiative forcing from preindustrial times to the present of 1.4–2.4 $W \cdot m^{-2}$, which is consistent with the observed warming (Knutti et al. 2002).

Simulations with energy balance and intermediate complexity models indicate that a combination of solar and volcanic forcings can explain periods of relative warmth and cold between A.D. 1000 and 1900, but anthropogenic forcings, particularly increases in greenhouse gases, are needed to reproduce the late 20th century warming (Crowley 2000, Bertrand et al. 2002, Bauer et al. 2003). Coupled atmosphere–ocean models have been used to simulate the relative roles of natural versus human-induced climate forcings in explaining the 20th century changes in global surface temperature constructed from instrumental records (Stott et al. 2000, Ammann et al. 2003) (Figure 10-6). Although the different model simulations use different specifications of the various natural and anthropogenic forcings and different parameterizations, the simulations are in agreement that anthropogenic forcing is the largest contributor to late 20th century warmth.

Current climate models have been tuned to optimize their ability to simulate the present climate, and they exhibit a range of climate sensitivities associated with different treatments of processes such as those associated with clouds and snow and ice (Webb et al. 2006, Winton 2006). Some models have been compared against data for past time periods that encompass major changes in forcings and climate responses, for example, the Last Interglaciation (Kaspar et al. 2005, Otto-Bliesner et al. 2006a) and the Last Glacial Maximum (Masson-Delmotte et al. 2006, Otto-Bliesner et al. 2006b). That these models' simulated climates for those epochs are consistent with proxy evidence lends credibility to their use for attribution of 20th century climate change and projections of future climate change.

11

Large-Scale Multiproxy Reconstruction Techniques

Using proxy evidence to study past climates helps us put the 20th century warming into a broader context, as well as to better understand the climate system and improve projections of future climate. The proxy climate records described in Chapters 3–8, which have been assembled and refined over a period of many decades, have been used to examine diverse aspects of climate history. Many of these studies have combined information from different proxy types to take advantage of the strengths of, and minimize the limitations of, individual proxies. In the late 1990s, scientists began to use this methodology for the specific purpose of estimating the variations in temperature over the last millennium, averaged at large (global and hemispheric) geographic scales. These large-scale multiproxy-based surface temperature reconstructions offer a quantitative assessment of large-scale surface temperature variations. They generally fall into two categories: those that combine multiple records of the same type of proxy (e.g., tree rings from various locations) and those that combine different types of records (e.g., tree rings together with documentary evidence, sediment records, etc.). Large-scale surface temperature reconstructions based on multiproxy techniques often have a time resolution as fine as decades or individual years; they also enable researchers to estimate the statistical uncertainties associated with the reconstruction technique, as described in Chapter 9. To improve spatial coverage, some reconstructions include proxies that may be more sensitive to precipitation than to temperature, in which case statistical techniques are used to infer the temperature signal, exploiting the spatial relationship between temperature and precipitation.

There are two general approaches that are commonly used to perform the calibration, validation, and reconstruction steps for large-scale surface temperature reconstructions. In the first approach, proxies are calibrated against time series of the dominant patterns of spatial variability in the instrumental temperature record and the results are combined to obtain a time series of large-scale mean surface temperature. In the second approach, the individual proxy data are first composited, and this composite series is then calibrated directly against the time series of large-scale temperature variations.

Both the number and the quality of the proxy records available for surface temperature reconstructions decrease dramatically from century-to-century moving backward in time (see, e.g., Figure O-2). At present, fewer than 30 annually resolved proxy time series extend further back than A.D. 1000; relatively few of these are from the Southern Hemisphere and even fewer are from the tropics. Although fewer sites are required for defining long-term (e.g., century-to-century) variations in hemispheric mean temperature than for short-term (e.g., year-to-year) variations (see Chapter 2), the coarse spatial sampling limits our confidence in hemispheric mean or global mean temperature estimates prior to A.D. 1600 and makes it very difficult to generate meaningful quantitative estimates of global temperature variations prior to about A.D. 900. Moreover, the instrumental record is shorter than some of the features of interest in the preindustrial period (i.e., the extended period of sporadic warmth from A.D. 800 to 1300 and the subsequent Little Ice Age), so there are very few statistically independent pieces of information in the instrumental record for calibrating and validating long-term temperature reconstructions.

EVOLUTION OF MULTIPROXY RECONSTRUCTION TECHNIQUES

The first systematic, statistically based synthesis of multiple climate proxies was carried out in 1998 by Michael Mann, Raymond Bradley, and Malcolm Hughes (Mann et al. 1998); their study focused on temperature for the last 600 years in the Northern Hemisphere. The analysis was later extended to cover the last 1,000 years (Mann et al. 1999), and the results were incorporated into the 2001 report of the Intergovernmental Panel on Climate Change (IPCC 2001). Later, Mann and Jones (2003b) extended the multiproxy reconstruction further back to cover the last 1,800 years (see Figure 10-4). On the basis of these reconstructions, it was concluded that temperatures gradually dropped from a relative maximum at about A.D. 1000 to a minimum at about 1850 and then increased sharply through the 20th century. The graph illustrating the trend, often called the hockey stick curve (reproduced in Figure O-4), received wide attention because it was interpreted by some people as definitive evidence of human-induced global warming. The ensuing debate in the scientific literature continues even as this report goes to press (von Storch et al. 2006, Wahl et al. 2006).

The Mann et al. large-scale surface temperature reconstructions were the first to include explicit statistical error bars, which provide an indication of the confidence that can be placed in the results. In the Mann et al. work, the error bars were relatively small back to about A.D. 1600, but much larger for A.D. 1000–1600. The lower precision during earlier times is caused primarily by the limited availability of annually resolved paleoclimate data: That is, the farther back in time, the harder it is to find evidence that provides reliable annual information. For the period before about A.D. 900, annual data series are very few in number, and the non-annually resolved data used in reconstructions introduce additional uncertainties.

Since the late 1990s, a number of alternative reconstructions have been generated using different statistical methods and proxy datasets (Esper et al. 2002a,b, 2003; Cook et al. 2004; Moberg et al. 2005b; Rutherford et al. 2005; Hegerl et al. 2006; D’Arrigo et al. 2006; Wahl and Amman in press). Figure 11-1 shows the results of several of these efforts, some of which are described in additional detail in the next section.

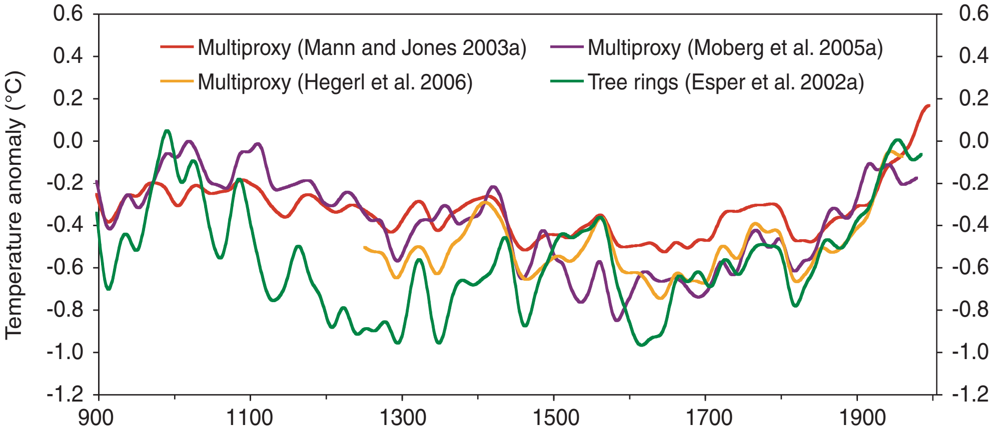

FIGURE 11-1 Four different large-scale multiproxy- and tree-ring-based surface temperature reconstructions, shown for the period A.D. 900–2005. See Figure O-5 for additional information on each data series.

Criticisms and Advances of Reconstruction Techniques

There have been criticisms of the techniques used to create large-scale surface temperature reconstructions and, in particular, of the work done by Mann et al. (e.g., Zorita and von Storch 2005; McIntyre and McKitrick 2003, 2005a,b; von Storch et al. 2004; Moberg et al. 2005b). One criticism is related to the question of whether century-to-century climate variations are underestimated in proxy records that have strong year-to-year variability and consist of segments that have been spliced together to obtain a chronology longer than any of the segments. Several research groups have developed reconstruction methods to address this problem. For instance, Esper et al. (2002a) developed a tree-ring-based reconstruction that attempts to remove the bias by using improved statistical methods explicitly designed to preserve low-frequency variability. Moberg et al. (2005b) separated annual records (tree rings) from smoother (non-annual) records (such as ice borehole temperatures and sediment based records) by using wavelet analysis. These studies indicate that the true amplitude of temperature variations over the last 1,000–2,000 years may have been roughly twice as large as was previously proposed (see Figure 11-1), although their results differ in geographic emphasis and in the details of the time sequence of the temperature changes. Von Storch et al. (2004) used a long-term climate model simulation to produce artificial proxy data and then compared reconstructions of hemispheric mean temperature with varying degrees of noise contamination; they found that the full amplitude of century-to-century variations were underestimated to an increasing degree as the noise level was increased. Thus, the reconstruction of century-long trends has substantial uncertainty when it is based on data that exhibit year-to-year variability.

A second area of criticism focuses on statistical validation and robustness. McIntyre and McKitrick (2003, 2005a,b) question the choice and application of statistical methods, notably principal component analysis; the metric used in the validation step of the reconstruction exercise; and the selection of proxies, especially the bristlecone pine data used in some of the original temperature reconstruction studies. These and other criticisms, explored briefly in the remainder of this chapter, raised concerns that led to new research and ongoing efforts to improve how surface temperature reconstructions are performed.

As part of their statistical methods, Mann et al. used a type of principal component analysis that tends to bias the shape of the reconstructions. A description of this effect is given in Chapter 9. In practice, this method, though not recommended, does not appear to unduly influence reconstructions of hemispheric mean temperature; reconstructions performed without using principal component analysis are qualitatively similar to the original curves presented by Mann et al. (Crowley and Lowery 2000, Huybers 2005, D'Arrigo et al. 2006, Hegerl et al. 2006, Wahl and Ammann in press). The more important aspect of this criticism is the issue of robustness with respect to the choice of proxies used in the reconstruction. For periods prior to the 16th century, the Mann et al. (1999) reconstruction that uses this particular principal component analysis technique is strongly dependent on data from the Great Basin region in the western United States. Such issues of robustness need to be taken into account in estimates of statistical uncertainties.

Huybers (2005) and Bürger and Cubasch (2005) raise an additional concern that must be considered carefully in future research: There are many choices to be made in the statistical analysis of proxy data, and these choices influence the conclusions. Huybers (2005) recommends that to avoid ambiguity simple averages should be used rather than principal components when estimating spatial means. Bürger and Cubasch (2005) use several dozen statistical methods to generate examples of reconstructions; these reconstructions differ substantially even though they are based on the same data. Many of these issues can be decided by using the validation data to select among competing models and focusing on the prediction intervals associated with a reconstruction (see Chapter 9). When the prediction intervals are taken into account, the differences among competing reconstructions may be deemed small relative to the large uncertainty of each individual estimate.

Regarding metrics used in the validation step in the reconstruction exercise, two issues have been raised (McIntyre and McKitrick 2003, 2005a,b). One is that the choice of "significance level" for the reduction of error (RE) validation statistic is not appropriate. The other is that different statistics, specifically the coefficient of efficiency (CE) and the squared correlation (r^2), should have been used (the various validation statistics are discussed in Chapter 9). Some of these criticisms are more relevant than others, but taken together, they are an important aspect of a more general finding of this committee, which is that uncertainties of the published reconstructions have been underestimated. Methods for evaluation of uncertainties are discussed in Chapter 9.

Several recent research efforts have explored how the selection of proxies affects surface temperature reconstructions. Osborn and Briffa (2006) used an alterative approach based on 14 proxy records, most of which extend back to A.D. 800, taken from sites widely dispersed throughout the Northern Hemisphere. Instead of reconstructing temperatures, they chose proxy records that correlated well with local thermometers over the last 150 years (regardless of whether they show warming), smoothed and standardized each record to have zero mean and unit standard deviation, and analyzed the excursions of the smoothed time series above or below selected thresholds (± 1 or 2 standard deviations). The authors showed that the excursions on the warm side were largest in the 20th century and that the deviation index produced graphs similar to those from other research (Figure 11-2). Osborn and Briffa's method shifts the focus of the argument from the statistical methods used to reconstruct temperature time series to the selection of proxy and site. The degree of spatial coherence shown by Osborn

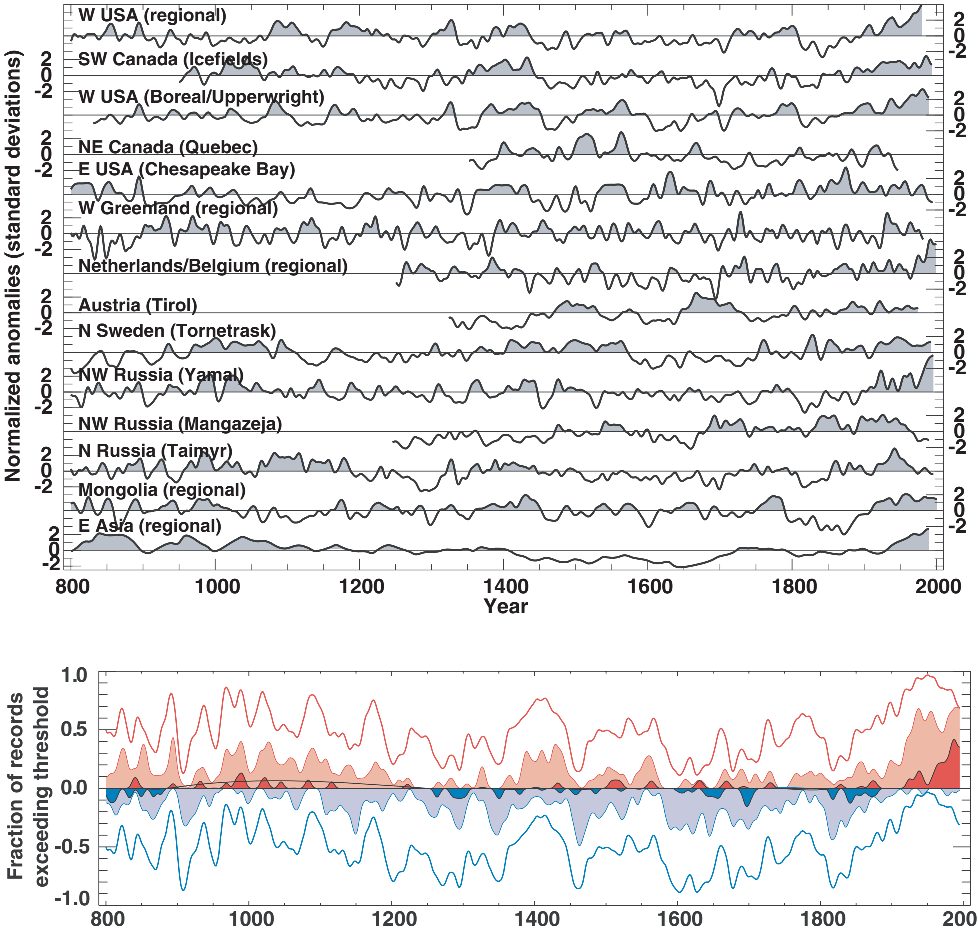

FIGURE 11-2 Upper panel: Fourteen temperature-related proxy records selected on the basis of their correlation with the instrumental record, as described by Osborn and Briffa (2006), filtered to remove variations on timescales less than 20 years and then normalized to have zero mean and unit standard deviation during the period A.D. 800–1995. Lower panel: Fraction of records available in each year that have normalized values greater than zero (red line), greater than 1 (light red shading), greater than 2 (dark red shading), less than zero (blue line), less than –1 (light blue shading), and less than –2 (dark blue shading), with the latter three series multiplied by –1 before plotting. SOURCE: Osborn and Briffa (2006).

and Briffa (2006), together with other reconstructions, provide supporting evidence for the statement that the warming during the late 20th century is more spatially coherent than during previous warm episodes back to at least A.D. 900 (see also Bradley et al. 2003).

The basic conclusion of Mann et al. (1998, 1999) was that the late 20th century warmth in the Northern Hemisphere was unprecedented during at least the last 1,000 years. This conclusion has subsequently been supported by an array of evidence that includes the additional large-scale surface temperature reconstructions and documentation of the spatial coherence of recent warming described above (Cook et al. 2004, Moberg et al. 2005b, Rutherford et al. 2005, D'Arrigo et al. 2006, Osborn and Briffa 2006, Wahl and Ammann in press) and also the pronounced changes in a variety of local proxy indicators described in previous chapters (e.g., Thompson et al. in press).

Based on the analyses presented in the original papers by Mann et al. and this newer supporting evidence, the committee finds it plausible that the Northern Hemisphere was warmer during the last few decades of the 20th century than during any comparable period over the preceding millennium. The substantial uncertainties currently present in the quantitative assessment of large-scale surface temperature changes prior to about A.D. 1600 lower our confidence in this conclusion compared to the high level of confidence we place in the Little Ice Age cooling and 20th century warming. Even less confidence can be placed in the original conclusions by Mann et al. (1999) that "the 1990s are likely the warmest decade, and 1998 the warmest year, in at least a millennium" because the uncertainties inherent in temperature reconstructions for individual years and decades are larger than those for longer time periods, and because not all of the available proxies record temperature information on such short timescales. However, the methods in use are evolving and are expected to improve.

STRENGTHS AND LIMITATIONS OF LARGE-SCALE SURFACE TEMPERATURE RECONSTRUCTIONS

The committee identified the following key strengths of large-scale surface temperature reconstructions:

- Large-scale surface temperature reconstructions are based on proxy records that are meaningful recorders of environmental variables. The connections between proxy records and environmental variables are well justified in terms of physical, chemical, and biological processes.
- Tree rings, the dominant data source in many reconstructions, are derived from regional networks with extensive replication, and they are a good indicator of environmental variables at the regional scale. Regional tree ring series are highly correlated with measures of temperature and drought. These connections have a convincing biophysical basis related to tree physiology and growing-season climate. Temperature dominates in some environments and precipitation in others, as is consistent with ecological expectations of limits to growth (Fritts 1976).
- The same general temperature trends emerge from different reconstructions. Some reconstructions focus on temperature-dependent trees and use wood density measures (Briffa et al. 2002), others focus on temperature-dependent trees and use ring widths (D'Arrigo et al. 2006), and still others incorporate extensive data from precipitation-dependent trees and ice cores and use climate field correlations to derive

temperature (Rutherford et al. 2005). One reconstruction does not use tree ring networks at all for century-scale and longer changes, but instead relies on a combination of geochemical and sedimentary proxies (Moberg et al. 2005b).

- Temperature records from about A.D. 1600 to the present derived from large-scale surface temperature reconstructions are consistent with other sources of temperature information for the period, including borehole temperatures and glacier length records.
- Prior to about 1600, information is sparser and the pattern of change is not necessarily synchronous, but periods of medieval warmth are seen in a number of diverse records, including historical information from Europe and Asia; cave deposits; marine and lake sediments; and ice cores from Greenland, Ellesmere Island, Tibet, and the equatorial Andes.

Many challenges remain as research progresses to use large-scale surface temperature reconstructions to learn about climate history (Hughes 2002, Rutherford et al. 2005, D'Arrigo et al. 2006). There are two major structural challenges. First, the amount of high-quality proxy data available for analysis decreases markedly as one moves back in time. The great richness of tree ring network data available for 1700, for example, is largely depleted by A.D. 1000. Large-scale temperature reconstructions should always be viewed as having a "murky" early period and a later period of relative clarity. The boundary between murkiness and clarity is not precise but is nominally around A.D. 1600. Second, the finite length (about 150 years) of the instrumental temperature record available for calibration of large-scale temperature estimates places limits on efforts to demonstrate the accuracy of temperature reconstructions. Further research should be aimed at providing independent checks on reconstructions using borehole temperatures, glacier length records, and other proxies.

The role of statistical methods is not trivial. Each individual proxy provides a record of environmental change, but the process of combining these environmental signals into a large-scale spatially averaged temperature requires statistical evaluation. Even if a single proxy is a perfect recorder of the local environment, the question remains of whether the local environments are adequately or representatively sampling the large-scale temperature field. In addition, most proxy records lack the annual chronological precision found in tree ring data; the typical dating error might be 1–5 percent of the age of the sample for annually layered records such as lake varves and 5–10 percent for radiometrically dated records spanning the last 2,000 years.

The committee identified the following limitations of large-scale surface temperature reconstructions that would benefit from further research:

- There are very few degrees of freedom in validations of the reconstructed temperature averaged over periods of decades and longer. The RE validation metric used by Mann et al. (1998, 1999) is a minimum requirement, but the committee questions whether any single statistic can provide a definitive indication of the uncertainty inherent in the reconstruction. Demonstrating performance for the higher-frequency component (e.g., by calculating the CE statistic) would increase confidence but still would not fully address the issue of evaluating the reconstruction's ability to capture temperature variations on decadal-to-centennial timescales.
- Using proxies sensitive to hydrologic variables (including moisture-sensitive trees and isotopes in tropical ice cores and speleothems) to take advantage of observed

correlations with surface temperature could lead to problems and should be done only if the proxy–temperature relationship has climatological justification.

- The observed discrepancy between some tree ring variables that are thought to be sensitive to temperature and the temperature changes observed in the late 20th century (Jacoby and D'Arrigo 1995, Briffa et al. 1998) reduces confidence that the correlation between these proxies and temperature has been consistent over time. Future work is needed to understand the cause of this "divergence," which for now is considered unique to the 20th century and to areas north of 55°N (Cook et al. 2004).
- For tree ring chronologies, the process of removing biological trends from ring-width data potentially obscures information on long-term changes in climate.
- Temperature reconstructions for periods before about A.D. 1600 are based on proxies from a limited number of geographic regions, and some reconstructions are not robust with respect to the removal of proxy records from individual regions (see, e.g., Wahl and Ammann in press). Because the data are so limited, different large-scale reconstructions are sometimes based on the same datasets and thus cannot be considered as completely independent.
- Reconstructions of low-frequency variations in the temperature record that make use of proxies other than tree rings (Moberg et al. 2005b) are limited by the small number of available records, by dating uncertainties, and by the sensitivity of many proxies to hydrologic variables as well as to temperature. These data gaps highlight the need for continued coordinated efforts to collect proxy data over broad geographic regions.

Specifically concerning the reconstructed temperature variability over short time periods (year-to-decade scale), the committee identified the following as limitations that would benefit from further research:

- Large-scale surface temperature reconstructions demonstrate very limited statistical skill (e.g., using the CE statistic) for proxy sets before the 19th century (Rutherford et al. 2005, Wahl and Ammann in press). Published information, although limited, also suggests that these statistics are sensitive to the inclusion of small subsets of the data. Some of the more regionally focused reconstructions (D'Arrigo et al. 2006) have better demonstrated skill back to the 16th century or so, and possibly earlier. To improve the skill of reconstructions, more data need to be collected and possibly new assimilation methods developed.
- Accurately inferring the absolute values of temperature for single years and decades from proxies sensitive to variability at this timescale requires accurate reconstruction of the longer term mean.

OVERALL FINDINGS AND CONCLUSIONS

Based on its deliberations and the materials presented in Chapters 1–11 and elsewhere, the committee draws the following overall conclusions regarding large-scale surface temperature reconstructions for the last 2,000 years:

- The instrumentally measured warming of about 0.6°C during the 20th century is also reflected in borehole temperature measurements, the retreat of glaciers, and other observational evidence, and can be simulated with climate models.

- Large-scale surface temperature reconstructions yield a generally consistent picture of temperature trends during the preceding millennium, including relatively warm conditions centered around A.D. 1000 (identified by some as the "Medieval Warm Period") and a relatively cold period (or "Little Ice Age") centered around 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 justified by the consistency of the evidence from a wide variety of geographically diverse proxies.
- Less confidence can be placed in large-scale surface temperature reconstructions for the period from A.D. 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 A.D. 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.
- Very little confidence can be assigned to statements concerning the hemispheric mean or global mean surface temperature prior to about A.D. 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.

WHAT COMMENTS CAN BE MADE ON THE VALUE OF EXCHANGING INFORMATION AND DATA?

The collection, compilation, and calibration of paleoclimatic data represent a substantial investment of time and resources, often by large teams of researchers. The committee recognizes that access to research data is a complicated, discipline-dependent issue and that access to computer models and methods is especially challenging because intellectual property rights must be considered. Our view is that all research benefits from full and open access to published datasets and that a clear explanation of analytical methods is mandatory. Peers should have access to the information needed to reproduce published results, so that increased confidence in the outcome of the study can be generated inside and outside the scientific community. Other committees and organizations have produced an extensive body of literature on the importance of open access to scientific data and on the related guidelines for data archiving and data access (e.g., NRC 1995). Paleoclimate research would benefit if individual researchers, professional societies, journal editors, and funding agencies continued to improve their efforts to ensure that these existing open-access practices are followed.

Tree ring researchers have recognized the importance of data archiving since 1974, when the International Tree Ring Data Bank was established to serve as a permanent repository for tree ring data (measurements, chronologies, and derived reconstructions). Its holdings are available online via the World Data Center for Paleoclimatology, as are a number of other proxy data from ice cores, corals, boreholes, lake and ocean sediments, caves, and biological indicators. As proxy datasets become increasingly available on the Web, all researchers are given the opportunity to analyze data, test methods, and provide their own interpretation of the existing evidence via recognized, peer-reviewed scientific outlets.

WHAT MIGHT BE DONE TO IMPROVE OUR UNDERSTANDING OF CLIMATE VARIATIONS OVER THE LAST 2,000 YEARS?

Surface temperature reconstructions have the potential to further improve our knowledge of temperature variations over the last 2,000 years, particularly if additional proxy evidence can be identified and obtained. Additional proxy data that record decadal-to-centennial climate changes, especially for the period A.D. 1–1600, would be particularly valuable. New data from the Southern Hemisphere, the tropics, and the oceans would improve our confidence in global temperature reconstructions, while additional data from regions that have already been sampled would help reduce the uncertainties associated with current reconstructions. In addition, many existing proxy records were collected decades ago and need to be updated in order to perform more reliable comparisons with instrumental records. Better data coverage would also make it possible to test whether or not past temperature changes had the same pattern as the warming during the last century. New methods, or more careful use of existing ones, may also help circumvent some of the existing limitations of large-scale surface temperature reconstructions based on multiple proxies. Each individual proxy provides a record of environmental change, but the process of combining these signals into a spatially averaged temperature signal requires careful statistical evaluation. It might be possible to circumvent some of the limitations associated with these reconstructions by employing a number of complementary strategies in analyzing the proxy data, including using them to constrain climate models, and by attempting to calibrate the proxy data against climatic variables in different ways.

Finally, some of the most important consequences of climate change are linked to changes in precipitation, especially the frequency and intensity of droughts and floods, as opposed to just temperature alone. Changes in regional circulation patterns, snowfall, hurricane activity, and other climate elements over time are also of interest. Hence, it would be valuable to see both regional and large-scale reconstructions of changes in precipitation and other climate variables over the last 2,000 years, to complement those made for temperature. Efforts to improve the reliability of surface temperature reconstructions also need to be complemented by efforts to improve our understanding of the forcings that have contributed to climate variability over the past 2,000 years. When analyzed in conjunction with historical and archeological evidence, paleoclimatic reconstructions can also tell us how past societies adapted to climate changes.

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Appendixes

A

Statement of Task

The committee will describe and assess the state of scientific efforts to reconstruct surface temperature records for the Earth over approximately the past 2,000 years. The committee will summarize current scientific information on the temperature record for the past two millennia, describe the main areas of uncertainty and how significant they are, describe the principal methodologies used and any problems with these approaches, and explain how central the debate over the paleoclimate temperature record is to the state of scientific knowledge on global climate change. As part of this effort, the committee will address tasks such as:

- Describe the proxy records that have been used to estimate surface temperatures for the pre-instrumental period (e.g., tree rings, sediment cores, isotopes in water and ice, biological indicators, indicators from coral formations, geological boreholes, historical accounts) and evaluate their limitations.
- Discuss how proxy data can be used to reconstruct surface temperature over different geographic regions and time periods.
- Assess the various methods employed to combine multiple proxy data to develop large-scale surface temperature reconstructions, the major assumptions associated with each approach, and the uncertainties associated with these methodologies.
- Comment on the overall accuracy and precision of such reconstructions, relevant data quality and access issues, and future research challenges.

B

R Code for Figure 9-2

```
n <- 600;
baseline <- n - 0:99;
phi <- 0.9;

HSIndex <- function(x)
{
 (mean(x[baseline]) - mean(x)) / sqrt(var(x));
}

SimulatePC1 <- function(p = 50)
{
 a <- matrix(NA, n, p);
 for (j in 1:p) {
 b <- arima.sim(model = list(ar = phi), n);
 a[ , j] <- b - mean(b[baseline]);
 }
 invisible(svd(a)$u[,1]);
}

a <- matrix(NA, n, 5);
for (j in 1:ncol(a)) {
 a[ , j] <- SimulatePC1();
}

b <- apply(a, 2, HSIndex);
c <- t(sign(b) * t(a));
matplot(c, type = “l”, xlab = “”, ylab = “”, lty = 2);
```

```
PopulationCov <- function(n)
{
 a <- matrix(NA, n, n);
 a[] <- phi^abs(row(a) - col(a));
 for (i in 1:n)
 a[i, ] <- a[i, ] - mean(a[i, baseline]);
 for (j in 1:n)
 a[ , j] <- a[ , j] - mean(a[baseline, j]);
 invisible(a);
}

e <- eigen(PopulationCov(n));
lines(e$vectors[,1], col = 2, lwd = 2);
```

C

Biographical Sketches of Committee Members

Gerald R. North (*Chair*) is Distinguished Professor of Meteorology and Oceanography and holder of the Harold J. Haynes Endowed Chair in Geosciences at Texas A&M University. His professional interests include climate analysis, climate and hydrological modeling, satellite remote sensing and mission planning, and statistical methods in atmospheric science. Dr. North and his research group are interested in climate change and the determination of its origins. They work with simplified climate models that lend themselves to analytical study, estimation theory as applied to observing systems, and the testing of all climate models through statistical approaches. Dr. North is a fellow of the American Association for the Advancement of Science (AAAS), the American Meteorological Society (AMS), and the American Geophysical Union (AGU) and is editor in chief of *Reviews of Geophysics*. He is a former member of the National Research Council's (NRC) Board on Atmospheric Sciences and Climate and Committee on Earth Studies. Dr. North received his Ph.D. in physics from the University of Wisconsin.

Franco Biondi is an associate professor of physical geography at the University of Nevada, Reno, where he is also a member of the Graduate Program of Hydrologic Sciences and the Ph.D. Program in Ecology, Evolution, and Conservation Biology. His interests are in climate and forest dynamics, Holocene processes, and environmental change. His long-term scientific goal is to understand climate processes affecting forest growth at multiannual timescales in current, past, and future environments, and he pursues this goal using natural archives such as tree rings. In 2001 he received the Paper of the Year Award from the Climate Specialty Group of the Association of American Geographers. Dr. Biondi received his Ph.D. in watershed management from the University of Arizona, Tucson.

Peter Bloomfield is a professor of statistics and a member of the financial mathematics faculty at North Carolina State University, Raleigh. His interests are in the application of statistical methods to problems in earth science and finance. He served on the National

Aeronautics and Space Administration/World Meteorological Organization (NASA/WMO) ozone trends panel and was lead author of an appendix on statistics for the panel's report. He has also served on panels of the NRC, Environmental Protection Agency (EPA), NASA, and the Intergovernmental Panel on Climate Change (IPCC). He has studied methods for detecting trends in geophysical time series such as stratospheric ozone, surface temperatures, and atmospheric concentration of chlorofluorocarbons (CFCs). Dr. Bloomfield also spent several years working in a financial institution, building a statistical model of the risks in special-purpose financial companies, and continues to consult on financial problems. He received his Ph.D. in statistics from the University of London.

John R. Christy is a professor of atmospheric science and director of the Earth System Science Center at the University of Alabama in Huntsville, where he began studying global climate issues in 1987. In 2000 he was appointed state climatologist of Alabama. In 1989, Dr. Roy Spencer (then a NASA/Marshall scientist) and Dr. Christy developed a global temperature dataset from microwave data observed from satellites beginning in 1979, for which they were awarded NASA's Medal for Exceptional Scientific Achievement. They also received a special award from AMS "for developing a global, precise record of earth's temperature from operational polar-orbiting satellites, fundamentally advancing our ability to monitor climate." Dr. Christy has served as a contributor and lead author for the IPCC reports in which the satellite temperatures were included as a high-quality dataset for studying global climate change. He is a former member of several NRC committees, including the Panel on Reconciling Temperature Observations and the Committee on Utilization of Environmental Satellite Data. Dr. Christy received his Ph.D. in atmospheric sciences from the University of Illinois.

Kurt M. Cuffey is a professor of geography at the University of California, Berkeley. Dr. Cuffey explores the interface between climatology and geomorphology and has a particular interest in the earth's great ice sheets. His research efforts emphasize environmental change of polar regions, with a focus on glaciological problems. He uses geophysical techniques to reconstruct histories of temperature and snowfall rate over the ice sheets. He is also working on a better understanding of the physical and chemical processes that determine ice composition as a function of climate. Dr. Cuffey pioneered the use of borehole thermometry to obtain a temperature calibration of the oxygen isotope record in ice cores from Summit Greenland. He is a fellow of the AGU, and in 2003 he was awarded AGU's Macelwane Medal. Dr. Cuffey received his Ph.D. from the University of Washington.

Robert E. Dickinson is a professor in the School of Earth and Atmospheric Sciences at the Georgia Institute of Technology. His areas of interest include the dynamics of atmospheric planetary waves, stratospheric dynamics, models of global structure and dynamics of terrestrial and planetary thermosphere, non-local thermodynamic equilibrium infrared radiative transfer in planetary mesopheres, global climate modeling and processes, the role of land processes in climate systems, the modeling role of vegetation in regional evapotranspiration, and the role of tropical forests in climate systems. Dr. Dickinson is a member of the National Academy of Sciences (NAS) and the National Academy of Engineering (NAE) and a fellow of AAAS and AGU. He has served on many NRC committees, including the Committee on the Science of Climate Change and Climate Research Committee. He is the recipient of the AMS Rossby Award and the AGU Revelle Medal. Dr. Dickinson received his Ph.D. in meteorology from the Massachusetts Institute of Technology.

Ellen R.M. Druffel is the Advance chair and professor of Earth System Science at the University of California, Irvine. Her research interests include coupling between climate and ocean ventilation and their effects on global carbon dioxide cycling and tracking the influence of climate change on present and past upper-ocean circulation using isotope studies of annually banded corals. Dr. Druffel is a fellow of AAAS and AGU; she is president of the Ocean Sciences section of AGU. She has served on several NRC committees, including the Ocean Studies Board and the Committee on Oceanic Carbon. She received her Ph.D. in chemistry from the University of California, San Diego.

Douglas Nychka is a senior scientist at the National Center for Atmospheric Research (NCAR). Before joining NCAR, he spent 14 years as a faculty member in the Statistics Department at North Carolina State University. In his current role, his primary challenge is interdisciplinary research and migrating statistical techniques to important scientific problems and using these problems to motivate novel statistical research. His personal research interests include nonparametric regression, statistical computing, spatial statistics, and spatial designs. Dr. Nychka currently serves on the NRC Committee on Applied and Theoretical Statistics. He received his Ph.D. from the University of Wisconsin.

Bette Otto-Bliesner is a scientist in the Climate and Global Dynamics Division at NCAR in Boulder, Colorado. She is head of the Paleoclimate Group and deputy head of the Climate Change Research Section. Her research interest is to use climate system models to investigate past climate and climate variability across a wide range of timescales. She is particularly interested in the range and modes of climate variability forced naturally (internally generated, volcanic episodes, solar changes, greenhouse gases) over the last 1,000 years and extending through the Holocene to the Last Glacial Maximum (21,000 years before present). Dr. Otto-Bliesner is chair of the AGU Paleoceanography and Paleoclimatology Focus Group and a member of the scientific steering committees of the Past Global Changes (PAGES) program of the International Geosphere-Biosphere Programme and the Paleoclimate Modeling Intercomparison Project (PMIP). She is also currently serving as a lead author on the IPCC Fourth Assessment report. She received her Ph.D. in meteorology from the University of Wisconsin, Madison.

Neil Roberts is the head of the School of Geography at the University of Plymouth. His main research interests are in Holocene environmental change, especially the lake sediment record of climate and human impact in low-latitude regions such as East Africa and the Mediterranean. Dr. Roberts is a fellow of the Royal Geographical Society and a member of the British Geomorphological Research Group, the British Ecological Society, and the American Quaternary Association. He is the author of *The Holocene: An Environmental History*. Dr. Roberts received his Ph.D. from University College London.

Karl K. Turekian is the Sterling Professor of Geology and Geophysics at Yale University. His research areas include atmospheric geochemistry of cosmogenic, radon daughter, and man-made radionuclides; surficial and groundwater geochemistry of radionuclides; marine geochemistry; and the study of Earth history using radiogenic isotopes. Dr. Turekian is a member of the NAS and a fellow of AAAS and AGU. He is the recipient of the Maurice Ewing Medal of the AGU, the Goldschmidt Medal of the Geochemical Society, and the Wollaston Medal of the Geological Society of London. Dr. Turekian has served on many NRC committees, including the Committee on the Atmospheric Dispersion of Hazardous Material Releases, Committee on Metrics for Global Change Research, Water Science and Technology Board, and Ocean Studies Board. Dr. Turekian received his Ph.D. in geochemistry from Columbia University.

John M. Wallace is a professor of atmospheric sciences and director of the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) at the University of Washington, Seattle. His research, and that of his students, has been directed at improving our understanding of global climate and its year-to-year and decade-to-decade variations, making use of observational data. They have contributed to documenting the existence of El Niño-like variability on a decade-to-decade timescale (e.g., the Pacific Decadal Oscillation) and are currently investigating two analogous patterns of weather and climate variability—the Northern and Southern Hemisphere "annular modes," which have played a prominent role in the climatic trends of the past 30 years. Dr. Wallace is a member of the NAS and a fellow of AAAS, AGU, and AMS. He has served on many NRC committees, including the Committee on the Science of Climate Change, Panel on Reconciling Temperature Observations, and the Climate Research Committee, and he is a current member of the Committee on Strategic Guidance for NSF's Support of the Atmospheric Sciences. He received his Ph.D. from the Massachusetts Institute of Technology.