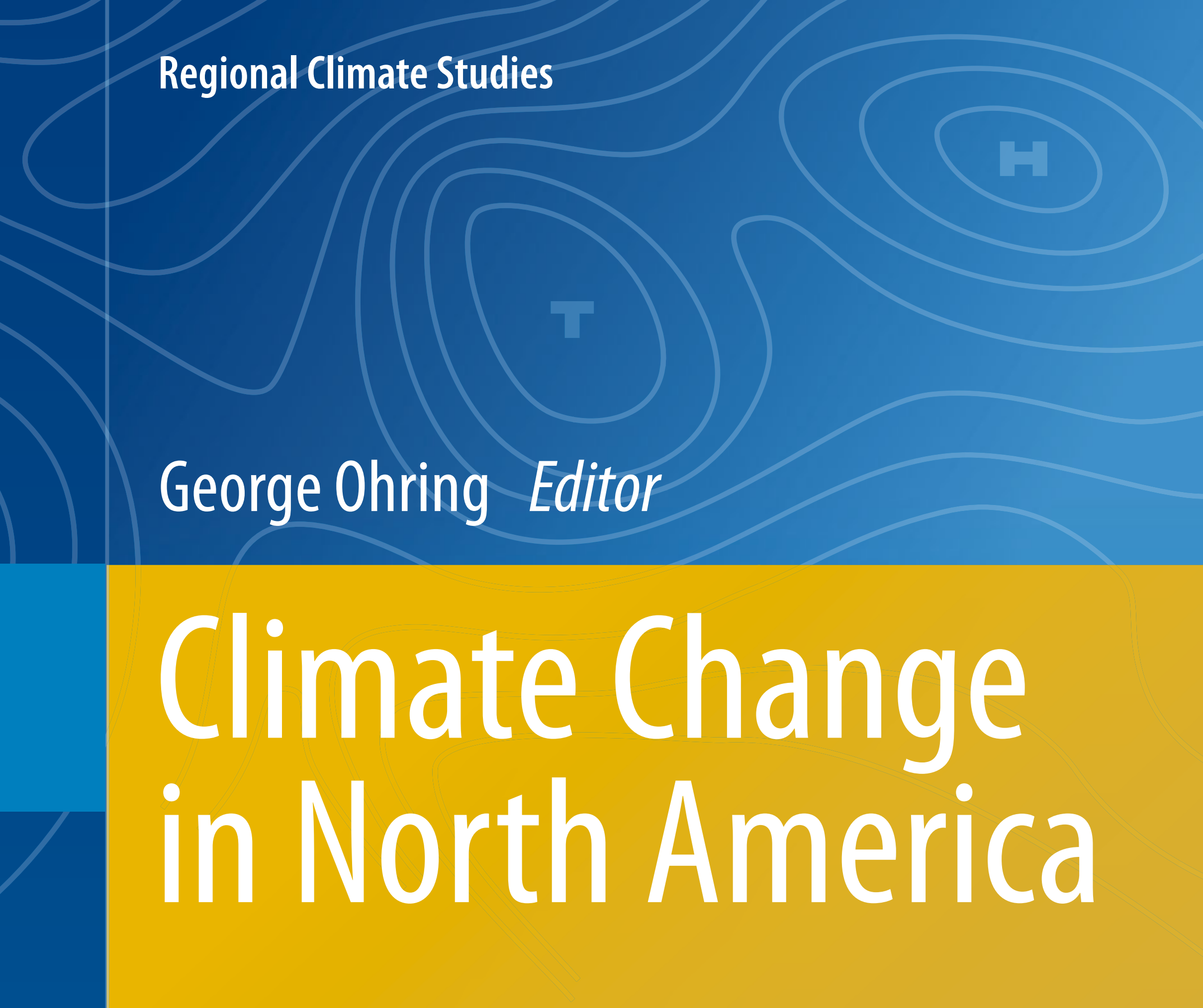
Regional Climate Studies

George Ohring *Editor*

Climate Change in North America



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Regional Climate Studies

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George Ohring
Editor

Climate Change
in North America

Springer

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In memory of Prof. Hans-Jürgen Bolle, a friend, a colleague, and a brilliant physicist (1929–2013)
The Series editor Prof. Hans-Jürgen Bolle has passed away

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Preface

About 10 years ago Hans-Jürgen, M. Menenti and I were talking about the fact that climate in different continents of the world is governed by many more factors other than just their latitudes. The most important of these are the oceans and seas in their neighborhoods. Also, there is the topography of land, changing vegetation cover, etc. Each continent has its own peculiarities and climate change in that region of the world depends on different forcings. These could be changing intensities of monsoons in South and East Asia, hurricanes and tornadoes in the Americas, ups and downs of the jet stream in Europe and around the world, expanding and shrinking of deserts in Africa and China, and finally the coming and going of El Ninõs affecting rainfall all the way from Florida to California on to Australia every 5–10 years. So we approached Springer's Dr. Witchel and presented the idea of publishing a series of books on Regional Climates. The first of these books was on Mediterranean Climate, followed soon after by a detailed text on how Land Surface Processes (can be) Assessed from Space. Hans-Jürgen and I knew enough people around the world to get for example, Dr. Congbin Fu and his colleagues to edit a magnificent book on Regional Climate Studies of China and Dr. von Storch to compile an assessment of Climate for the Baltic Sea Basin. But we didn't forget North America. We approached Dr. George Ohring of NOAA who with his colleagues has produced this text which I hope will be useful as a source for current debate on American Climate.

Unfortunately, Hans-Jürgen Bolle passed away in March 2013 but his memories guided us to the completion of this book as well. I will not be able to carry on with this series alone. I sincerely hope that Springer will find some folks to use the material in these books, complete them on other continents like South America, and tie them together with 50 years of data collected around the globe by satellites and ground measurements and come up with better and deeper insight into Global Climate Change in the future.

NASA Headquarters, Washington, DC
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Introduction

From the Editor's Desk

In August 2009, the President of the United States, Barack Obama, met with his counterparts Mexican President Felipe Calderón and Canadian Prime Minister Stephen Harper, at the North American Leaders Summit in Guadalajara, Mexico. At the conclusion of their deliberations, they issued a Joint Statement that included the pronouncement "We recognize climate change as one of the most daunting and pressing challenges of our time…" and they agreed to work collaboratively to combat climate change.

This is a book about *Climate Change in North America*. As with all books, it has a beginning and an end. It begins about 65 million years ago; it ends some 100 years from now. In between, it tells the story of the changing climate of the continent as revealed by observations and theory.

In the distant past, instruments—thermometers, rain gauges—to observe weather or climate were certainly not available. The climate history of those times—the subject matter of paleoclimatology—is inferred from records of the effects of changing climates on the landforms, flora, and fauna of the Earth. This observational information is supplemented with numerical models based on our theoretical understanding of how the climate system operates. These complex numerical models attempt to incorporate all the physical, chemical, and biological processes controlling the atmosphere and its interaction with the underlying oceans, land, and cryosphere. The models simulate past climates based on the key forcing factors that govern climate over time—for example, variations in solar radiation, atmospheric composition, and volcanism. Over the past few centuries, instrumental measurements, mainly from weather stations, have become increasingly available, and the climate record has become more reliable. And, over the past few decades, measurements from Earth observing satellites have filled in the gaps in the surface observing network and provided information on climate variables not easily accessible from conventional measurements, e.g., sea ice coverage in the Arctic.

When it comes to understanding why the climate has changed and what the climate will be like in the future, *again* one must turn to simulation models. As with the paleoclimatic models, they are integrated over time subject to external forcing factors to construct the climate record. But the external forcings now also include anthropogenic components: greenhouse gas emissions, in particular, carbon dioxide; aerosol pollution; and land-use change.

An online search for “Climate Change in North America” or a search for books on the topic yields a broad mix of publications. They include books focusing on: impacts of climate changes on various sectors of the economy, climate change in a particular geographical area, climate change policy, and climate change and energy. This book is unique in that it includes in one publication the scientific knowledge of climate change in all of North America from paleoclimate to future climate, using both observations and numerical models of the climate.

This book complements two other publications:

1. The reports of the United Nations Intergovernmental Panel on Climate Change, which assess the state of scientific, technical, and socio-economic knowledge on climate change, its causes, potential impacts, and response strategies. Thousands of scientists contribute to the work of the IPCC and their periodic assessments provide the most authoritative information on climate change. The focus is on global climate, whereas this book centers on the regional climate of North America.
2. The National Climate Assessments of the US Global Change Research Program, which are prepared by over 300 contributors. These assessments emphasize the impacts of climate change on economic sectors and particular regions of the US, whereas this book covers all of North America and centers on climate change alone, not its impacts.

Chapter 1 of this book discusses the North American Climate of the past 65 million years, with special emphasis on the last 21,000 years, as revealed by paleoclimatic observations and climate models.

Chapter 2 analyzes weather observations over the past century to develop a picture of more recent climatic trends.

Chapter 3 summarizes what satellite observations, available for only the past three decades, add to our knowledge of recent climate.

Chapter 4 explains how global climate models are used to simulate and project climate, and discusses the application of these models to reproduce recent climate variations and predict future North American climate.

Chapter 5 focuses on the issue of modeling regional climates. Because of relatively poor horizontal resolution, global models cannot provide details of climatic structures below large regional scales. The chapter discusses the basis of various downscaling techniques and the results of applying them to obtain more detail on regional changes in North American climate.

Chapter 6 examines the critical questions of detection and attribution of climate change in North America. Has the climate changed, and, if so, is this due to natural variations or to human activity?

An important question is “What are the uncertainties in our knowledge?” Observational uncertainties of climate trends include possible time-dependent errors (an unknown drifting systematic error, for example) associated with the measurement systems or statistical uncertainties associated with extracting a small long-term trend signal from a noisy (due to shorter term natural variations) climate time series. Uncertainties in climate model results arise from any errors in the representation of climate processes and in the specification of the external forcing factors. As opposed to weather forecast models, whose reliability can be checked often by verifying them against observations, the accuracy of climate models can only be estimated by comparing their simulations of the general features of the prevailing climate and its recent history with the actual climate record. As they are most often used, climate models do not attempt to predict the timing of internal climate variations such as the ENSO cycle; this can complicate the comparison of model projections to observations. Uncertainties also exist in our knowledge of the internal variability of the climate on decadal to centennial scales, which could affect detection and attribution results as well as model projections of future climate.

The authors of the various chapters have attempted to address these uncertainty issues. But, as a former American Secretary of Defense remarked, "There are things we do not know we do not know."

Whom is this book directed at? The content level of the book should be accessible to all climate scientists, to geophysicists in general, to policy makers dealing with climate change issues in North America, and to all students of climate change.

The reports of the Intergovernmental Panel on Climate Change and the US National Climate Assessments aim to develop consensus conclusions from the contributions of over 1,000 scientists to the former and over 300 scientists to the latter. The present book relies on the expertise of its authors, some of whom are participating in the preparation of the IPCC and US national assessments, to review the results in their respective fields, including their own original research.

Each chapter concludes with a list of key findings. The highlights of these key findings are presented below.

Highlights of Key Findings

Paleoclimate

- Climate varies on all timescales, with longer term variations generally larger in magnitude than shorter term ones.
- Climate variations over the past few million years are both progressive (general trends) and recurrent. The principal driver of the recurrent climate variations is the variation in insolation related to changes in Earth's orbit, which are amplified sufficiently to generate glacial–interglacial cycles.

- The hierarchy of controls of the climate of individual locations or regions over the last 21 kyr is clearly illustrated by model simulations. The general trends of North American climate change over this period differ among seasons.
- Continental-scale climate anomalies largely related to insolation forcing are also a principal feature of Holocene (last 12 kyr) climates and include:
  - the development of widespread aridity in the midcontinent, likely related to the direct (through the surface energy and water balances), and indirect (through atmospheric circulation) response to the positive summer insolation anomaly;
  - a concomitant amplification of the North American monsoon;
  - pervasive summertime cooling at high latitudes across North America.
- Over the past millennium, multidecadal and centennial-scale climate variations have occurred, some in response to variations in insolation, atmospheric composition (GHGs and aerosols), and changes in land-use/land-cover, and likely some in response to free or unforced variations. In the case of drought, these variations over the past millennium are larger than those described by the instrumental record, but small relative to those during the Holocene (the past 11,700 years).

Current Climate and Trends Over the Past Century

- Temperature
  - Annual trends in temperature are positive and statistically different from zero for the last 109, 60, and 35 years in Canada, the continental US, and Mexico, and have increased with time. For example, in the US, the trends for the three time periods are 0.07, 0.11, and 0.26 °C/decade.
  - Seasonal temperature trends for all regions and the three time durations discussed are all positive, but not necessarily statistically significant. Within the year, for the entire 109-year period, the positive trends for all seasons and regions are statistically significant, except for the continental US in autumn.
- Precipitation
  - Seasonal and annual precipitation trends are mixed and vary geographically and over different time periods. The most robust trend is a general increase in precipitation in eastern portions of North America over the past full century (1–2 % per decade) and half-century (2–3 % per decade). For North America as a whole, annual precipitation has increased by about 0.7 % per decade over the last century.
  - Precipitation intensity has been increasing in eastern North America, less so in the northwest US, and very little in the US Southwest. The frequency of

  occurrence of heavy precipitation is increasing for event durations from 1 to 20 days, and return intervals for heavy precipitation are decreasing.

- Snow cover
  - Spring snow cover for the entire Northern Hemisphere declined by 7 % in March and 11 % in April from the 1922 to 1970 period to the 1970 to 2010 interval. In March, most of this decrease was contributed by Eurasia, but in April both Eurasia and North America showed significant decreases in areal extent.

Satellite Observations of Climate Trends Over the Past Three Decades

- Atmospheric temperature
  - The North American mid-troposphere warmed at a rate of 0.32 °C/decade and the North American lower stratosphere cooled at a rate of 0.18 °C/decade during the 32-year period from 1979 to 2010.
- Cloudiness
  - During the three decades 1983–2011, North American cloudiness fraction decreased at a rate of about 0.02/decade.
- Precipitation
  - Trends in North American precipitation are not statistically significant over the period of satellite records.
- Insolation
  - Trends in North American insolation over the 1983–2004 period are not statistically significant.
- Snow cover
  - North American snow cover decreased rapidly in the 1970s and early 1980s and gradually increased during the last 20–25 years to values close to the mean value of the 1967–2012 satellite record.
- Ice cover
  - Annual mean sea ice extent in the Arctic has decreased at a rate of about 3 % per decade over the period 1979–2009. But, during the month of annual minimum (September), ice cover has shrunk more rapidly: 13 % per decade from 1979 to 2012.

- Vegetation
  - The most distinct changes in North America in the last 26–28 years are a substantial increase of vegetation in the arctic tundra region and a predominant decrease in the boreal forest zone.

Global Climate Models

- Global climate models capture the primary features of historical observed climate in North America, with some notable limitations.

Aspects of future North American climate change about which there is strong consensus include:

- Temperature
  - Higher temperatures will prevail in all regions and seasons. Warming will vary greatly by region and season, with roughly 2× higher warming in extreme northerly latitudes than in the southern part of North America. Under the SRES A2 high emissions scenario, end of century annual mean warming ranges from 3 to 4 °C in southern North America to upwards of 7 °C in the Arctic.
  - Increases in the frequency of occurrence of previously rare summer temperatures;
- Precipitation, drought, and growing season
  - Annual mean precipitation in North America as a whole will increase modestly, roughly 5 % by mid-century and 5–10 % by end of century.
  - Precipitation changes will vary geographically, with some regions experiencing much greater than average increases, and the Southwest projected to get less precipitation on average.
  - Nearly all regions will experience increases in precipitation intensity and more frequent extreme precipitation.
  - The area affected by drought will increase substantially.
  - There will be widespread increases in growing season length.

Aspects of future North American climate that remain highly uncertain are:

- Change in the overall number of tropical Atlantic cyclones.
- The date by which the Arctic Ocean will be seasonally ice-free.

Downscaling

- On a large region level, the climate changes projected by downscaling techniques are not dissimilar from those produced by global models. However, there is mounting evidence that downscaling does provide additional information—added value—beyond that of the driving large-scale models in topographically complex regions and coastal areas as well as for certain types of extremes (e.g., daily precipitation).
- Comparisons of the methods (e.g., statistical downscaling vs. dynamical downscaling) indicate that they sometimes result in different climate changes.
- Commonalities in downscaled projections of temperature (which in general agree with global models) include:
    - increased temperatures, particularly in winter (although the patterns of increase are more spatially complex over mountainous regions compared to results from global models);
    - increased duration of the growing (or frost-free) season;
    - increase in the frequency of occurrence of extreme temperatures.
- A growing consensus from downscaling results is appearing with respect to some precipitation regimes. For example, recent dynamical and statistical downscaling studies indicate increased rainfall in the northern Pacific Northwest in winter and drying of large areas within the continental interior in summer.

Detection and Attribution

- Human activities have contributed significantly to warming over North America. Over the 1901–2010 period greenhouse gases contributed 1.2–2.4 °C, other anthropogenic forcings contributed −1.4 to −0.2 °C, and natural forcings contributed 0.0–0.1 °C to the observed 1.1 °C North American mean warming trend.
- A significant warming in response to human activities has been identified separately over seven North American sub-regions: Western, Central, Eastern, and Southern North America, as well as Alaska, Canada, and Greenland.
- A detectable human influence has been identified on snowpack, streamflow timing, and other hydrological measures in the western United States, and on the area burnt by forest fires in Canada.

George Ohring

Chapter 1
Paleoclimate

Patrick J. Bartlein, Steven W. Hostetler and Jay R. Alder

1.1 Introduction

As host to one of the major continental-scale ice sheets, and with considerable spatial variability of climate related to its physiography and location, North America has experienced a wide range of climates over time. The aim of this chapter is to review the history of those climate variations, focusing in particular on the continental-scale climatic variations between the Last Glacial Maximum (LGM, ca. 21,000 years ago or 21 ka) and the present, which were as large in amplitude as any experienced over a similar time span during the past several million years. As background to that discussion, the climatic variations over the Cenozoic (the past 65.5 Myr, or 65.5 Ma to present) that led ultimately to the onset of Northern Hemisphere glaciation at 2.59 Ma will also be discussed. Superimposed on the large-amplitude, broad-scale variations from the LGM to present, are climatic variations on millennial-to-decadal scales, and these will be reviewed in particular for the Holocene (11.7 ka to present) and the past millennium.

1.1.1 The Climate System and Its Controls

The *climate system*, a set of coupled environmental systems, whose controls, interactions, state, and variability can be thought of as the subject matter of *climatology*, can be described by a set of external controls, "fast-response" variables that vary with characteristic time scales of seconds to years, a set of "slow-response variables" with characteristic time scales of variation of years and longer,

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and a third set of environmental subsystems that vary in response to climate (Fig. 1.1; Harrison and Bartlein 2012). The external controls that "force" the climate system include *solar radiation* (insolation), which depends on the output of the sun and the Earth's orbital variations that govern the latitudinal and seasonal variations of insolation, and *geodynamics* that influence topography and bathymetry of the globe, and the location and variability of volcanism. The slow-response variables of the climate system include such components as the ice sheets, the deep ocean, the thermohaline circulation of the ocean (otherwise known as the global conveyor belt or AMOC, the Atlantic meridional overturning circulation), and the major reservoirs of global biogeochemical cycles (for example, the terrestrial biosphere and trace-gas composition of the atmosphere). Fast-response variables include those components that are often thought of as weather, such as atmospheric circulation and its control of precipitation and surface temperature, but they also include the characteristics of the land-surface, i.e. snow, ice and water, vegetation, variations in biogeochemistry and the surface layer of the ocean.

Also included in the climate system are the major environmental subsystems, such as the surface hydrology, biosphere, and humans. In general, the state of the climate system can be considered to be governed by a hierarchy of controls and responses in which the external controls force the slow-response variations as in, for example, the way that insolation controls global ice volume and ocean temperatures; the slow-response variables, in turn, force the fast response variables as in, for example, the way that the Laurentide Ice Sheet (LIS) controls atmospheric circulation (see following sections). The fast-response variables in turn govern individual environmental subsystems (Fig. 1.1). This hierarchy of control and response is not strictly unidirectional, inasmuch as the "current state" of the ocean and land surface can ultimately feed back to the slow response variables. The specific roles the individual components play in generating climatic variation is strongly dependent on the time and space scales under consideration. For example, on the longest of time spans considered here, the Cenozoic (65 Ma to present), continental-scale glaciation was controlled by the overall state of the climate, in particular global-average temperature. On shorter time scales, such as the Quaternary (2.59 Ma to present) the volume of ice varied with insolation as its "pacemaker", and the size of the ice sheets can be considered to be a general index of the global climate. On still shorter interannual to decadal time scales, rather than being considered a response variable, the size and shape of the large ice sheets remain constant enough for them to be considered a large-scale control (e.g. of atmospheric circulation). Individual components of the climate system thus may play different roles depending on the time scale and the attendant state of the system—acting as the responses on one time and space scale, but as controls on another. Because, for example, the growth and decay of ice sheets is determined by the balance between accumulation and melting at the surface, those responses lower in the hierarchy, when integrated over time, become the proximate controls of those components higher in the hierarchy of controls and responses.

There are two general approaches for the study of past climate, the reconstruction of past climatic variations from various sources of paleoclimatic evidence,

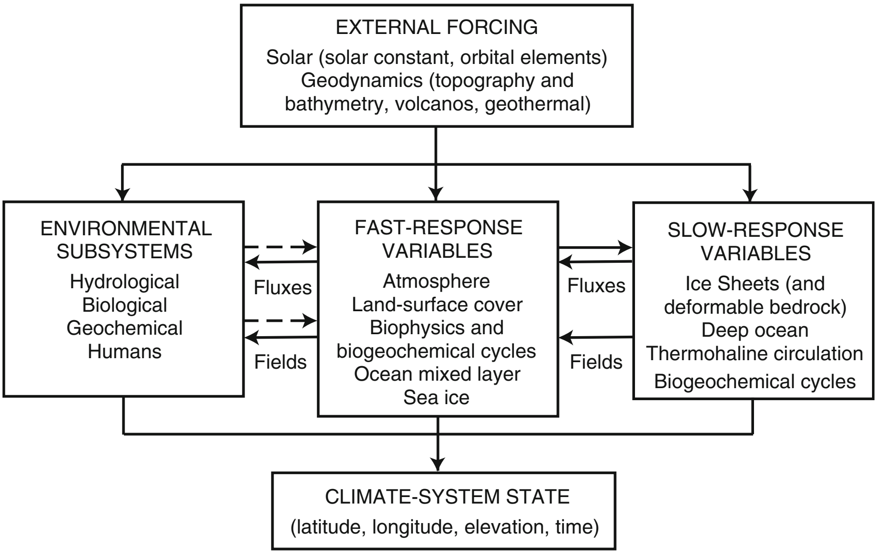


Fig. 1.1 The climate system (after Saltzman 2002; Harrison and Bartlein 2012)

and the simulation of past climates using a range of different kinds of climate models (Bartlein and Hostetler 2004). The two approaches are complementary: paleoclimatic evidence documents what has happened in the past, but it cannot explain the source or mechanisms that caused the variations without invoking some kind of model, either conceptual, statistical or mechanical, whereas mechanistic models can yield such explanations, but only if the models are known to be correct, and this can be evaluated with paleoclimatic data. At first glance, this relationship may appear circular, but it is in fact iterative, because our current understanding of past climates is used to generate hypotheses that can be tested with models, leading in turn to refinements in our understanding of climate and improvements to the climate models, which allows for the development of further testable hypotheses.

1.1.2 Paleoclimate Data Sources

The evidence for past climatic variations is generally provided by environmental subsystems that record the current state of their controls. Paleoclimatic data sources include a range of biological and geochemical indicators retrieved from sediments, as well as direct lines of geomorphic or geological evidence such as the former shorelines of lakes or end moraines of glaciers. The data sources and methods of paleoenvironmental reconstruction are described well in books by Bradley (1999) and Cronin (2010), and are not discussed at length here.

1.1.3 Paleoclimate Models

There are several classes of paleoclimate models (Bartlein and Hostetler 2004). These classes include (a) conceptual models that describe the variability of individual components of the climate system as well as the system as a whole, (b) elemental models that mechanistically describe one or more components, but usually in highly generalized ways, and current-generation "coupled" models that describe several or more individual components of the climate system, including (c) general circulation models of the ocean, atmosphere and terrestrial biosphere (OAVGCMs), and (d) Earth System Models of Intermediate Complexity (EMICs) that do the same at generally reduced spatial resolution and with a more stylized representation of some key components than in GCMs (allowing long simulations with many components to be made), and finally (e) the emerging Earth-System Models (ESMs) that aim to include all of the climatically relevant processes and subsystems that comprise the climate system.

In their application to simulate past climatic variation, the models are supplied with a set of "boundary conditions" or the large-scale controls of climate, such as atmospheric composition, insolation, and the topography of the major ice sheets, and then "integrated" (run) to produce a large number of variables that are consistent with the specified boundary conditions. This procedure in effect mimics in the computer the experiments performed by Nature with the real climate system.

Our focus here will be on the results from a fully-coupled ocean–atmosphere general circulation model (OAGCM) GENMOM (Alder et al. 2011), that are pertinent to North America, and provide a sequence of simulations of a variety of climate variables at 3 kyr intervals from the LGM to present. These new simulations update previous simulations that were performed with models in which ocean temperatures were specified (COHMAP Members 1988) or calculated using a "mixed-layer" ocean (Bartlein et al. 1998) and consequently did not adequately represent key paleoclimatic controls such as the reorganization of ocean circulation.

We also use time series of temperature extracted from a "transient" climate simulation conducted with the Community Climate System Model-3 (CCSM3) (Liu et al. 2009) that was run continuously from 22 ka to present, with "realistic" variations in the controls, in particular the fresh-water forcing responsible for the abrupt climate changes during deglaciation (Clark et al. 2012). These time series illustrate seasonal changes in climate over the past 22 kyr, and also show the regional variations in the expression of abrupt climate changes during this interval.

1.2 Long-Term Paleoclimatic Variations: Cenozoic Cooling and the Onset of Glaciation

The pronounced glacial-interglacial climate variations of the Quaternary, which have played a prominent role in shaping the landscape of North America (both within and beyond the limits of glaciation), represent the culmination of a long period of cooling. Although large in amplitude, the long cooling trend and glacial-interglacial variations have superimposed upon them equally significant variations of climate on millennial-to-interannual time scales.

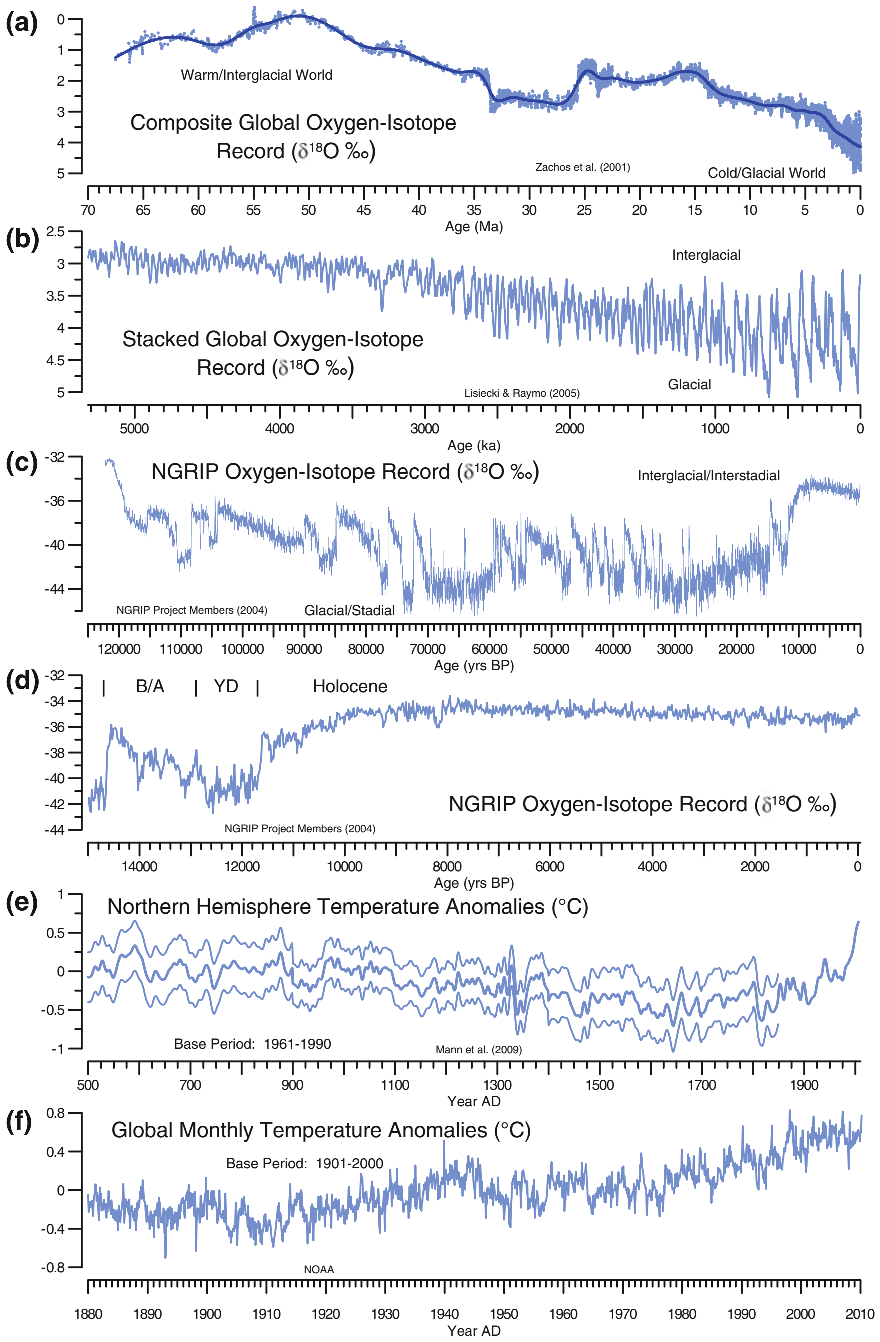
1.2.1 A "Powers-of-Ten" Review of Climate Variability

Climate varies continuously, and although the state of the climate tends to remain within well-defined "corridors" over long periods of time, the concept of an "average" climate is an incomplete one–most of the time the climate system is in one state or configuration, and trending toward another. This style of variation can be seen by examining variations of climate on different time scales by the "powers-of-ten" approach (Fig. 1.2). Although the curves described here represent global climate, climatic variations over North America reflect those of globe. The individual records will also show that there is a limit in resolution in any paleoclimatic record that is a joint function of the intrinsic resolution of a record and of the analysis approaches. Most terrestrial and marine records spanning many thousands or millions of years generally cannot be analyzed at, for example, annual or decadal resolutions because sedimentation rates are limiting (one sample may span hundreds to thousands of years) or because analytical issues may arise (short-term variations may be undetectable using common laboratory and analytical procedures). Likewise, high-resolution records are generally short, owing to interventions in the particular observing system (e.g. annual-resolution dendroclimatic records extend only to the life of individual trees or to those of cross-dated groups of trees).

Over the Cenozoic (the past 65.6 Myrs, Fig. 1.2a), the main change in global climate has been a nearly monotonic trend toward cooler conditions, as indexed by oxygen-isotope values in the composite record from marine sediments shown in the Figure (Zachos et al. 2001). Other modes of climatic variability are evident in the records (Bartlein 1997) including an abrupt (at the time scales described by the curve) event or "spike" in temperatures around 53 Ma, known as the Paleocene-Eocene Thermal Maximum (PETM), several downward "steps" in temperature, such as those around 35 Ma when Antarctica became glaciated, and in the past 5 Myrs accompanying the closure of the Central American seaway.

When that 5 Myr interval is expanded in a "stacked" or composite oxygen-isotope record, again from marine sediments (Fig. 1.2b), the nature of the variability that is superimposed on the Cenozoic trend is revealed (Lisiecki and Raymo 2005), and what appears as a step in the Cenozoic time series is a trend over this 5 Myr interval. As will be described further below, this variability is largely an expression of the response of global climate to orbitally driven variations in insolation. Changes in the variability of climate can also be noted, particularly around 2.5 Ma, and again at 1 Ma. The persistence of these changes in variability demonstrates that the climate of any interval cannot be simply described by only its long-term mean.

Figure 1.2c shows the oxygen-isotope record from the NGRIP (North Greenland Ice Core Project Members 2004) ice core, and expands the last 100 kyr of the


(a)
Composite Global Oxygen-Isotope Record (δ^{18}O ‰)
Warm/Interglacial World
Cold/Glacial World
Zachos et al. (2001)
0
1
2
3
4
5
70 65 60 55 50 45 40 35 30 25 20 15 10 5 0
Age (Ma)
(b)
Stacked Global Oxygen-Isotope Record (δ^{18}O ‰)
Interglacial
Glacial
Lisiecki & Raymo (2005)
2.5
3
3.5
4
4.5
5
5000 4000 3000 2000 1000 0
Age (ka)
(c)
NGRIP Oxygen-Isotope Record (δ^{18}O ‰)
Interglacial/Interstadial
Glacial/Stadial
NGRIP Project Members (2004)
-32
-36
-40
-44
120000 110000 100000 90000 80000 70000 60000 50000 40000 30000 20000 10000 0
Age (yrs BP)
(d)
B/A
YD
Holocene
NGRIP Oxygen-Isotope Record (δ^{18}O ‰)
NGRIP Project Members (2004)
-32
-34
-36
-38
-40
-42
-44
14000 12000 10000 8000 6000 4000 2000 0
Age (yrs BP)
(e)
Northern Hemisphere Temperature Anomalies (°C)
Base Period: 1961-1990
Mann et al. (2009)
1
0.5
0
-0.5
-1
500 700 900 1100 1300 1500 1700 1900
Year AD
(f)
Global Monthly Temperature Anomalies (°C)
Base Period: 1901-2000
NOAA
0.8
0.4
0
-0.4
-0.8
1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010
Year AD

◀**Fig. 1.2** Powers-of-ten depiction of climate variations over the past 65.5 Myrs. (Zachos et al. 2001; Lisieki and Raymo 2005; North Greenland Ice Core Project Members 2004; Mann et al. 2009; Mann et al. 2008), also (f) NOAA (http://lwf.ncdc.noaa.gov/sotc/) The oxygen-isotope curves are plotted such that colder conditions are represented by the low values of each curve and warmer conditions by the high values. **a** Composite Global Oxygen-Isotope Record (δ^{18}O ‰), **b** Stacked Global Oxygen-Isotope Record (δ^{18}O ‰), **c** NGRIP Oxygen-Isotope Record (δ^{18}O ‰), **d** NGRIP Oxygen-Isotope Record (δ^{18}O ‰), **e** Northern Hemisphere Temperature Anomalies and Reconstruction Uncertainties (°C), **f** Global Monthly Temperature Anomalies (°C)

stacked marine record. In addition to the "saw-tooth" pattern of the last glacial-interglacial cycle, the ice-core record reveals the frequent abrupt changes of climate known as the Dansgaard-Oeschger "cycles". (Although repeated, these variations are clearly not truly periodic or even quasi-periodic and so are not cyclical). Figure 1.2d shows an expanded plot of the last 15 kyrs of the NGRIP record, and illustrates the most recent large-amplitude variation of the longer record, and the relatively (in this record) lower amplitude variations of climate in Greenland over the Holocene (the past 11.7 kyr). The cool interval between 12.9 and 11.7 ka, known as the Younger Dryas climate reversal, will be discussed further below. Although the Holocene seems far less variable than the earlier intervals in the NGRIP record, there are still trends and abrupt "events", such as that around 8.2 ka, evident in the record.

Reconstructed Northern Hemisphere temperatures (Fig. 1.2e), (Mann et al. 2009; Mann et al. 2008) exhibit a general high-latitude cooling trend over the past millennium that is present in other records (Kaufman et al. 2009). There is a clear reversal of that trend in the past 200 years, with the commencement of anthropogenic warming (IPCC 2007). Relative to the past 1000 years, and to the Holocene as a whole, this reversal appears more event-like than a change in trend. Global-average monthly temperatures from observations (Fig. 1.2f) show the anthropogenic trend, and also reveal the magnitude of interannual variations of climate, which are larger for individual regions and locations than those in this globally averaged record.

When the individual records are compared with one another, two basic conclusions emerge: (1) the higher frequency variations evident in the shorter records (e.g. Fig. 1.2e, f) are also present over longer time spans, but the resolution and the nature of the longer-term records complicate their detection and (2) higher-frequency variations are contingent on the long-term changes in the climate system that are represented by the longer term, lower-frequency records.

1.2.2 The Last 3 Million Years and the Onset of Glaciation

The onset of Northern Hemisphere glaciation around 2.65 Ma was a major transition of climate that marks both the beginning of the Quaternary and the beginning of the repeated climate variations that have shaped both the landscapes and biota of North America (Lisiecki and Raymo 2005), Fig. 1.2b. Although there were likely regional areas of glaciation in North America prior to this time that also

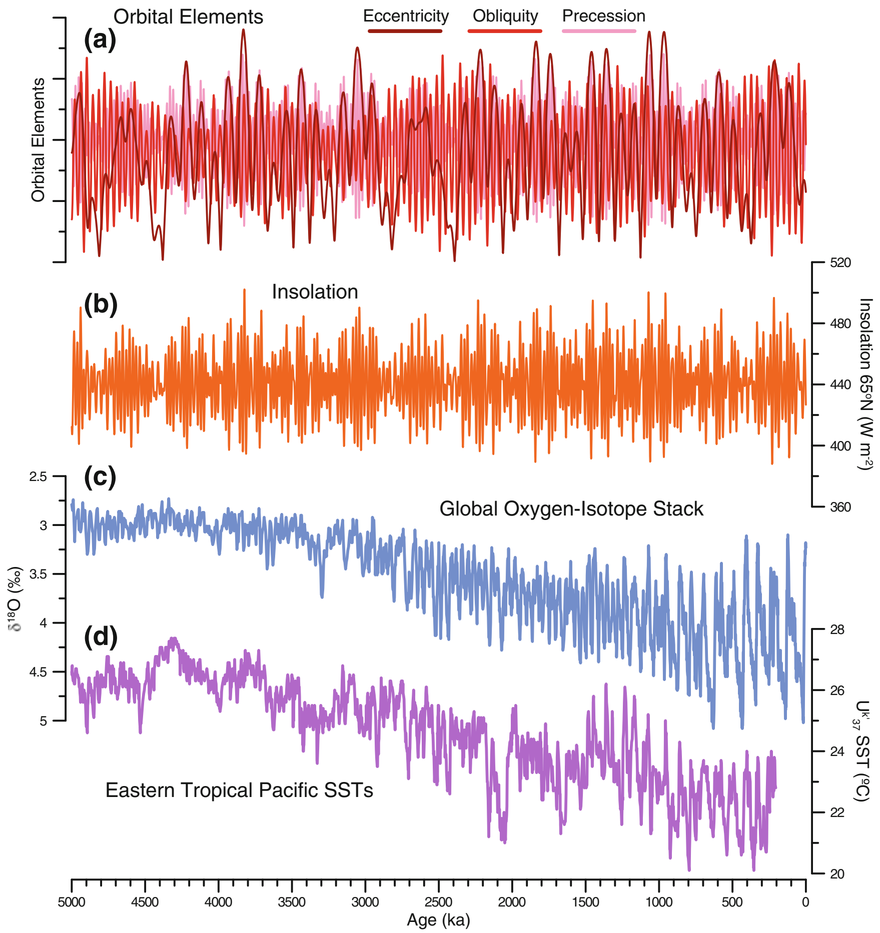


Fig. 1.3 The last 5 million years. **a** orbital elements (Berger and Loutre 1991); **b** July insolation at 65 N; **c** global oxygen-isotope record stack (Lisiecki and Raymo 2005), **d** eastern tropical Pacific alkenone SSTs (Lawrence et al. 2006). The two marine records show the trend toward cooler conditions, the steeper transition around 2.5 Ma signaling the onset of Northern Hemisphere glaciation, as well as the change in variability of the series. The insolation record (and the orbital elements that determine it), does not show the transitions or trends in the observations, but clearly shows its role in pacing the climatic variations

varied in concert with insolation (see Cronin (2010), Chap. 4 for review), after 2.65 Ma there were repeated large-scale glaciations of North America, varying first primarily on the 41 kyr time scale of obliquity (Fig. 1.3) from 2.65 Ma to around 1 Ma, and thereafter on the 100 kyr cycle of eccentricity (See Harrison and Bartlein (2012) for a discussion of orbital time-scale variations in insolation, including the variations in month and season lengths related to variations in Earth's orbit.).

Global and regional climates (Fig. 1.3c, d) both show substantial variation on the timescales of the orbital elements, but the onset of glaciation is difficult to attribute to a particular pattern of insolation variations, and instead is likely related to progressive changes in other controls of climate, in particular the long-term decrease in atmospheric CO_2 levels during the Cenozoic (Beerling and Royer 2011), and to geodynamic variations, such as the closure of the “Panamanian Straits” (Haug et al. 2005; Haug and Tiedemann 1998). The general decrease in CO_2 levels and associated change in radiative forcing favors glaciation through direct and indirect influence on surface temperatures. Changes in ocean circulation accompanying the uplift of the Isthmus of Panama, which reduced the amount of heat transferred from the tropical Atlantic to the Pacific, supported glaciation in a counter-intuitive way—a warmer tropical Atlantic would have resulted in greater transport of warm water and water vapor to the circum-North Atlantic region, thereby increasing snowfall in the regions where the large Northern Hemisphere ice sheets develop.

That insolation variations pace the paleoclimatic variations on orbital time scales is clear; however, the specific mechanisms that implement that pacing remain unknown, despite over a century-and-a-half of research, except that it is evident that the climate system must include mechanisms for amplifying insolation and other forcing (Harrison and Bartlein 2012; Kohler et al. 2010), and for generating the characteristic 41 and 100 kyr variations of ice volume (Ruddiman 2006; Abe-Ouchi et al. 2013). A succinct review of some of the many hypotheses that have been advanced is provide by Table 5.1 in Cronin (2010).

The influence of insolation variations is not limited to the regular pacing of the growth and decay of ice sheets; the variations also force orbital-time scale variations of land–ocean temperature contrast, and hence modulate monsoonal circulation systems and associated mid-continental moisture levels. Even in the absence of large ice sheets, climatic variations have occurred on orbital timescales, and considering that the monsoon regions encompass global areas more extensive than glaciated regions, orbital time-scale variations of climate independent of glaciation should be considered the principle mode of climate variability on times scales from thousands to millions of years. These non-glacial, insolation-driven variations are easily illustrated using the Holocene record of climate change of North America, which will be discussed later.

An important perspective provided by the record of climatic variations over the past few million years is that climate changes are both progressive and recurrent. Over this interval, the long-term mean state exhibits gradual cooling together with an increase in amplitude of the variation, with warm, interglacial intervals cooling less than the cold, glacial intervals. On top of these progressive changes are repeated and rapid (on this time scale) glacial/interglacial variations. Although recurrent, the climate variations within a given cycle are not identical with those of other cycles (nor in detail are the driving insolation variations), so while the individual cycles broadly resemble one another, they are not exact replications. One consequence of the recurrent nature of the orbital variations is that the terrestrial and marine biospheres (including both plants and animals) must have evolved in way that lets them respond to the high-amplitude orbital variations with only occasional extinctions (Bartlein and Prentice 1989; Bennett 1997).

1.3 The Last Glacial Cycle: Orbital Time-Scale Variations and Abrupt Climate Change

The last glacial cycle spans the interval from around 130 ka to present, and paleoclimatic records show orbital time-scale variations and abrupt variations on shorter time scales (Fig. 1.4). Figure 1.4 shows a selection of long paleoclimatic time series from around North America, as well as January and July insolation anomalies (differences from present) at 45°N (Berger 1978), and the SPECMAP (Imbrie et al. 1992) stacked-and-smoothed record of marine oxygen-isotopic variations as an index of global ice volume (plotted on an inverse scale, with warm, less-ice conditions at the top, and cold, more-ice conditions at the bottom).

1.3.1 The Previous Interglacial to the Holocene

The previous interglacial period in North America, known as the *Sangamon*, and equivalent to the European *Eemian* (both outmoded, but frequently used terms arising from the now obsolete idea that there were four glacial stages, separated by interglacials, on both continents) is equivalent to marine oxygen-isotopic stage 5e (MIS-5e, 128–122 ka). The July (boreal summer) insolation and global ice-volume records illustrate two of the major controls of regional climates over the past glacial-interglacial cycle (see the next section) and they serve as well as a general index of global climate. Northern Hemisphere summers during the previous interglacial were likely warmer than those of the present interglacial (the Holocene, i.e. 11.7 ka to present), owing to the greater northern summer insolation then, as well as sufficiently reduced global ice volume (relative to the current interglacial) to create global sea levels that were 6 m higher than present (Overpeck et al. 2006; Anderson et al. 2006). From the previous interglacial to the Last Glacial Maximum (LGM), (26.5 to 19 ka; Clark et al. 2009) global climate cooled in stages, with increases in ice corresponding to falling levels of July insolation, and slight decreases accompanying increases in July insolation.

Paleoclimatic records from around North America, including the NGRIP ice-core record from Greenland (North Greenland Ice Core Project Members 2004), North Atlantic (Wolff et al. 2012) and Caribbean (Schmidt et al. 2004) sea-surface temperature (SST) records, Santa Barbara Basin oxygen-isotope and marine taxon records (Hendy and Kennett 2003; Hendy et al. 2002) and pollen records from Utah (Jiménez-Moreno et al. 2008) and Florida (Donders et al. 2011a; Grimm et al. 1993) are all either dominated by or reflect to some extent the general trends of insolation and ice volume, a pattern that is typical of paleoenvironmental records that extend over this interval (Webb and Bartlein 1992; see also Whitlock and Bartlein 1997).

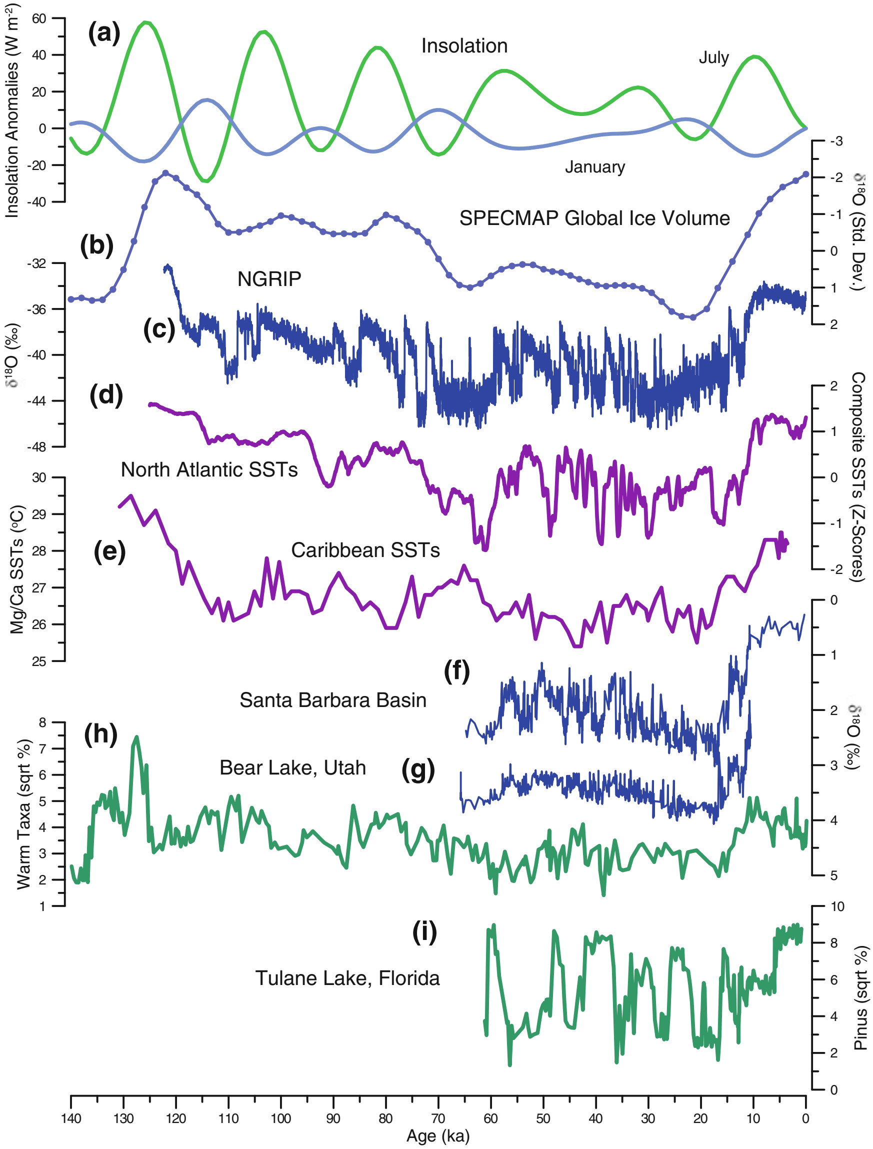


Fig. 1.4 Representative time series that span the past 130 kyr—the last glacial/interglacial cycle. **a** insolation in January and July at 45°N (Berger and Loutre 1991); **b** global ice volume (Martinson et al. 1987); **c** NGRIP oxygen-isotope values (North Greenland Ice Core Project Members 2004); **d** a stack of North Atlantic SST records (Harrison et al., in prep); **e** Caribbean SSTs (Schmidt et al. 2004); **f**, **g** Santa Barbara basin oxygen-isotope values (Hendy and Kennett 2003; Hendy et al. 2002); **h** Bear Lake, Utah pollen data (Jimenez-Moreno et al. 2007); **i** Tulane Lake, Florida pollen data (Donders et al. 2011b)

1.3.2 Abrupt Climate Changes

The most striking features of the individual records shown in Fig. 1.4, however, are the many abrupt changes of climate with amplitudes that often exceed more than half of the total range of variation between full glacial and interglacial conditions. This is best illustrated by the NGRIP oxygen-isotope record, which approaches annual resolution throughout (North Greenland Ice Core Project Members 2004). During the interval from 80 ka to around 15 ka, around 25 individual fluctuations, known as Dansgaard–Oeschger (D-O) "cycles" occurred (although the individual fluctuations vary considerably in duration and are therefore not really cyclical; Sanchez Goñi and Harrison 2010). The origin of these fluctuations is likely related to variations in AMOC, and its influence on ocean heat transport, initiated by freshwater discharges to the North Atlantic. However, like the orbital variations, the specific mechanisms involved in the response have yet to be fully articulated (Wolff et al. 2010). The individual fluctuations have a characteristic sawtooth-curve shape, with abrupt warming steps, followed by gradual cooling over varying time spans (Fig. 1.4).

Variations in terrestrial (Jiménez-Moreno et al. 2010) and marine (e.g. Hendy and Kennett 2003; Hendy et al. 2002) conditions are evident around North America, and their expression in paleo records depends chiefly on the resolution of the records—those that have sampling resolutions of a few decades or less typically show these abrupt changes, although there are also some spatial variations in the expression of the fluctuations that will be illustrated below.

The most recent abrupt change—and the last during glacial times—is the Younger Dryas climate reversal (YDCR) that is characterized by a cooling trend beginning around 14.5 ka with more rapid intervals of cooling around 13.5 and 12.9 ka, and was terminated by abrupt warming around 11.7 ka (Alley et al. 2003; Steffensen et al. 2008). Like the earlier D-O cycles, the YDCR is expressed in terrestrial records from North America (Shuman et al. 2002; Shuman 2012) and also like the earlier fluctuations, the genesis of the YDCR has been related to the shutdown of the AMOC, in particular by the rapid drainage of Lake Agassiz and other proglacial lakes (in the midcontinent at the southern edge of the ice sheet) and the consequent flow of fresh water to the Atlantic (Carlson et al. 2007; Liu et al. 2012). Alternative explanations for the YDCR are that it was forced by outflow of the proglacial lakes along the LIS into the Arctic Ocean by way of the Yukon (Condron and Winsor 2012; Teller 2012), which is still consistent with the idea of an AMOC shutdown, or that it resulted in some way from the impact of an extraterrestrial object (Firestone et al. 2007).

Many of the individual lines of evidence claimed to support this latter explanation have been difficult to reproduce (Pinter et al. 2011; Boslough et al. 2012) or have much simpler alternative explanations (Marlon et al. 2009; Carlson 2010) but perhaps the main challenge for the impact mechanism is that it is simply unnecessary—abrupt climate changes like the YDCR occur throughout the record, and large climate reversals at the beginning of interglacial intervals are features of

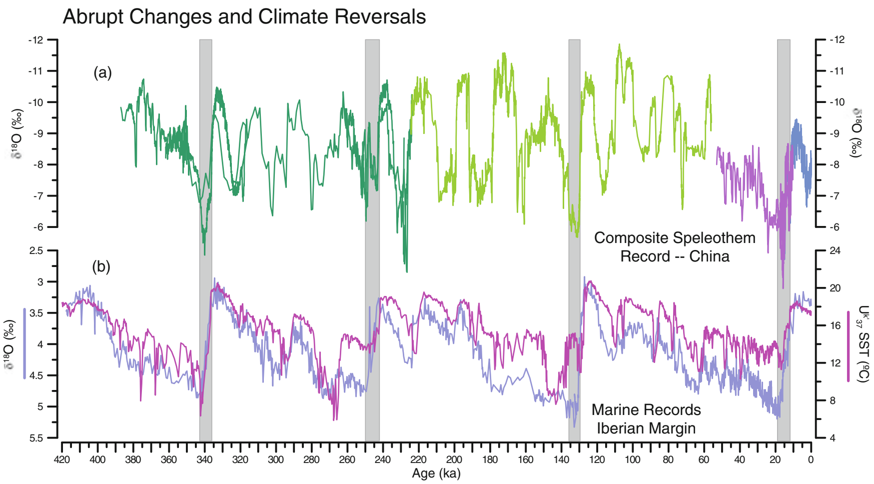


Fig. 1.5 Abrupt climate changes during the past four glacial/interglacial cycles. **a** composite speleothem oxygen-isotope record from China (Cheng et al. 2009); **b** marine records from the Iberian Margin (North Atlantic; Martrat et al. 2007). The records show that the abrupt climate changes like the Yonger Dryas Climate Reversal (YDCR) that occurred during the last glacial/ transition are ubiquitous in previous deglaciations, and therefore do not require special explanations

earlier deglaciations. Figure 1.5 shows two records of sufficient length to span several glacial/interglacial cycles and sufficient resolution to record abrupt climate changes: a composite speleothem oxygen-isotope record from China (Cheng et al. 2009). and a temperature and oxygen-isotope record from the North Atlantic (Martrat et al. 2007). Although not specific to North America, there is nothing to suggest that the climatic variations shown in the these records are regionally unique or idiosyncratic (compare Figs. 1.4 and 1.5), and it is likely that abrupt climate changes like those in China and the western Atlantic also occurred during earlier glacial-interglacial variations in North America. These records clearly show that abrupt climate changes during the last glacial/interglacial cycle are not unprecedented, and that YDCR-like fluctuations often occur at glacial terminations (Broecker et al. 2010), eliminating the need for an exceptional or special explanation for the YDCR.

1.4 The Last Glacial Maximum to Present

Between the Last Glacial Maximum (LGM) and present, the climate system as a whole, and North America in particular experienced a range of climates as large as any that occurred during the past 2.65 Myr. The scope of these variations and the changes in the large-scale controls of climate that generated them provide a set of

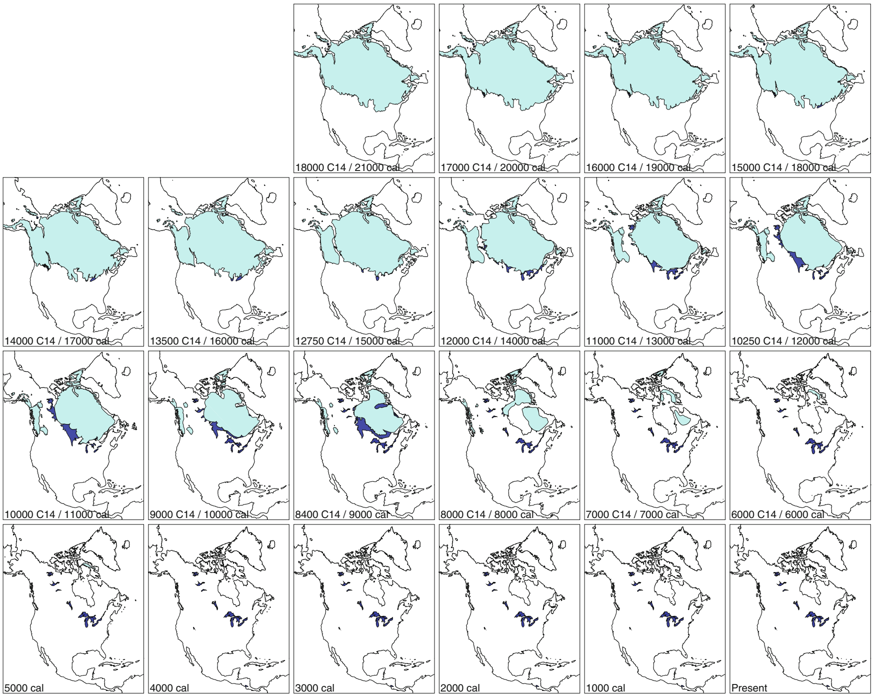


Fig. 1.6 Deglaciation of North America (after Dyke 2004), with continental outlines inferred from data in Peltier (2004)

"natural experiments" that can be exploited through the comparison of climate-model simulations and paleoclimatic data syntheses. Such "data-model" comparisons can lead to mechanistic explanations for patterns recorded by the data and can also be used to test the climate models. Although such an approach may seem to be circular it is actually iterative, with one generation of data-model comparisons leading to refinements of the hypotheses and the overall experimental design and to the identification of particular features of climate that are well or poorly simulated by the models (Harrison and Bartlein 2012; Harrison et al. 2013).

1.4.1 Boundary Condition Changes Over the Past 22 kyr

The most obvious control of regional climate changes in North America since the LGM is the LIS (Fig. 1.6). At 21 ka, the ice sheet stretched from the Aleutians to southeastern Canada, and extended into the northern tier of states south of the U.S./ Canada border (Dyke 2004), and at the same time, global sea level was ~120 m lower than present, exposing the continental shelves in general, and the Beringian land bridge in particular. As the ice sheet retreated over time, large fresh-water

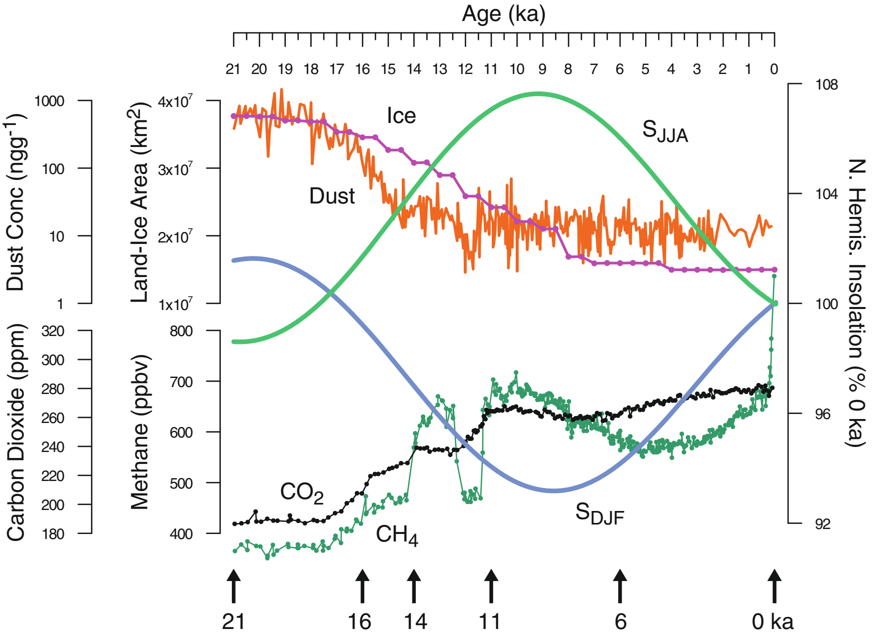


Fig. 1.7 Boundary conditions for climate-model simulations from the LGM to present (redrawn from Harrison and Bartlein 2012)

(proglacial) lakes formed along the southern margin, where Lake Agassiz attained its maximum size between 12 and 9 ka. By 8 ka, the LIS had disintegrated enough to open the present-day Hudson Bay, and the last remnants of ice (excluding present-day ice on Baffin Island and Greenland) melted just after 6 ka.

On longer (orbital) time scales, the volume and area of the ice sheets can be regarded as "dependent" or internal variables in the climate system. On shorter time scales, ice sheets change slowly enough to be considered as an external control of climate, in much the same way that Antarctica controls Southern Hemisphere climate today. Concentrations of GHGs and aerosols in the atmosphere, like the ice sheets, changed slowly enough on the time span of the last 22 ka so that they can also be regarded as controls as opposed to responses, (Fig. 1.7). The one major control of climate that is truly external over all timescales is the latitudinal and seasonal distribution of insolation. Over the past 21 kyr, summer insolation in the Northern Hemisphere gradually increased as a consequence of the shift of perihelion into the northern summer (a consequence of the variations in precession), and the greater obliquity then. Summer insolation peaked around 10 ka and decreased thereafter toward the present day. Winter insolation showed the opposite behavior over the interval from 21 ka to present.

Together, the changing boundary conditions provide a set of somewhat idealized experiments in which some controls differ from present while others are nearly the same as today (Fig. 1.7). For example, around the time of the LGM