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Modeling Earth System Changes of the Past

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Introduction

The earth's climate and related components of the earth system have always been changing and will no doubt continue to change. The earth system has a past and a future. The state of the earth system of the future is unknown, but major efforts are under way to estimate the changes that may be associated with increases of greenhouse gases. Until fairly recently the state of the earth system during the past has only been described qualitatively. This situation is now changing. New and more detailed and accurate information is available from analyses of historical records and from environmental records that provide accurate annual dating, such as tree rings, laminated lake or ocean sediments, glacial ice, and coral. Although lacking annual time-scale resolution, new observational techniques are also being used to obtain long-term environmental records from soils, other lake and deep ocean sediments, and ice strata. These records are accurately dated by radiometric methods and are being obtained worldwide, so that near global coverage is possible. As a result, we are gaining detailed information about the evolution of the atmosphere and ocean, of shifts of continents and rise and fall of mountains, and of the wax and wane of ice sheets, forests, lakes, and deserts.

This wealth of new knowledge has in turn activated efforts to simulate climates of the past with the aid of climate models. These modeling studies serve a number of purposes. First, modeling studies help us identify potential causes of climatic change by testing the sensitivity of the model's climate to changes in external forcing or orographic and geographic boundary conditions. For example, the possible sensitivity of climate to changes of earth's orbital parameters was suggested more than a century ago (Croll, 1864), but the idea received serious consideration only decades later when quantitative estimates of the climatic effects of the orbital changes were made with the aid of a zonal-average energy budget climate model (Milankovitch, 1920). Second, modeling studies help us explore the internal mechanisms of climate change, such as the coupled interactions of the atmosphere, oceans, ice sheets, and biosphere as the climate shifts between glacial and interglacial states. Third, comparisons of the results of simulations of past climate with observations of past climate help us evaluate the adequacy and accuracy of climate models.

This review outlines some of the challenging problems to be faced in understanding the causes and mechanisms of large climatic changes and gives examples of initial studies of these problems with climate models. The review covers climatic changes in three main periods of earth history: (1) the past several centuries, (2) the past several glacial-interglacial cycles, and (3) the past several million years. The review will concentrate on studies of climate but, where possible, will mention broader aspects of the earth system.

All of the modeling studies described here are called climate sensitivity experiments. In such experiments, we analyze the response of a climate model (and up to now an incomplete climate model) to some known or hypothetical change in forcing. Qualitative comparisons of the modeled outcome with observations help to evaluate the possible importance of the change in forcing for explaining the observed climatic change. Climate sensitivity experiments have proven to be very helpful for identifying causes and mechanisms of climate change. Alternatively, if all external and surface boundary conditions are properly prescribed and if the model is an appropriately complete representation of the coupled climate system, then the studies are called climate simulation experiments. In climate simulation experiments, the model results should agree rather closely with the geologic evidence, provided, of course, that both the model and the geologic estimates are accurate. Achieving this level of climate simulation experimentation remains largely a task for the future.

Studies of past climates use a broad range of models. Atmospheric general circulation models (AGCMs) or AGCMs coupled to ocean mixed-layer models are being used to explore the full three-dimensional structure of past climates, including details of the hydrologic cycle. However, the extensive computing resources required for AGCMs have precluded, until now, very long simulations. For similar reasons, extensive work with fully coupled AGCMs and ocean general circulation models (OGCMs) remains largely a task for the future.

Simplified climate system models, such as energy budget models, are often used to explore the long-term evolution of climate.

This chapter is limited to a brief introduction to climate sensitivity experiments pertinent to the study of past climates; more comprehensive overviews are in Saltzman (1985, 1990). Frakes (1979) and Crowley (1983) provide excellent and concise summaries of the geological records of climatic change. Both observations and model studies are treated extensively in the report of the 1989 Global Change Institute (GCI) on Global Changes of the Past (Bradley, 1991a) and in Crowley and North (1991). This chapter draws extensively on material from the 1989 GCI report.

Changes of the Past Several Centuries

The environmental records of the past several centuries have the potential to provide detailed information about the natural decade- to century-scale variability of the earth system. Environmental records are available from historical accounts, tree rings, annually laminated lake or ocean sediments containing fossil pollen or planktonic records, high-resolution ice cores, coral, and mountain glaciers (Bradley, 1991b).

One example of the kind of information forthcoming from these records is illustrated in Figure 1, where the $\delta^{18}O$ records from a north-south transect of ice cores show the centuries-long Little Ice Age event that existed from about A.D. 1550 to 1850–1900 (Thompson, 1991). While many independent records corroborate this evidence for a cold period, detailed regional analyses of decade- to century-scale changes of climate are possible only for North America, Europe, and East Asia (Hughes, 1991). These regional analyses are derived primarily from tree-ring and historical records and provide estimates of temperature and precipitation, drought frequency, and other climatic extremes. What is needed now is a synthesis of existing spatial and temporal records that will allow regional or continent-wide analyses in some areas and also highlight those areas where more work needs to be done (Hughes, 1991).

Although records of the climate of the Little Ice Age are incomplete, the global average temperature of recent decades is estimated to be perhaps 0.4–0.5°C higher than it was during the Little Ice Age. It would be of great interest to know the cause of this recent century-scale warming. The cooling and subsequent warming marking, respectively, the onset and the termination of the Little Ice Age must be part of a natural climatic cycle, because events like the Little Ice Age occur in records from previous millennia. However, this most recent century-scale warming may also have been influenced by the

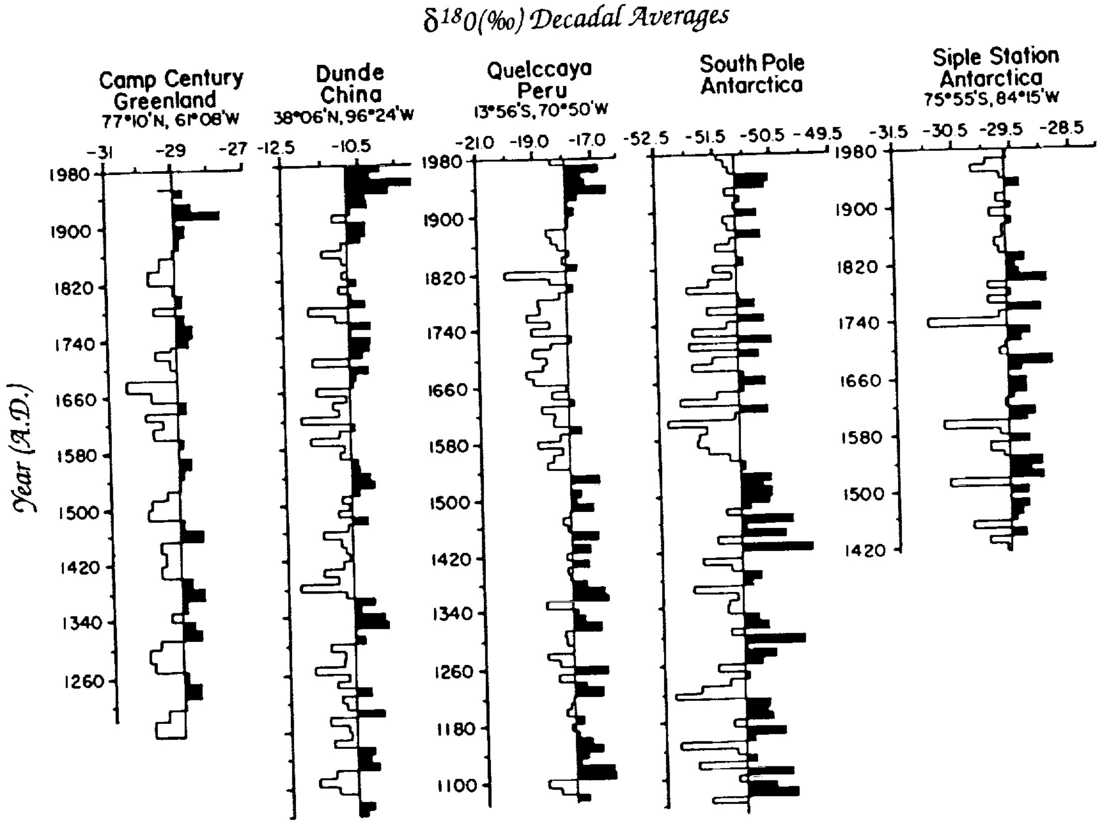


Figure 1. Decadal averages of the $\delta^{18}O$ records in a north-south global transect from Camp Century, Greenland, in the north to the South Pole. The shaded areas represent isotopically less negative (warmer) periods and the unshaded areas isotopically more negative (colder) periods relative to the mean of the individual records. Values shown with reference to the long-term mean at each station for the periods shown (from Thompson, 1991).

increasing concentration of greenhouse gases which grew from preindustrial levels of about 270 ppmv to 350 ppmv at present.

Are decade- to century-scale changes of climate the result of internal oscillations of the coupled system (atmosphere, ocean, ice, etc.), or are they triggered, at least in part, by external changes? Overpeck (1991) has summarized various hypotheses for explaining the occurrence of the Little Ice Age. Two "external" mechanisms suggested frequently are increased volcanic aerosols and decreased solar irradiance (Schneider and Mass, 1975; Hansen and Lacis, 1990). Examples of internal mechanisms that might be associated with longer-term climate changes are natural oscillations of the ocean or of the coupled ocean-atmosphere-cryosphere system.

Major volcanic eruptions produce small decreases in land surface temperature that persist for one or more years following the eruption (Hansen et al., 1978; Rampino et al., 1988; Bradley, 1988). Observations of recent eruptions, such as El Chichon, are helping to calibrate the relationship between eruptions, increased stratospheric aerosol loading, decreased solar radiation reaching the surface, and lowered temperature. At somewhat longer time scales, Porter (1986) has found that Northern Hemisphere glacier advances of the past two centuries appear to follow closely after major volcanic eruptions as recorded in the Greenland ice sheet acidity profile. Conversely, glacier retreats during an earlier warm period (A.D. 1100–1200) occurred at a time of decreased acidity in Greenland ice. Although acidity records in ice cores are a useful qualitative index of volcanic activity, allowance must be made for the effect of the distance of the erupting volcano from the ice sheet on the acidity level in the core. If such bias errors could be removed, then acidity records would be even more useful as a quantitative global index of volcanic activity.

Experiments with AGCMs or coupled models could be used to test climate sensitivity to externally imposed stratospheric volcanic aerosol loadings. These kinds of experiments have not been used extensively, perhaps because of uncertainties about the chemical and radiative properties of the aerosol and its likely vertical and horizontal distribution. However, Wigley (1991) used a simple global average energy balance climate model to illustrate that a Little Ice Age–scale temperature reduction on the order of 0.4°C would require 20 eruptions the size of the Krakatau event: one every 5 years for 100 years. He assumed that a Krakatau-size eruption had an aerosol loading effect equivalent to a 2% reduction in solar irradiance. The size of the temperature response depends, of course, on the climate sensitivity of the model. Because there is no evidence for so many large eruptions, Wigley concluded tentatively that volcanic eruptions alone are not likely to explain fully the observed temperature lowering during the Little Ice Age.

Solar variability has also been proposed as an external cause of climatic change on the decade to century time scale (Eddy, 1976; Eddy et al., 1982). For example, the coldest periods of the Little Ice Age correspond approximately to extended periods of sunspot minima. However, the possible magnitude of variations in solar irradiance has until recently been unknown. Over the past decade, radiometric observations from satellites have documented that the total solar irradiance decreased by about 0.1% between the sunspot maximum in 1981 and the minimum in 1986. Foukal and Lean (1990) have used the recent radiometric data to develop an empirical model of total solar irradiance variation between 1874 and 1988, and this time series is now available for climate studies.

For many years prior to the era of satellite measurements, the evidence for longer-term solar variability came primarily from observations of sunspots or auroras. Now, two other independent lines of evidence are available, $\delta^{14}C$ records from tree rings and ^{10}Be concentrations in ice cores (Stuiver and Braziunas, 1991; Beer et al., 1988). Both ^{14}C and ^{10}Be variations are produced by variations in cosmic ray flux, and the cosmic ray flux varies due to changes in the solar wind or earth's magnetic field. The two radioisotopic records agree fairly well with each other, and with historical records of sunspot number. This agreement offers encouragement that a reliable index of solar variability covering the past several centuries may be achievable.

Wigley and Kelly (1990) have used a simple energy budget climate model to estimate the solar irradiance reduction required to produce a Little Ice Age–scale global average temperature reduction of 0.4°C. In their model, the required irradiance reduction is between 0.2 and 0.5%, depending again upon the assumed climate sensitivity coefficient for the model. These hypothetical irradiance changes are small, but nevertheless significantly larger than recent measurements of total solar irradiance variability over the 11-year sunspot cycle. Therefore, if solar irradiance changes played a major role in producing the cooling of the Little Ice Age, or the subsequent warming into the 20th century, then either those solar irradiance changes were larger than the shorter-term (11-year-cycle) changes observed recently with satellites, or the model's sensitivity is too small.

Borisenkov et al. (1985) calculate that there are additional small perturbations (on the order of 0.05%) of the latitudinal and seasonal solar irradiance associated with an 18.6-year period of nutation of earth's rotational axis. There are also very small seasonal trends (on the order of 0.1% per century) associated with the slowly changing Milankovitch cycles (see following section).

In summary, climate sensitivity experiments with energy budget climate models suggest that external forcing changes associated with volcanic activity or solar irradiance would have to be larger than is now indicated by observations in order to explain fully the cause of the Little Ice Age. Nevertheless, and in view of all the uncertainties, changes in volcanic and solar activity remain candidates for producing climate variability on the scale of decades to centuries. Further experimentation with external forcing changes is needed, especially with AGCMs and coupled models incorporating feedbacks associated with components of the climate system not explicitly calculated in energy balance climate models. Improved data sets of decade- to century-scale climate change and accurate measures of volcanic and solar variability are also needed.

While this section has focused on possible external factors that might cause decade- to century-scale climate change, the internal operation and oscillations of the climate system could also be responsible for climate change, or could amplify or modify the effects of external changes. There is considerable evidence, particularly in the Atlantic, that the oceans are strongly involved in these decade- to century-scale variations. Long records of sea ice (Mysak et al., 1990) and salinity (Dickson et al., 1988) show decade- or century-scale variability, and model studies illustrate the possibility of long-term variability in the thermohaline circulation (Bryan, 1986; Manabe and Stouffer, 1988). Isotopic records recovered from corals show promise of providing long decade- to century-scale records of El Niño–Southern Oscillation events (Cole and Fairbanks, 1990).

Changes of the Past Several Glacial-Interglacial Cycles

Observational studies have shown that variations of earth's orbital parameters are pacemakers of glacial-interglacial cycles (Hays et al., 1976) and of wet-dry cycles in the tropics (Rossignol-Strick, 1983; Prell, 1984; Prell and Kutzbach, 1987). A significant fraction of the variance in time series of the estimated volume of glacial ice and indicators of temperate-latitude vegetation and tropical monsoons is phase-locked with the orbital cycles. Illustrations of this kind of phase-locking are in Figure 2.

The discovery that large climatic changes are apparently paced by relatively small changes in the earth's orbital parameters presents a major opportunity and challenge: namely, to analyze and explain the processes and feedbacks that produce the observed large climatic response to the precisely known changes in external forcing that modify the seasonal and latitudinal distribution of insolation. If we are successful, we will have learned a great deal about the internal workings of the climate system. Variations of the earth's orbital parameters include changes in the axial tilt (range, 22 to 24.5 degrees; period, about 41,000 years), season of perihelion (range, all times of the year; period, about 22,000 years), and orbital eccentricity (range, 0 to 0.06; period, about 100,000 years). In this section, several topics related to these orbital changes and climate modeling studies are reviewed.

6000–9000 Years Ago

A recent time of substantially altered orbital parameters was around 6000 to 9000 years ago (6–9 ka), when perihelion was reached during northern summer (it is now reached in northern

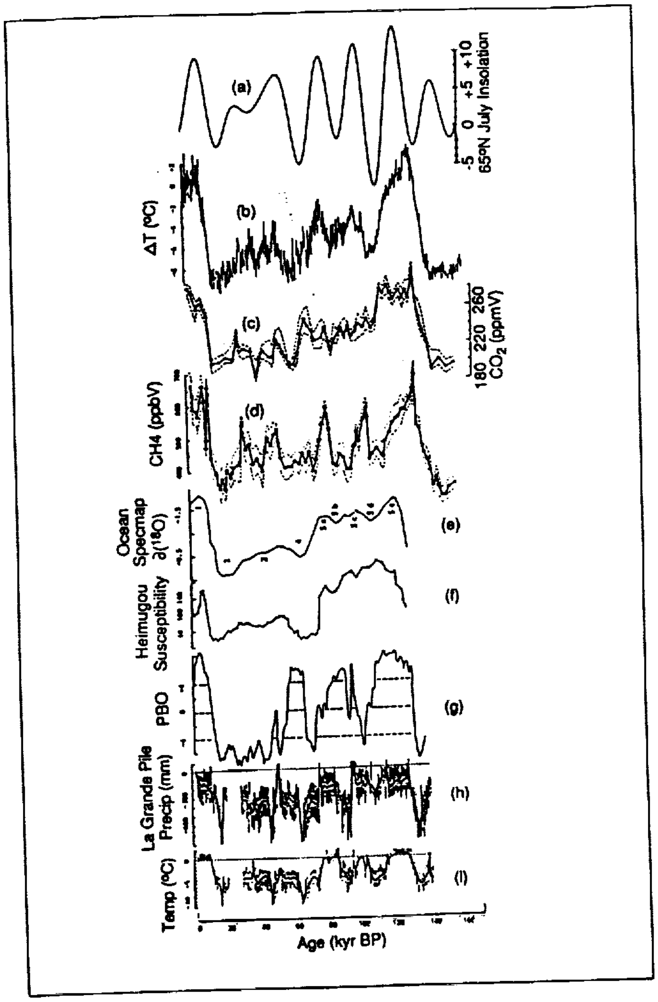


Figure 2. Examples of data on global forcings and earth system responses. (a) July insolation at 65°N (the Milankovitch forcing parameter) expressed as the percentage deviation from the present value (from Berger, 1978). (b–d) Records of temperature deviations from present in °C, based on oxygen isotope data (Jouzel et al., 1987), atmospheric CO_2 (Barnola et al., 1987), and atmospheric CH_4 (Barnola et al., 1987) determined on gas trapped in the Vostok (Antarctica) ice core (from Houghton et al., 1990). (e) SPECMAP O isotopic record (Imbrie, 1984), indicating major isotopic stages (from An et al., 1990). (f) Magnetic susceptibility profile from Heimuguon loess section, Loess Plateau, central China (from An et al., 1990). (g) Palaeogeoclimatic operator (PBO, or best possible climate profile of fossil vegetation changes) time series reconstructed from la Grande Pile pollen records (from Guiot et al., 1989). (h-i) Annual total precipitation and mean temperature reconstructions (expressed as deviations from modern values) for la Grande Pile, based on determination of modern analogue for fossil pollen assemblages (from Guiot et al, 1989).

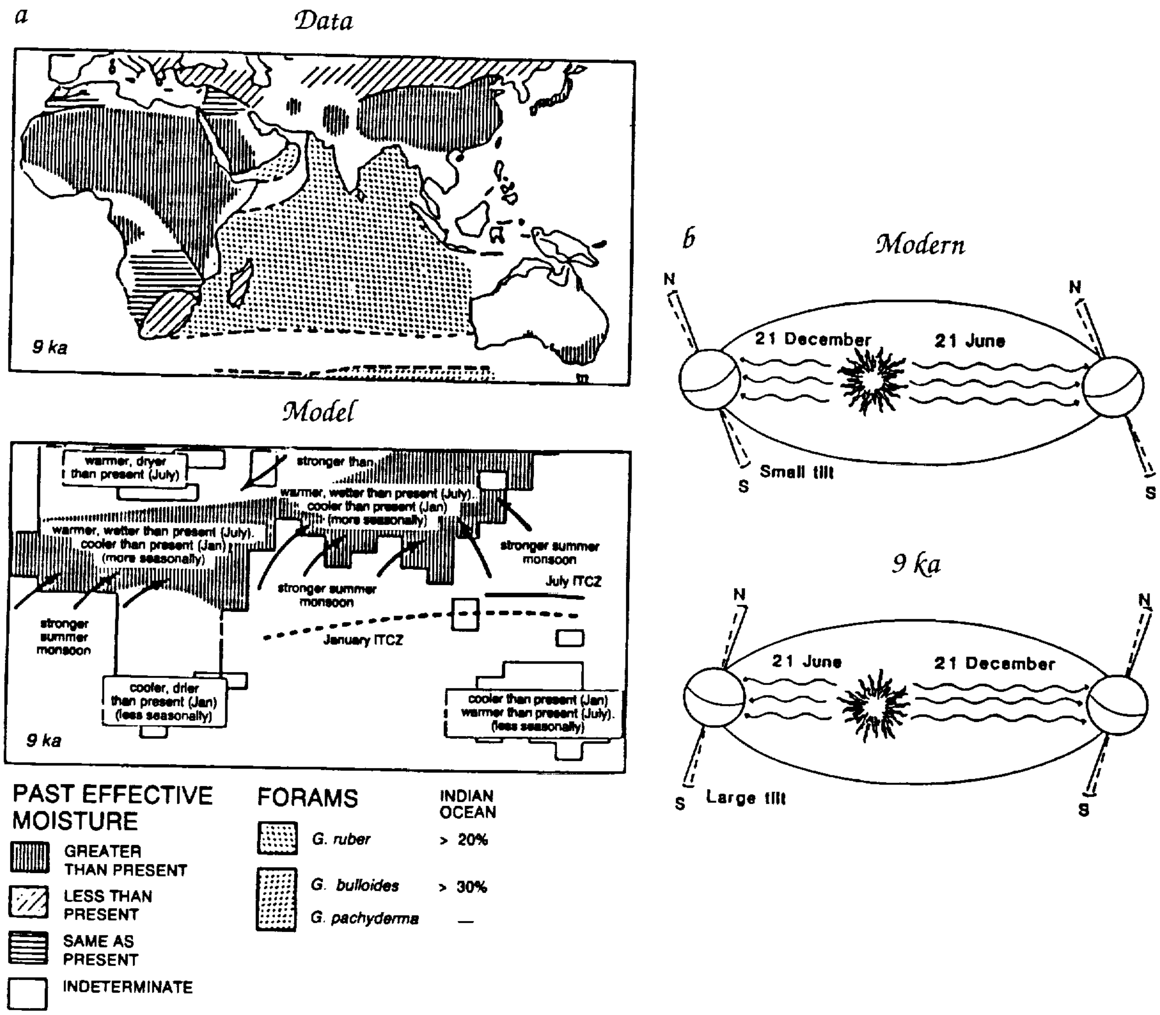


Figure 3. (a) Features of the earth's climate around 9 ka based on geologic and paleoecologic evidence (top panel) and climate model simulations of enhanced monsoonal circulations (bottom panel). (b) Changes in the earth's orbit from the present configuration, where perihelion (minimum earth-sun distance) is reached in northern winter, to the configuration for 9 ka, where perihelion was reached in northern summer and the axial tilt was 24° (from COHMAP Members, 1988).

winter) and the axial tilt was greater than at present. The solar radiation in July of 9 ka, averaged over the Northern Hemisphere, was about 7% (30 W/m^2) greater than it is at present. In January of 9 ka, solar radiation was correspondingly less than present (Figure 3). Climate sensitivity experiments have helped to show how the orbitally caused changes in the seasonal cycle of solar radiation interact with the different thermal properties of land and ocean to cause large climatic changes. These climate sensitivity experiments were made first with AGCMs with prescribed (modern) sea surface temperature. They have subsequently been made with AGCMs coupled to mixed-layer ocean models. The only coding changes required, relative to control (modern) simulations, are adjustments of the axial tilt, season of perihelion, and orbital eccentricity.

The change between the orbital configuration of 6–9 ka and today therefore provides us with an experiment, performed by nature, for studying the climatic response to an enhanced seasonal insolation cycle in the Northern Hemisphere, and a reduced seasonal insolation cycle in the Southern Hemisphere. The enhanced seasonal insolation cycle in the Northern Hemisphere produces strengthened Northern Hemisphere monsoons (Kutzbach, 1981; Figure 3). Northern continents are warmer in summer (temperature increase of 2–4°C) and colder in winter; the temperature changes of the surrounding oceans are much less owing to their large heat capacity. In northern summer, the warming of the land relative to the ocean increases the land/ocean temperature contrast and produces an increased land/ocean pressure gradient (lower pressure over land relative to ocean) and a significantly expanded and intensified region of low pressure across North Africa and South Asia. Summer monsoon winds are strengthened and precipitation is increased for parts of North Africa and South Asia (Kutzbach and Guetter, 1986; Kutzbach and Gallimore, 1988; Mitchell et al., 1988; COHMAP Members, 1988). These simulated changes in the hydrologic regime of past millennia are in qualitative agreement with geologic and paleobotanical observations of changes in tropical lake levels and vegetation (Kutzbach and Street-Perrott, 1985). For example, between 12 ka and 6 ka lakes and savanna vegetation existed about 1000 km north of present limits in tropical North Africa. In the model experiment, northern continental interiors were warmer (in summer) and drier than at present, and this too agrees qualitatively with observations (Gallimore and Kutzbach, 1989). The increased insolation in northern summer, stemming both from the summertime perihelion passage and the increased tilt, produces considerable melting of Arctic sea ice. Some observational evidence also suggests reduced sea ice cover around 9 ka.

Although many features of the observed climate around 6–9 ka are in qualitative agreement with the results of the climate sensitivity experiments for orbitally caused insolation changes, the agreement is far from perfect. Much needs to be learned about the response of soil moisture, runoff, vegetation, sea ice, and ocean currents to the changed insolation. In keeping with the sense of the definition of sensitivity experiments given earlier, the simulated climate sensitivity will change, perhaps significantly, as models of the climate system become more complete and accurate. There is also a need to refine the climatic estimates derived from the observations and, in some regions, to expand the data coverage.

125,000 Years Ago

Data from the previous (Eemian) interglacial, the period around 125 ka, indicate a climate significantly warmer than present and also warmer than the warmest period of the current interglacial (6–9 ka). Estimates of the climate of the previous interglacial have been made for parts of the middle and high latitudes of the Northern Hemisphere by Velichko (1984) and Vinnikov et al. (1988). The patterns of high-latitude warmth around 125 ka are similar to the 6–9 ka patterns, but the magnitude of the changes is larger (4 to 6°C warmer than present at 125 ka, compared to 2 to 4°C warmer than present at 6–9 ka), and in some cases the boundaries are shifted. Dramatic evidence of warmer conditions is also provided by Koerner (1989), who estimates that the Greenland ice sheet was significantly smaller, or nearly absent, during this interglacial period, and by Andrews (1991), who reviews evidence that sea level was 5 m (or more) above present. The Vostock ice-core records show relative maxima in atmospheric concentrations of CO_2 and CH_4 during this period. In the tropics, there is evidence of stronger monsoons (Prell and Kutzbach, 1987; Petit-Maire, 1986). All of these indicators of significantly altered climate provide a rationale for studying this period as an example of a climate regime warmer than present. Moreover, the phase-locking of many of the above-mentioned climate variables with insolation records at the precessional and tilt periods indicates that orbital configurations are of great importance for producing interglacials (Figure 2).

The seasonal and latitudinal changes in solar radiation caused by orbital changes are approximately twice as large at 125 ka as at 6–9 ka. This is because the eccentricity of the earth's orbit was significantly larger then (so that the earth-sun distance was significantly smaller at perihelion), and because perihelion passage occurred in northern summer around 125 ka, whereas now it occurs in northern winter. Summertime radiation was increased by more than 50 W/m^2 (12–13%), compared to present, and wintertime radiation was decreased. Owing to the increased axial tilt at 125 ka (23.9°) compared to the present (23.4°), the annual average insolation in the polar regions was increased by 3–4 W/m^2, compared to the present.

Royer et al. (1984), Prell and Kutzbach (1987), Kutzbach et al. (1990), and MacCracken and Kutzbach (in press) have reported on climate sensitivity experiments with AGCMs using 125-ka orbital parameters. High-latitude warmth, decreased sea ice extent, increased midcontinent aridity, and strengthened tropical monsoons are among the simulated responses. More work is needed to compare model results with observations, to improve the observational records, and to repeat these kinds of studies using improved models of the climate system.

Glacial Cycles

When we address the relationship between orbital changes and the glacial portion of glacial-interglacial cycles, issues of climate sensitivity are more complicated. The geologic evidence provides us with the challenge of explaining not only the accumulation and wastage of several-kilometer-high ice sheets, but also substantial changes in ocean circulation, sea ice extent, vegetation zones, and atmospheric concentrations of carbon dioxide and methane (Figure 2). Describing in detail how this system operates will require the use of fully coupled climate system models, including descriptions of ice sheets, upper lithosphere adjustments to ice loading, and biogeochemical cycles capable of producing changes in atmospheric composition.

One aspect of the problem of explaining glacial-interglacial cycles has received considerable initial attention. Climate sensitivity experiments have shown that orbital conditions favoring cool northern summers might reduce temperatures sufficiently to prevent the melting of high-latitude snows. If snow were to persist through the summer months, glaciation could be initiated. This condition would be favored at times of large eccentricity, January perihelion, and minimum axial tilt. North et al. (1983) used an energy budget climate model to show that for these orbital conditions summer temperatures could be several degrees Celsius lower than present in northern continental interiors where present-day summer temperatures are only a few degrees Celsius above freezing. When an ice-albedo feedback was included, the cooling was enhanced. While this result lends some support to the hypothesis that certain orbital configurations favor initiation of glaciation, the role of the ice-albedo feedback mechanism remains uncertain because the energy budget model has no explicit hydrologic cycle. Similar sensitivity experiments with AGCMs, with explicit precipitation and snow cover parameterizations, are therefore needed. One such AGCM experiment produced lowered temperatures in summer and year-round, and wetter conditions in high northern latitudes and especially Canada (Royer et al., 1983). Rind et al. (1989), on the other hand, found in their AGCM experiment with orbital conditions set to favor cool summers that temperature was not lowered sufficiently to maintain snow cover through the summer. Clearly, the sensitivity of climate to the insolation changes depends upon model parameterizations, resolution, and other prescribed (or interactive) boundary conditions (see Oglesby, 1990).

18,000 Years Ago

Leaving aside, for the moment, the question of the ultimate cause of glacial-interglacial cycles, it remains of great interest to explore the characteristics of glacial-age climates because conditions were so different from those existing now. Many features of the most recent glacial-age climate have been simulated with AGCMs (Gates, 1976; Manabe and Hahn, 1977), using prescribed lower boundary conditions such as ice sheets, sea ice, sea surface temperature, and land vegetation as estimated from geologic evidence. Here, the pioneering work of the CLIMAP project (CLIMAP Project Members, 1981) has been instrumental in providing accurate lower boundary conditions for the most recent glacial maximum around 18 ka. Moreover, analysis of fossil air trapped in glacial ice and retrieved from ice cores in Antarctica and Greenland has shown that the atmospheric concentration of CO_2 was about 200 ppmv during glacial times (Barnola et al., 1987). In the simulations of glacial climates with AGCMs, large anticyclones develop over the ice sheets. Temperatures are generally lower and precipitation rates are reduced. In the middle and upper troposphere, the presence of the large North American ice sheet causes the Jet Stream to split into two branches, a northern branch along the Arctic flank of the ice sheet and a southern branch located well south of the ice sheet border (Manabe and Broccoli, 1985; Kutzbach and Wright, 1985). The details of the climatic sensitivity are a function of ice sheet size and shape (Shinn and Barron, 1989). The sensitivity of the North Atlantic ocean to upstream glacial-age ice sheet boundary conditions was explored by Manabe and Broccoli (1985). They used an AGCM coupled to a motionless ocean mixed layer in which ice sheets were prescribed but sea surface temperatures were allowed to vary. The northern branch of the split atmospheric flow brought cold Arctic air over the North Atlantic, producing cold water and extensive sea ice cover that agreed with the marine geologic evidence (CLIMAP Project Members, 1981). While many of the results of these experiments agree with paleoclimatic observations, many puzzles remain, such as the changed behavior of the ocean circulation and biogeochemical cycles, as manifested in the reduced atmospheric concentration of carbon dioxide.

Role of the Ocean and Other System Components

Learning more about the role of the ocean in large climatic changes is of particular importance. For example, observational evidence indicates that North Atlantic deep water flow was significantly reduced during glacial times; that the upper waters of the oceans, and particularly the North Atlantic, were depleted in nutrients compared to today; and that the deep ocean was cooler (Boyle and Keigwin, 1982, 1987). If the vertically overturning thermohaline circulation of the Atlantic, described as a conveyor belt, slowed down or stopped, the climate of the North Atlantic region would be much colder than at present. Broecker et al. (1985) and Broecker and Denton (1989) have described evidence for this bimodality, both on the long-term scale of glacial-interglacial cycles and on the abrupt "event" scale of centuries. Paralleling these observational findings have been studies with ocean models of possible bimodality in the ocean's thermohaline circulation (see Bryan, 1986, and references to earlier work therein). Multiple experiments with a coupled ocean-atmosphere GCM found, with identical boundary conditions but different initial conditions, two stable equilibria: In one the North Atlantic had a vigorous thermohaline circulation and a relatively warm climate in regions bordering on the Atlantic; in the other there was no thermohaline circulation, and the regional climate of adjacent lands was much cooler (Manabe and Stouffer, 1988) (Figure 4). Birchfield (1989) has examined similar kinds of bimodality in coupled atmosphere-ocean box models. These oceanic changes are very likely linked to changes in biogeochemical cycling that may ultimately explain the glacial-interglacial differences of about 70 ppmv in the atmospheric concentration of CO_2 ($\cong$ 270 ppmv preindustrial value; $\cong$ 200 ppmv glacial-age value). Some of these indicators of ocean climate show significant amplitude variability and consistent phase relationships with orbital cycles (Imbrie et al., 1989).

Tracer studies are another important earth system linkage now being explored for past climates (Jouzel, 1991). The spatial and temporal distribution of isotope species, such as $\delta^{18}0$ in precipitation, and aerosol (desert dust, loess, marine aerosol, indicators of volcanicity) are important paleoclimatic indicators. Various modeling studies are employing tracers for isotopes and dust in AGCMs for both modern and 18-ka simulations (Jouzel et al., 1986; Joussaume and Jouzel, 1987; Joussaume et al., 1989). Tracer studies can provide a stringent test for evaluating models of present-day conditions. Tracer studies are also useful for checking paleoclimatic inferences made from the spatial and temporal distribution of isotopes or dust in geologic records and, in fact, were first undertaken by those involved in the interpretation of paleoclimatic records.

The amount and climatic importance of aerosol loading of the glacial-age atmosphere is a very important and unresolved question (Harvey, 1988). The possibility exists that significant aerosol loading could have contributed to the observed lowering of glacial-age temperature. However, improved estimates of the location, amount, and radiative properties of the aerosol are needed.

For large climatic changes, there are also significant changes in the distribution of land vegetation and soil carbon (Prentice and

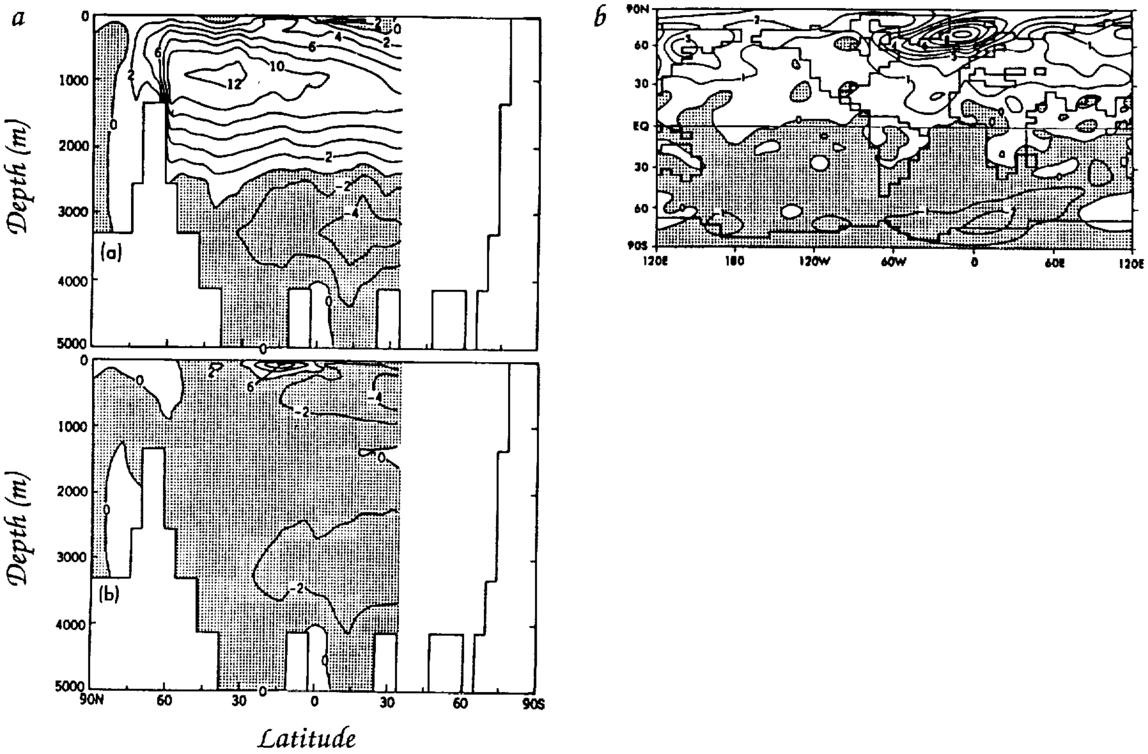


Figure 4. (a) Streamfunction illustrating meridional circulation in the Atlantic Ocean. Units are Sverdrups (10^6 m^3/s): (top) Experiment I, (bottom) Experiment II. In experiment I there is a strong thermohaline circulation, whereas in experiment II it is absent. The streamfunction is not shown in the southern Atlantic ,which is not enclosed by coastal boundaries and freely exchanges water with other oceans. (b) Difference in surface air temperature (°C) between experiments I and II. The surface air temperatures in the North Atlantic sector are significantly warmer with strong thermohaline circulation and large poleward heat transport in the North Atlantic ocean (from Manabe and Stouffer, 1988).

Fung, 1990) and possible biosphere-albedo feedbacks (Cess, 1978; Street-Perrott et al., 1990).

Evolution of Climate

In general, paleoclimate simulation experiments (in contrast to climate sensitivity experiments) are largely a task for the future because models are not yet adequate for incorporating all parts of the climate system. For the period since the last glacial maximum, however, there is detailed information on the size of the wasting ice sheets, the atmospheric concentration of carbon dioxide, and the ocean surface temperature (as inferred from information in marine sediments). Using these geologic observations to prescribe surface boundary conditions of ice sheets and ocean temperature and, in some cases, atmospheric CO_2 levels, along with orbitally prescribed insolation, AGCMs have been used to simulate "snapshots" of the climate at 3000-year intervals from 18 ka to the present (COHMAP Members, 1988). The simulated climate agrees qualitatively with many features of the observed climate (COHMAP Members, 1988). These initial attempts at simulating sequences of paleoclimates will no doubt be repeated in coming years using more complete models and more complete observational data sets for model/data comparisons. In order to facilitate model/model and model/data comparisons, there will be a need to develop standard data sets for selected times such as 6 ka and 18 ka.

Embedded in the general deglaciation of the past 18,000 years are one or more very abrupt changes in climate (Boyle and Keigwin, 1987; Broecker et al., 1989). For example, between 11,000 and 10,000 years ago the general warming trend was interrupted by a very significant return to cold conditions that persisted for a few centuries, which was in turn followed by an equally abrupt warming. The cause of this reversal, known as the Younger Dryas, and other such abrupt events is unknown. Perhaps the climate is sensitive to small changes of ice sheet height or shape or to meltwater discharge to the Gulf of Mexico or the North Atlantic. The possible causes of these and other abrupt events are under investigation (Rind et al., 1986; Schneider et al., 1987; Overpeck et al., 1989; Oglesby et al., 1989).

The above-mentioned studies with GCMs provide detailed snapshots of the relatively fast response of the atmosphere, land surface, and upper ocean to insolation changes. The more general questions of the time-dependent behavior of the fully coupled climate system during glacial-interglacial cycles are being addressed currently with the aid of highly simplified models of the climate system. These models incorporate, often in heuristic fashion, the slow-response climate variables such as ice mass, bedrock depression, deep ocean temperature, and atmospheric concentration of carbon dioxide. Papers by Saltzman and Sutera (1984), Saltzman and Maasch (1991), Ghil et al. (1987), Pollard (1983), and Peltier (1982) illustrate this approach. These models have typically simulated the time-dependent variations of one or more climate variables, such as global ice volume; these model-derived time series are then compared with observations of ice volume variations inferred from oxygen isotope records. Some studies have focused on understanding the forced response of these coupled systems to changes of orbital parameters, while others have demonstrated that the coupled systems themselves exhibit free oscillatory behavior resembling, to some extent, observed variations (Saltzman, 1990).

In part because of computing limitations, time-dependent climate models simulating the slow-response variables use very simplified treatments of the atmosphere. This limitation will certainly be relaxed as computing power increases. In the meantime, an intermediate class of atmospheric models, statistical-dynamical models, is efficient enough to be used in time-dependent integrations. For example, Berger et al. (1988, 1990) have performed a time-dependent integration with a two-dimensional (latitude-height) zonal average atmospheric model coupled asynchronously to mixed-layer ocean and ice sheet models. They simulate the climatic response to orbital changes of the past 125,000 years in the form of an ice volume chronology that matches the observational record quite well. With enhanced computing resources and improved and coupled AGCMs and OGCMs it should become possible to study the three-dimensional evolution of the climate system over this full interglacial-glacial-interglacial cycle.

In summary, the strong empirical evidence linking precisely known changes in external forcing of the climate system (namely, the changes in the earth's orbital parameters) to glacial-interglacial cycles in high northern latitudes and cycles of enhanced or weakened monsoons in middle and tropical latitudes provides a major opportunity to explore the internal workings of the climate system. Much has already been accomplished, but many puzzles remain. The initial studies show encouraging agreement between experiments and geologic observations and underscore the notion that we can learn a great deal about the general behavior of the climate system by parallel studies with observations and models of the large climatic changes of the geologic past.

Changes of the Past Several Million Years

The early Pliocene (roughly 3 to 5 million years ago) is the most recent period with existing observational evidence that climates were *substantially* warmer than present. For example, temperatures in high latitudes may have been 5–10°C higher than present (Zubakov and Borzenkova, 1988). Glacial-interglacial cycles similar to those of the past few hundreds of thousands of years began about 2.5 million years ago. However, compared to the more recent geologic periods mentioned in previous sections, the observational record from this period is relatively poor.

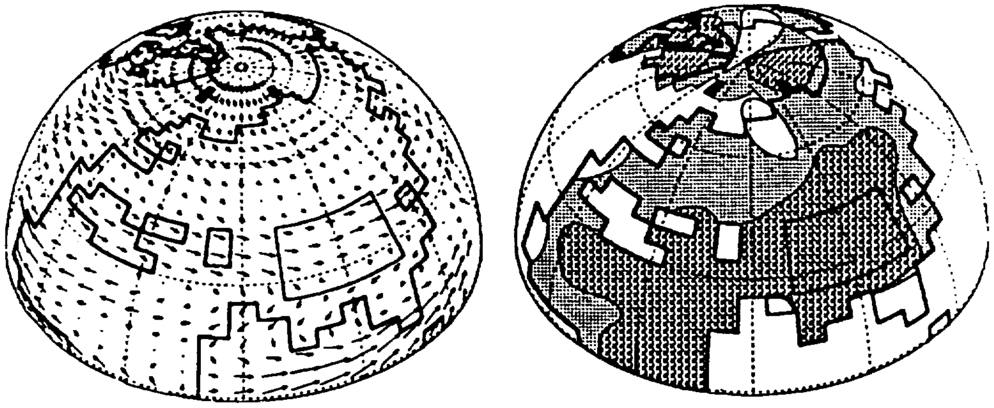
Plate movements (changing geography), crustal movements (changing orography), and associated changes in outgassing, weathering, and biogeochemical cycles must exert a strong "lower-boundary" forcing on earth's climate on the scale of millions of years. To the extent that these "solid earth" processes are viewed as external to the climate system, these more distant geologic periods also provide extraordinary opportunities for understanding the full range of behavior of the climate system in response to external change. These ancient climates are very different from the present and include periods when the earth was warmer than at present and likely experienced higher concentrations of atmospheric CO_2.

Climate sensitivity experiments performed with energy budget climate models have been particularly useful, because of their computational efficiency, in exploring the first-order effects on climate of the location and size of continents. The primary boundary condition changes are land/ocean distributions, and the primary climatic response is due to the different thermal response characteristics of land and ocean to the seasonal insolation cycle and the influence of the size of the land mass on the continentality of its climate. Crowley et al. (1986) illustrated how, over the past 100 million years, the gradual isolation and movement of Antarctica toward the South Pole and the gradual northward drift and separation of Greenland from adjacent land masses may have both lowered the average temperature and reduced summertime warmth (decreased seasonality of temperature owing to the decreased in continent size) and thereby favored the development of permanent ice sheets.

In the past several million years the overall plate movements have been relatively small; yet geologic observations suggest significant changes of climate toward cooler and generally drier conditions, with the cooling leading ultimately to the initiation of glacial-interglacial cycles around 2.5 million years ago. Since orbital variations occurred prior to this time, one interpretation is that some other factor (or factors) caused the climate to cool to the point where orbitally caused glacial cycles could occur. Mountain uplift, lowering CO_2 levels, and changes in ocean circulation are among the suggested factors. Ruddiman et al. (1989) have presented evidence that major worldwide uplift of plateaus and mountains has occurred in the past five to ten million years, with a possible doubling of heights in many regions. In a series of climate sensitivity experiments with AGCMs for no-mountain, half-mountain (perhaps approximating the situation of five to ten million years ago), and full (present-day) mountains as prescribed lower boundary conditions, but with ocean temperatures prescribed at modern values, Ruddiman and Kutzbach (1989) show that many of the patterns of regional cooling and drying that have been estimated from geologic observations can be explained by uplift (Figure 5). By comparing simulations with and without the Tibetan plateau, Manabe and Broccoli (1990) show that the modern-day Asian deserts are simulated correctly only with the Tibetan plateau present. These kinds of studies with AGCMs give useful preliminary indications of the atmospheric changes to be expected from changing

(a) Winds: without mountain

(c) Change in temperature



(b) Winds: with mountain

(d) Change in precipitation

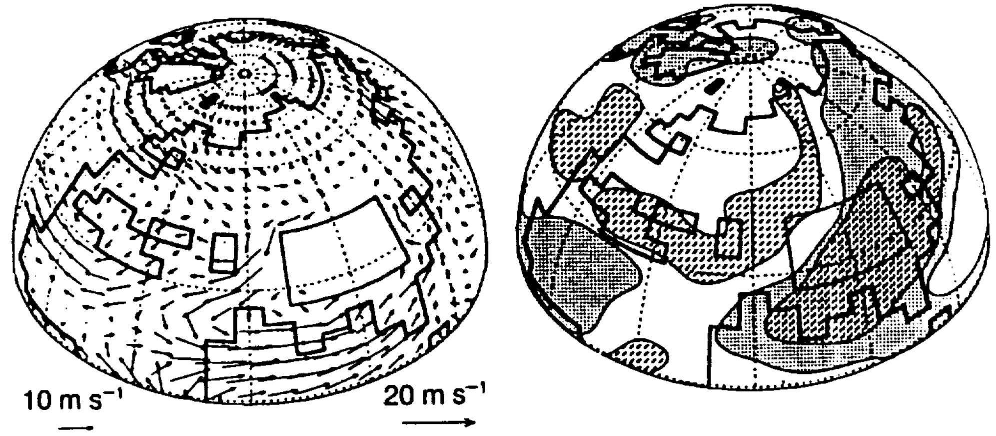


Figure 5. Model simulation of uplift-induced circulation changes in Eurasia for July. (a) Near-surface winds in "no mountain" experiment. (b) Near-surface winds in "mountain" experiment. (c) Change in surface temperature due to uplift; cooler regions stippled, warmer regions blank. (d) Change in precipitation due to uplift; wetter regions stippled, drier regions blank. Diagonal (broken-line) shading in (c) and (d) is used for areas where temperature or precipitation changes are significant at the 99% confidence level (from Ruddiman and Kutzbach, 1989).

orography but ignore the likely changes in ocean temperature and circulation that would also occur. A climate model with a fully coupled ocean will be needed to simulate more completely the response of the climate system to uplift, and the model will also likely need to include interactive coupling with biogeochemical and vegetation processes. This is so because changes in weathering associated with uplift might be expected to change the carbon cycle and lower atmospheric CO_2 concentration (Raymo et al., 1988).

Ocean gateways may also open or shut in response to otherwise subtle horizontal or vertical crustal movements. Maier-Reimer et al. (1991) have used an OGCM forced by modern observed wind stress and surface air temperature in a sensitivity experiment on the possible consequences of the closing or near-closing of the central American isthmus that is believed to have occurred over the past ten million years. They found that with an open isthmus lower-salinity waters from the Pacific dilute the salinity of the North Atlantic surface waters, and this dilution leads to drastically reduced strength of the thermohaline circulation cell and the poleward ocean heat transport in the North Atlantic.

Many questions remain concerning the causal factors that produced the general cooling of climate over the past several million years. All of the above mentioned factors (uplift, falling levels of CO_2, and changes in ocean circulation or in ocean gateways) may have played a role (Crowley, 1991). Improved data sets would provide a focus for modeling studies of this period and could lead to improved understanding of the potential behavior of the earth system during periods substantially warmer than the present.

Conclusions

The climatic history of our earth provides an increasingly data-rich environment for testing ideas about the causes and mechanisms of large climatic changes. Moreover, it may be possible in the future to use modeling studies in combination with geological observations to assess the adequacy and accuracy of climate models.

This brief overview has illustrated some of these opportunities and some of the obstacles. Of necessity, most studies have used models of the climate system that fall well short of the desired level of breadth and detail. On the one hand, studies with fully coupled models are greatly simplified and include only a few variables (global ice volume, global deep ocean temperature, etc.). On the other hand, detailed studies with individual system components (atmospheric or ocean GCMs) are likewise of limited value because they are not coupled to other important components of the climate system.

The climate sensitivity experiments that are used to infer the possible effects of past changes in orbital parameters, geography and orography, CO_2 levels, and solar irradiance are similar in methodology to the climate sensitivity experiments that are used to infer possible effects of future increases in greenhouse gases. The advantage of the former is that the paleoclimatic observations help us assess the model's response. Stated slightly differently, an advantage in studying the climates of the past is that we know (or can find out) what happened.

As we develop coupled climate models, we will need to evaluate their accuracy. One test of the accuracy of coupled climate models will be the degree to which they can simulate the observed seasonal cycle. The recent few decades and the past century of historical records are useful for testing the accuracy of coupled climate systems on the scale of interannual variability. Records of the past several centuries and the past millennia are useful for estimating and understanding decade- to century-scale variability. However, only the more distant paleoclimatic records of past millennia provide examples of climatic changes of a magnitude that might be associated with doubling or tripling of atmospheric concentrations of CO_2 and increases in other greenhouse gases over the next century. For example, the estimated global average warming from the most recent glacial maximum (around 18 ka) to the present is about 4°C—roughly the same order as the anticipated warming caused by increased greenhouse gases over the next century. Because the future changes may occur perhaps 100 times more rapidly than the deglacial warming, which occupied a period of about 10,000 years, abrupt as well as gradual changes in climate need to be studied. Another example of a period of the past that is now of substantial interest is the climate of several million years ago. This period had generally warmer conditions than present and perhaps elevated CO_2 levels. It appears to be the most recent example of a climate substantially warmer than present.

If we can construct realistic models of the coupled climate system and of the even broader earth system, we will have many opportunities to use them—not only for addressing practical questions that we face in the next century, but also for working in an interdisciplinary mode with geologists, ecologists, archaeologists, and paleontologists in solving puzzles about the earth's past.

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