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Climate: Is the past the key to the future?

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Abstract The climate of the Holocene is not well suited to be the baseline for the climate of the planet. It is an interglacial, a state typical of only 10% of the past few million years. It is a time of relative sea-level stability after a rapid 130-m rise from the lowstand during the last glacial maximum. Physical geologic processes are operating at unusual rates and much of the geochemical system is not in a steady state. During most of the Phanerozoic there have been no continental ice sheets on the earth, and the planet's meridional temperature gradient has been much less than it is presently. Major factors influencing climate are insolation, greenhouse gases, paleogeography, and vegetation; the first two are discussed in this paper. Changes in the earth's orbital parameters affect the amount of radiation received from the sun at different latitudes over the course of the year. During the last climate cycle, the waxing and waning of the northern hemisphere continental ice sheets closely followed the changes in summer insolation at the latitude of the northern hemisphere polar circle. The overall intensity of insolation in the northern hemisphere is governed by the precession of the earth's axis of rotation, and the precession and ellipticity of the earth's orbit. At the polar circle a meridional minimum of summer insolation becomes alternately more and less pronounced as the obliquity of the earth's axis of rotation changes. Feedback processes amplify the insolation signal. Greenhouse gases (H_2O, CO_2, CH_4, CFCs) modulate the insolation-driven climate. The atmospheric content of CO_2 during the last glacial maximum was approximately 30% less than during the present interglacial. A variety of possible causes for this change have been postulated. The present burning of fossil fuels, deforestation, and cement manufacture since the beginning of the industrial revolution have added CO_2 to the atmosphere when its content due to glacial-interglacial variation was already at a maximum. Anthropogenic activity has increased the CO_2 content of the atmosphere to 130% of its previous Holocene level, probably higher than at any time during the past few million years. During the Late Cretaceous the atmospheric CO_2 content was probably about four times that of the present, the level to which it may rise at the end of the next century. The results of a Campanian (80 Ma) climate simulation suggest that the positive feedback between CO_2 and another important greenhouse gas, H_2O, raised the earth's temperature to a level where latent heat transport became much more significant than it is presently, and operated efficiently at all latitudes. Atmospheric high- and low-pressure systems were as much the result of variations in the vapor content of the air as of temperature differences. In our present state of knowledge, future climate change is unpredictable because by adding CO_2 to the atmosphere we are forcing the climate toward a "greenhouse" mode when it is accustomed to moving between the glacial–interglacial "icehouse" states that reflect the waxing and waning of ice sheets. At the same time we are replacing freely transpiring C3 plants with water-conserving C4 plants, producing a global vegetation complex that has no past analog. The past climates of the earth cannot be used as a direct guide to what may occur in the future. To understand what may happen in the

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future we must learn about the first principles of physics and chemistry related to the earth's system. The fundamental mechanisms of the climate system are best explored in simulations of the earth's ancient extreme climates.

Key words Climate change · Paleoclimatology · Cretaceous · Holocene · Quaternary

Introduction

In 1830 Charles Lyell published the first volume of "Principles of Geology." Approximately one third of the volume is devoted to a discussion of changes in the earth's climate over time. He correctly interpreted the coal measures as representing swamps with tropical vegetation that grew under temperatures much warmer than in the England of his day. From these and other deposits he concluded that the temperatures and rainfall had varied considerably over geologic time. He supposed that paleogeographic changes were largely responsible for the different climates of the past, reasoning that if there were more land in the polar regions, the earth would be cooler. If there were more land in the equatorial region, the earth would be warmer. A century and a half later, Lyell's reasoning was confirmed by numerical climate model experiments (Barron et al. 1984; Hay et al. 1990).

Despite the fact that climate change has been a major concern of geology for almost two centuries, there had been little advance in understanding how the climate system works until the past two decades. James Hutton's Principle of Uniformitarianism, the idea that the present is the key to the past, has been a valuable guide to understanding many aspects of geology, but not necessarily the climates of the earth's more distant past. The reason is that there have been times in the past when conditions having no modern analog were widespread. Some processes that play a minor or trivial role today, such as the deposition of salt or burial of organic carbon, were very important in the past. They may have significantly altered the salinity and circulation of the ocean and the CO_2 and CH_4 content of the atmosphere, affecting the global climate. Recent major advances in understanding climates of the past have come from quantitative documentation of the record of ancient climates and from attempts to simulate the climates of the past using numerical models.

The unsuitability of the Holocene as a baseline for the earth's climate

In a geologic context, the Present is the Recent or Holocene, the interval since 10 000 years BP. In James Hutton's time, the Present earth was only beginning to be modified by the industrial revolution. His Principle of Uniformitarianism was implied, not directly stated, in his "Theory of the Earth" (Hutton 1795). Hutton's ideas about the earth having been shaped by processes that can be observed presently were popularized by Playfair (1802), and most clearly stated as "uniformitarinism" by Lyell (1830). Today it is interpreted loosely, as meaning that the processes that have acted on the earth in the past are the same as those that act on it presently, while recognizing that the rates of different processes may have changed. Hutton probably took his ideas more literally; otherwise, he would not have had a standard for gauging the immensity of geologic time.

Instead of being a typical sample of the earth's younger geologic history, the Holocene is one of the most peculiar of geologic ages; its climate is characteristic of only brief intervals during the Quaternary. As shown in Fig. 1A, it is an interglacial characterized by large ice sheets covering the Antartic and Greenland, and smaller ice sheets and glaciers in some mountainous areas. It is a time of relative sea-level stability succeeding a rapid 130-m rise from the lowstand during the last glacial maximum (LGM). At high latitudes, large areas of the continents are covered by fresh morainal material which is just beginning to weather to form soil. Glacial lakes trap the detritus from streams, preventing sediment from being transported onward to the sea. Forests and grasslands migrated rapidly during the deglaciation. The effects of the rapid sea-level rise have shaped the present coastlines: flooded river valleys form estuaries, again trapping sediment that would otherwise reach the sea, and coastal swamps and barrier islands characterize much of the rest of the low relief coastline. The rise of sea level flooded the continental shelves, but because of the trapping of sediment in estuaries, most of the terrigenous continental shelves expose relict sediments from the last sea-level lowstand. Carbonate platforms experienced rapid growth upon being flooded by the sea-level rise, and large amounts of $CaCO_3$ are being precipitated by shallow-water benthic organisms.

In summary, the Holocene is a short-term climate event in which physical geologic processes result in many diverse deposits being formed in small areas at high rates of sedimentation. As a result, much of the geochemical system is not in a steady state (Hay et al. 1994).

Compared with other interglacials, the Holocene appears to be atypical. It is characterized by climatic and sea-level stability, but is cooler than the last interglacial (Bauch 1996; Bauch et al. 1996; Neumann and Hearty 1996). Berger et al. (1981) suggest that in the absence of human interference, the Holocene might be the longest interglacial of the Quaternary, lasting for almost 70 000 years in comparison to the 10 000 years typical for most earlier interglacials.

Conditions like those of the Holocene have persisted for probably less than 10% of the past 1 million years. Large ice sheets have been the most prominent features

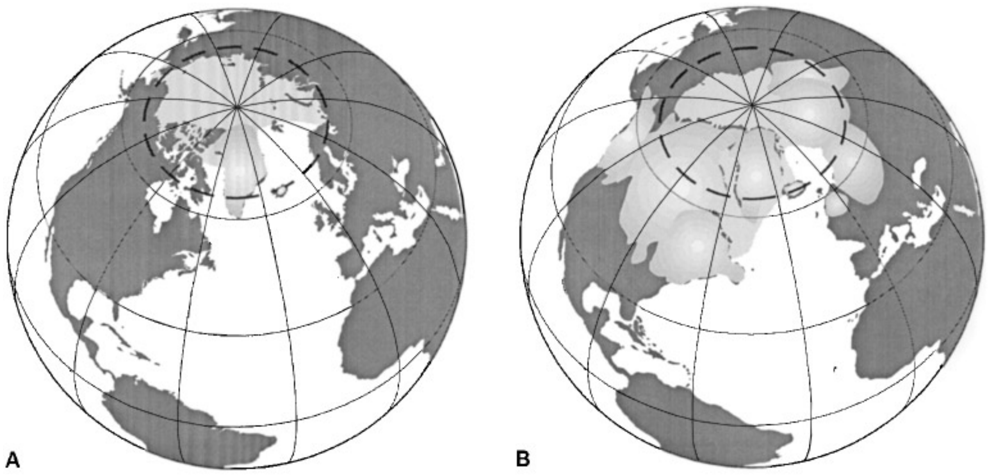


Fig. 1A, B Distribution of ice in the northern hemisphere. **A** At present (Holocene) and **B** during the last glacial maximum (LGM) approximately 24 000 BP. The *dashed latitudinal circle* at 65 °N marks the site of the meridional summer insolation minimum

of northern hemisphere geography during most of the late Quaternary, as shown in Fig. 1B. They have acted as frigid plateaus, forcing a stronger meridional temperature gradient, blocking atmospheric circulation, and creating their own pressure systems. Sea level has been lower and shelf seas were much reduced in area. Most carbonate platforms, such as the Bahama Banks, were subaerial plateaus. They were sites of dissolution, not deposition. During the glacial times, the fixation of $CaCO_3$ was accomplished mostly by marine plankton. Cooler global temperatures during the glaciations imply a lesser role for latent heat transport by the atmosphere, and hence a different partitioning of energy transport between the ocean and atmosphere. During the Quaternary, the rates of erosional and depositional processes were significantly higher than during the earlier Cenozoic (Hay 1994).

The times when there have been periodic developments of large-scale continental ice sheets on the earth are also not typical of the planet's "average" state. There have been large continental ice sheets during no more than 30% of the Phanerozoic (Crowell 1982). The planet's "normal" state is to have a meridional temperature gradient less than half that of today, to be free of continental ice sheets, and to have erosion and sedimentation processes operating at rates approximately one fourth of those at present (Frakes et al. 1992; Hay 1994). Fischer and Arthur (1977) coined the terms "icehouse" and "greenhouse" for these states of the earth's climate. Frakes et al. (1992) discussed the Phanerozoic history of the earth in terms of an alternation between these two states.

The climate system

The reason why the climate system is difficult to understand (and predict) becomes evident from Fig. 2, which shows the interactions between the five major components of the climate system, the atmosphere, land, ocean, cryosphere, and biosphere. There is no general theory of climate and climate change that can be used to predict conditions on the earth from a given set of boundary conditions. Instead, there are a series of equtions that describe the components of the climate system and their interactions at different levels of sophistication. The atmospheric and oceanic circulation can be described by equations that express the conservation of mass, momentum, and energy: the equations of continuity, motion, vorticity, thermodynamic energy, water vapor, and equations of state for atmosphere and ocean (Peixoto and Oort 1992). These equations are forced by the solar radiation, the physical configuration of the earth's surface, absorbing gases in the atmosphere aerosol content, land and sea ice cover, vegetation, soils, etc. They yield results that describe the thermohydrodynamical characteristics of the climate: temperature, density, velocity, moisture content, precipitation, evaporation, salinity of the surface ocean, etc. The other components of the climate system are described by equations, but often with less certainty so that they are not necessarily an accurate reflection of the processes involved. Most of the equations describing different aspects of the climate system are non-linear and amenable to solution only by numerical methods, which requires large computational capabilities. The ocean operates on a timescale much longer than that of the atmosphere; the cryosphere operates on a timescale longer than that of the ocean. The biosphere not only operates on a different timescale, but has evolved over time so that the characteristics of its interaction with other parts of the climate system have changed.

The major suspects for inducing climate change are changes in solar insolation, atmospheric greenhouse gases, paleogeography, and vegetation. In this paper we discuss only the first two topics because they are considered critical for climate change over the next few

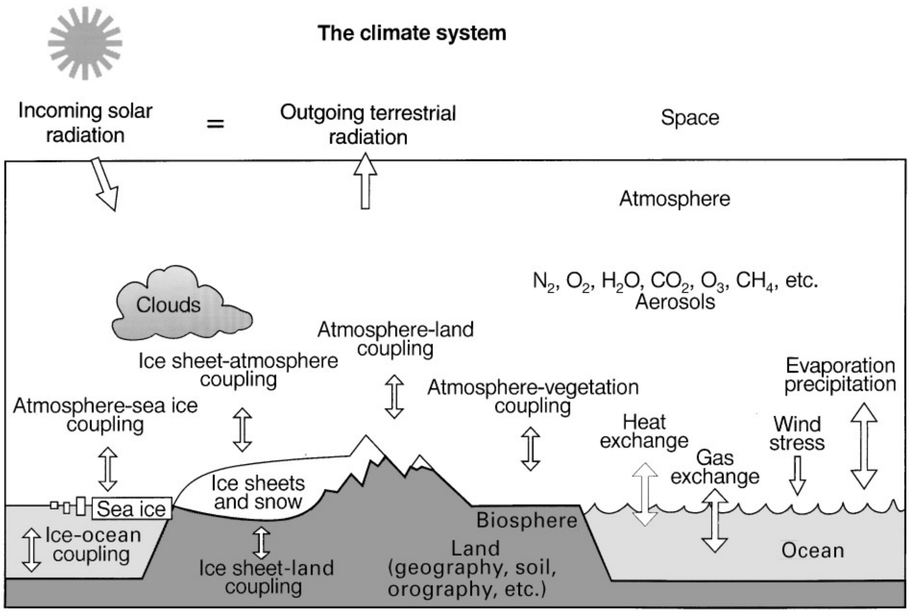


Fig. 2 The climate system. (Modified after Houghton 1984)

thousand years. Except for the change resulting from glacial–interglacial falls and rises in sea level, paleogeography evolves over much longer timescales. The role of changing paleogeography was the subject of a recent review (Hay 1996). The effects of changes in vegetation are critical for climate change over both the short and long term, but the role of vegetation in climate is only beginning to be understood (Overpeck et al. 1992; DeConto et al., submitted A, submitted B).

Insolation, feedbacks, and climate

Despite the complexity of the system, some major changes in the earth's climate can be related directly to specific causes. Most notably, the alternate growth and melting of ice sheets in the northern hemisphere has been attributed to waxing and waning of the radiation received from the sun (insolation) as a result of changes in the earth's orbital parameters (Milankovitch 1920, 1930; Emiliani and Geiss 1959; Hays et al. 1976), amplified by positive feedback mechanisms (Saltzman et al. 1984; Saltzman and Maasch 1988; Broecker 1995).

Insolation

The annual variations in insolation resulting from the tilt of the earth's axis relative to the plane of the earth's orbit around the sun produce the seasons (summer, fall, winter, and spring). The intensity of the seasonal insolation varies on timescales of 10^4–10^5 years because of variations in the earth's orbital parameters (Berger 1977, 1978a, 1981, 1984; Imbrie and Imbrie 1980). The major orbital variations affecting insolation are shown in Fig. 3: (a) the ellipticity of the earth's orbit, which changes the distance from earth to the sun during the course of the year and varies on a roughly 95 000-year timescale, with a longer cycle of variation at a 400 000-year timescale (Fig. 3A); (b) the tilt ("obliquity") of the earth's axis of rotation relative to the plane in which it orbits the sun (ecliptic), which varies between 22°2′ and 24°30′ on a 41 000-year timescale (Fig. 3B); (c) the precession of the elliptical orbit of the earth, which changes the time of the year when the planet is closest to the sun and has a period of approximately 105 000 years (Fig. 3C); and (d) the precession of the earth's axis of rotation, which changes the season at which the earth is closest to the sun and has a period of 27 000 years (Fig. 3D). The combined effect of precession of the axis of rotation and the elliptical orbit is to produce an apparent period of 23 000 years. Similarly, the cyclic changes in ellipticity and precession of the axis of rotation combine to produce an apparent period of 19 000 years. The two apparent periods, 23 000 and 19 000 years, blend together so that perihelion coincides with seasonal summer in each hemisphere approximately every 21 700 years. This combined effect is termed the precession of the equinoxes, and is shown in Fig. 3E. These orbital motions are induced by the combined gravitational attraction of the moon, sun, and other planets. The changes in orbital motions produce only a negligible change in the total amount of insolation received by the earth during a year, but they redistribute the amounts of energy received at different latitudes during different seasons. As shown in Fig. 3A, changes in the ellipticity change the amount of insolation received by the earth at perihelion and aphelion and the length of the seasons. If the orbit is circular, the

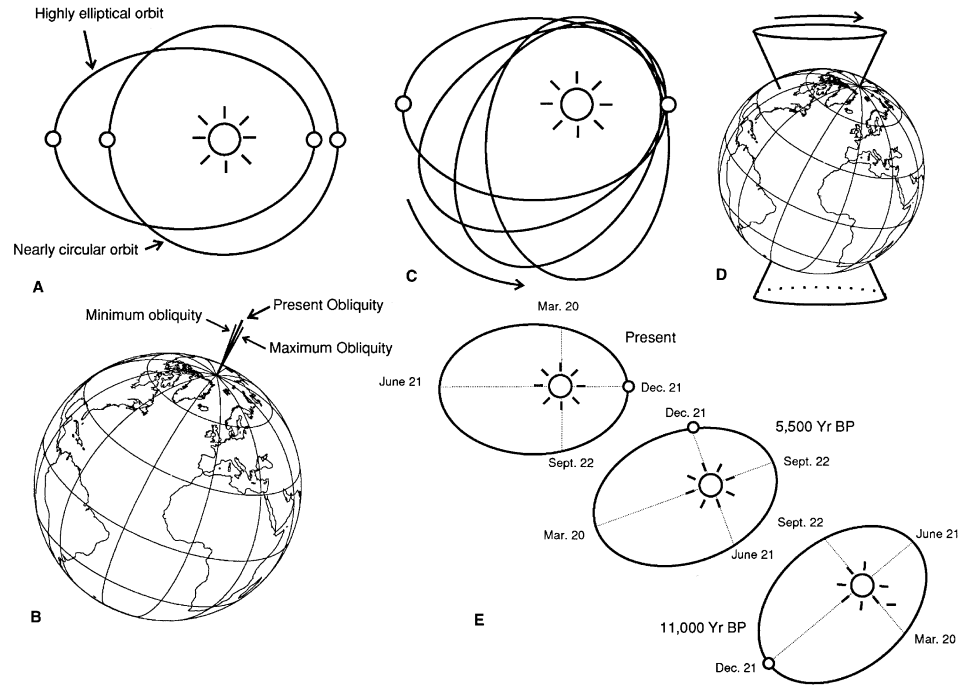


Fig. 3A–E Milankovitch orbital variations affecting the distribution of solar insolation on the earth during the course of a year. **A** view from above the solar system, showing how changes of the ellipticity of the earth's orbit change the earth–sun distance at perihelion and aphelion. The closer approach to the sun at perihelion results in increased insolation, producing "caloric summer," whereas aphelion results in "caloric winter." **B** View in the plane of the earth's orbit showing the effect of the change in tilt of the earth's axis of rotation (obliquity); at a steeper inclination of the axis of rotation to the ecliptic, more insolation is concentrated in the polar region. **C** View from above the solar system, showing the precession of the elliptical orbit. **D** View in the plane of the earth's orbit showing the precession of the axis of rotation. **E** View from above the solar system showing the combined effect of precession of the elliptical orbit and the axis of rotation, the "precession of the equinoxes"

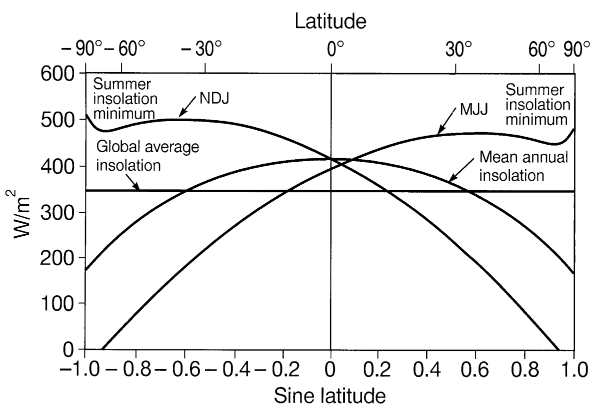


Fig. 4 Present global average, mean annual, and summer insolation for northern (*MJ*) and southern (*NDJ*) hemispheres, showing the summer insolation minima centered at approximately 65 °N and S latitudes. (From data of Berger 1978)

insolation received during the year is equal at all times. Presently, the ellipticity is 0.0167 and the insolation received at perihelion is approximately 351 W/m^2, and at aphelion 329 W/m^2, a difference of more than 6%. At the maximum eccentricity in the past 5 million years given by Berger (1987b), 0.0607, the difference in insolation between perihelion and aphelion is approximately 30%. The distribution of the energy received at perihelion and aphelion is modulated by the precession of the elliptical orbit and axis of rotation, so that the effects are concentrated alternately in one hemisphere, and then the other. The results are (a) an oscillation of the intensity of seasonality between the northern and southern hemispheres, (b) displacement of the caloric equator into the hemisphere closest to the sun during its seasonal summer, and (c) shifts of the low-latitude climate zones. The changes in obliquity redistribute the energy received at high latitudes, alternately concentrating and dispersing the insolation poleward of the polar circle. This results in alternate intensification and diminishing of the meridional minimum of summer insolation associated with the polar circle, shown in Fig. 4.

It has recently been suggested that a fourth orbital variation may be responsible for the 100-kyr cycle of glaciations and interglacials, the inclination of the earth's orbit. Muller and MacDonald (1995) calculated the inclination of the earth's orbit relative to the plane of symmetry of the solar system by direct integration of the planetary perturbations, and found that the inclination minima have the same period as but precede the glacial maxima, as indicated by ^{18}O, by 33 ± 3 kyr. They imply that there may be a concentration of dust in the plane of symmetry of the solar system, and as the inclination of the earth's orbit decreases relative to the plane of symmetry of the solar system, the insolation received by the earth is reduced. They suggest that if this is the cause of the 100-kyr-year glacial cycles, it should be possible to find a 100-kyr cycle in the rate of accumulation of meteoritic dust.

Primarily because of the increase in day length during the summer, the polar regions receive more insolation over the 3-month season than other areas. Summer insolation has a secondary maximum at approximately 40° as a result of both the increase in day length and elevation of the sun. However, as shown in Fig. 4, there is a minimum in summer insolation at the latitude of the polar circle, approximately 66.5 °N and S. This spatial summer insolation minimum is closely associated with the growth and decay of the northern hemisphere ice sheets. Snow which accumulates during the fall, winter, and spring is most likely to remain where the solar insolation is minimal during summer. Figure 1B shows that the major northern hemisphere ice sheets are located between 55 and 75 °N, and the largest, the Laurentide and Scandinavian ice sheets, are centered on 65 °N.

Feedbacks

The solar insolation changes are thought to be too small to have been solely responsible for the glacial–interglacial cycles, so there has been a search for mechanisms in the climate system that might amplify the signal. The feedback mechanisms are of two sorts, those that directly affect the earth's radiation balance and those that act to change the concentrations of greenhouse gases in the atmosphere. Feedback mechanisms that act to change the radiation balance include: ice-albedo feedback, isostatic adjustment of the earth's surface to the ice load, instability of ice sheets grounded below sea level, effect of meltwater on supply of moisture to the ice sheets, changes in the atmospheric dust flux, and changes in vegetation (Broecker and Denton 1989; Broecker 1995). The feedback mechanisms changing greenhouse gas concentrations and their climatic effects are discussed in the section Atmospheric greenhouse gases.

The ice-albedo feedback is directly related to insolation. Once an initial accumulation of snow occurs in upland or highland areas, its high reflectivity reduces the absorbed insolation. This increases the amount of snow and ice that survives summer melting and results in a strong positive feedback promoting further accumulation of snow (Flint 1943; Budyko 1968; Sellers 1969; Ives et al. 1975; Crowley and North 1991). The ice-albedo feedback is such an effective mechanism that simple climate models indicate that if a polar region is snow covered it cannot be melted, and if it is not snow covered, snowfall does not survive the summer (Hay et al. 1990).

On the longer term, the isostatic adjustment of the earth's surface to the ice loads may be the cause of the 100 000-year periodicity of growth and decay of the northern hemisphere ice sheets of the later Quaternary (Weertman 1976; Oerlemans 1980, 1981, 1982; Birchfield et al. 1981, 1982; Pollard 1982; Hyde and Peltier 1985). As the ice sheet slowly grows, its weight depresses the crust; at its maximum thickness of approximately 3.5 km the ice sheet may depress the crust by approximately 1 km. If the equilibrium snow line, which separates the region of accumulation from that of ablation, were to remain constant for a long period of time, the ice sheet would reach a steady state. However, the equilibrium snow line moves up and down with insolation changes much more rapidly than the isostatic adjustment can occur. When the equilibrium snow line rises, the area of the ice sheet undergoing ablation increases, and there is more melting than accumulation. Because of the long response time of the isostatic adjustment to the lighter load, the area of ablation increases. This positive feedback mechanism could be responsible for the rapid melting of the northern hemisphere ice sheets at the end of each glacial. If the isostatic response plays a major role, the changes in eccentricity and obliquity may have acted as triggers for ice growth and decay, rather than as continuous external forcing mechanisms.

The inherent instability of ice sheets gounded below the level of surrounding fresh or marine waters has been cited as a cause of rapid deglaciation. Andrews (1973) suggested that the large proglacial lakes may have promoted rapid calving of ice from the Laurentide ice sheet. The large proglacial lakes of Russia (Grosvald 1979) would have similarly affected the Eurasian ice sheets. Rising sea level buoys grounded maritime ice sheets and makes them subject to surging. The layers of ice-rafted detritus deposited by flotillas of icebergs known as Heinrich events (Heinrich 1988; Broecker et al. 1990; Andrews and Tedesco 1992; MacAyeal 1993; Bond and Lotti 1995) are thought to reflect instability and surging of maritime ice sheets. Surging associated with sea-level rise may well have been the cause of the disintegration of the Barents ice sheet early in the last deglaciation (Sarnthein et al. 1992). This process has been suggested as a mechanism that could affect the West Antartic ice sheet, causing a rapid rise in sea level of a few meters (Mercer 1978).

Changes in vegetation affect both the albedo and the concentration of greenhouse gases in the atmosphere. In interglacials the high albedo (60–95%) ice and snow covering northern North America, Europe, and Asia have been replaced by low albedo (15–20%) evergreen forests and tundra (COHMAP 1988; Overpeck et al. 1992). Extensive sand deserts at lower latitudes were replaced by tropical forests and grasslands (Sarnthein 1978).

For many years it had been assumed that there were significant lags between insolation changes and climatic response. It is easy to understand why the growth of ice sheets should lag behind the insolation minima because it takes time for the ice to accumulate, and as it accumulates, the earth's surface responds to the load through isostatic adjustment. Until recently, it was thought that the LGM occurred 18 000 years ago, whereas the insolation curve calculated from orbital data indicated that the minimum insolation was approximately 24 000 years ago (Berger 1978b). The lag was explained as being due to the initially small change in insolation; only when the insolation had become significantly greater did the ice sheets begin to melt rapidly. The 18 000 year age of the LGM was based on ^{14}C dating, but lay beyond the interval that could be corrected for changes in the rate of ^{14}C generation using tree ring data. Fairbanks (1989) documented the record of sea-level change recorded by corals from Barbados, dated by ^{14}C, and concluded that the sea-level minimum was just prior to 17 000 years BP.

In recent years it has become apparent that glacial–interglacial climates can closely track the solar insolation in both space and time. Bard et al. (1990) reported that the coral samples from Barbados had been dated using the mass-spectrometric U–Th technique, making it possible to calibrate the older part of the ^{14}C scale. As shown in Fig. 5, the new U–Th dates demonstrate than the sea-level minimum occurred between 22 000 and 26 000 years BP. It was essentially coincidental with the 24 000 year BP insolation minimum marking the phase in the precession of the equinoxes when the earth is farthest from the sun in the northern hemisphere summer. Although it proceeded unevenly (Fairbanks 1989; Locker et al. 1996), almost all of the deglaciation took place during the increase in insolation between 24 000 and 11 000 years BP, very closely following the increase in insolation.

If we were living 11 000 years ago, knew the history of the LGM and the deglaciation, and had calculated solar insolation curves, we would expect that another, milder glaciation would occur 11 000–12 000 years in the future, i.e., today. If we knew only the past 35 000 years of the astronomical cycles, we would think that the climate is totally dominated by the precession cycle which produced the prominent northern hemisphere insolation minima at present and at 24 000 years BP, and maxima at 11 000 and 34 500 years BP shown in Fig. 5. However, Fig. 6 shows Berger's (1978b) calculations of insolation over the past 15 000 years, and it is immediately apparent that the past 35 000 years are exceptional. There have been major changes in insolation that departed from the sinusoidal form of the variation over the past 35 000 years. The interval from 35 000 to 70 000 years BP was particularly aberrant. The precession minimum which can be recognized at

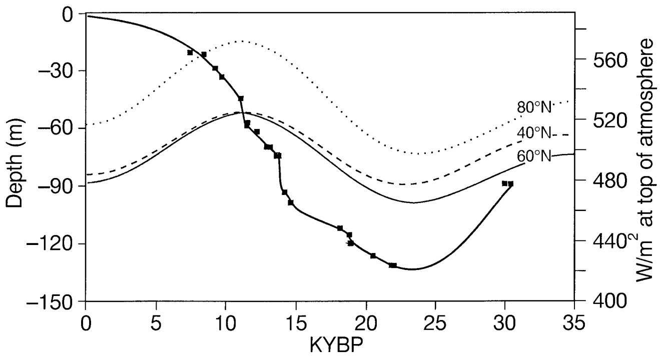


Fig. 5 Solar insolation curves and sea level for the past 35 000 years. Insolation curves for 80°, 60°, and 40 °N are from Berger (1978). Ages of Barbados corals which lived within a few meters of the sea surface are based on U–Th mass spectrometry (Bard et al. 1990). Depths at which the corals lived were corrected assuming a constant rate of uplift for Barbados of 0.3 m/1000 years, following Fairbanks (1989)

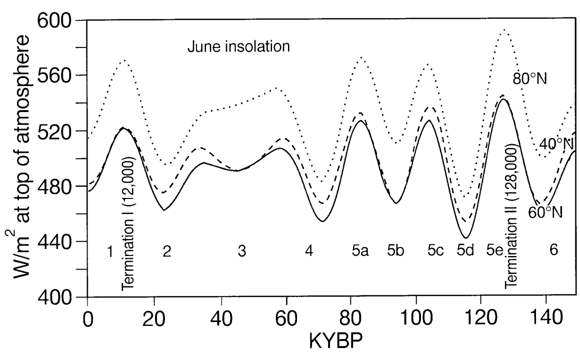


Fig. 6 Solar insolation curves for the past 150 000 years. Insolation curves for 80°, 60°, and 40 °N are from Berger (1978). Also shown are the glacial and interglacial stage numbers (*odd numbers* are interglacials, *even numbers* are glacials) and the terminations (deglaciations) of the last and penultimate major glaciations with their ages. (After Broecker 1995)

46 500 years BP at 40 °N is merely a change in the slope of the insolation curve at 80 °N. The last glaciation was different from many of the preceding glaciations because of this peculiar insolation history. The insolation during the present interglacial and next 60 000 years is unusual because the ellipticity of the earth's orbit is unusually low, in one of the 400 000-year minima. Because of the low eccentricity, the role of the obliquity effect is enhanced. Berger et al. (1981) suggested that the first strong cooling forced by orbital variations, the cooling that in the absence of anthropogenic perturbations would lead to a major glaciation, will not come until 60 000 years from now.

The intensity of the latitudinal insolation minimum associated with the polar circle also changes with time, as shown in Figs. 5 and 6. This is a result of the interference of the change in obliquity of the earth's axis of rotation with the precession-ellipticity cycles.

The reduction in the intensity of the meridional insolation minimum may be why the northern hemisphere ice sheets are not forming again presently, even though there is a northern hemisphere insolation minimum. Another possible explanation is that the present temporal and latitudinal summer insolation minima are both less than at 24 000 years BP. The growth of the northern hemisphere ice sheets to their maximum size from 30 000 and 24 000 years BP was probably a result of the intensity of both the temporal and latitudinal summer insolation minima. The disappearance of the latitudinal summer insolation minimum between 24 000 and 11 000 BP was a major factor in promoting the rapid deglaciation. We are presently at a minimum for northern hemisphere summer insolation. In 11 000 years the northern hemisphere summer will again coincide with perhelion. Over the next few tens of thousands of years, the northern hemisphere insolation will resemble that between 30 000 and 60 000 years BP, and a return to an intense minimum of insolation at the northern hemisphere polar circle will occur in approximately 60 000 years (Berger 1987b; Berger et al. 1981).

Insolation fails to explain one major aspect of the earth's recent climate history, the synchroneity of the southern and northern hemisphere of at least the last climate cycle of glaciation and deglaciation. Genthon et al. (1987) postulated that the interhemispheric synchroneity was forced by changes in atmospheric CO_2. It is more likely that it was forced by sea level change.

Atmospheric greenhouse gases

A second major variable in the climate system is the greenhouse gases in the atmosphere. All air molecules with more than two atoms, such as H_2O, O_3, CO_2, CH_4, and the man-made chlorofluorocarbons, capture incoming or outgoing radiation (Wells 1986). Some of the gases are more efficient at capturing incoming short-wave solar radiation; others preferentially trap the long wave outgoing radiation from the earth's surface, and are the greenhouse gases proper.

Water vapor

Water vapor is the most effective greenhouse gas, but its content in the atmosphere is strongly dependent on temperature, as shown in Fig. 7. Because of the meridional temperature gradient that exists presently, the effectiveness of water vapor as a greenhouse gas is largely limited to equatorial and tropical regions. Because of the cooling of air as it rises, most of the moisture in the equatorial and tropical atmosphere is trapped in the lower troposphere. Much of the capture of long-wave radiation by water vapor occurs within a few hundred meters of the earth's surface (Wells 1986).

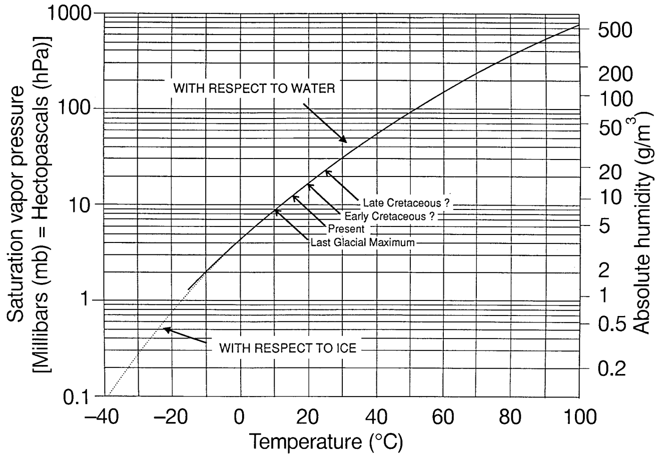


Fig. 7 Saturation vapor pressure for H_2O vs temperature. The average amounts of water vapor that can be incorported in air at different global temperatures are indicated

This means that there is a positive feedback effect, with the water-vapor-warmed air increasing the amount of water vapor that the air near the surface can hold.

Methane

Methane has been suspected as another greenhouse gas that may have played a significant role in the climate of the past. Methane is produced by anaerobic decomposition of organic matter in swamps and bogs, and by ruminant animals, such as cows and perhaps dinosaurs (Bakker 1986). Ice core studies have shown that during the LGM methane levels in the atmosphere were about half of their pre-industrial value (Stauffer et al. 1988), and that they have doubled since the industrial revolution (Craig and Chou 1982). The increase since the last glaciation is most likely due to the increase in area of high-latitude peat bogs and lower latitude coastal swamps.

Carbondioxide

Carbon dioxide is the other greenhouse gas and suspected of having been a major factor in influencing the earth's climate in the past. Shortly after it was discovered by Arrhenius that CO_2 traps radiation and moderates the temperature of the atmosphere, Chamberlin (1899) suggested that higher levels of atmospheric CO_2 might be responsible for the warm climates of the Mesozoic. Because of its effects as a greenhouse gas, Budyko and Ronov (1979) proposed that increased levels of atmospheric CO_2 were responsible for the warm polar conditions that prevailed during the Late Cretaceous. They also believed that they could quantify major long-term increases and decreases in the CO_2 content of the atmosphere from the masses of carbonate rocks of different ages preserved on the continents. This proved to be incorrect because they had neglected to include the carbonate deposited in the deep sea (Hay 1985) and because they did not take sedimentary recycling into account. However, Budyko and Ronov (1979) and Budyko et al. (1987) reasoned that the CO_2 content of the atmosphere should parallel the waxing and waning of volcanic activity recorded by the mass/age distribution of volcanic rocks, a correct assumption. Berner et al. (1983), Lasaga et al. (1985), and Berner (1991, 1994) have attempted to quantify the concentrations of atmospheric CO_2 in the past using estimates of variations of the rate of sea-floor spreading as a proxy for global volcanic activity. Their geochemical modeling supported the idea of long-term fluctuations in the CO_2 content of the atmosphere. In the earlier versions of their model the Cretaceous concentrations were estimated to be more than ten times greater than present. Although modifications and improvements have reduced the estimate, they still predict concentrations of up to six times greater than present in the Mesozoic. In their models the CO_2 is supplied by volcanic activity at spreading centers and subduction zones and is directly related to the rate of sea-floor spreading. Larson (1991a, b) proposed that intraplate volcanism during the Early Cretaceous may also have been a major source of CO_2 to the atmosphere. Coffin and Eldholm (1992) have compiled a list of large igneous provinces that formed during short-lived episodes of massive hot-spot volcanism. Each of these could have added large amounts of CO_2 to the atmosphere.

Carbon dioxide is permanently removed from the atmosphere when organic carbon is buried and when igneous rocks weather through the carbonation reaction:

$$\underset{\text{wollastonite}}{CaSiO_3} + 2H_2O + 2CO_2 \xrightarrow{\text{weathering}} \underset{\text{in river water}}{Ca^{++} + 2HCO_3^- + 2H^+ + SiO_3^=} \xrightarrow{\text{transport}}$$

$$\xrightarrow{\text{deposition}} \underset{\text{Calcite}}{CaCO_3} + \underset{\text{Opal}}{SiO_2 \cdot H_2O} + H_2O + CO_2$$

where $CaSiO_3$ is one of the many possible silicate minerals. The carbonation reaction with silicate minerals is thought to be the ultimate mechanism for consumption of atmospheric carbon dioxide, but proceeds very slowly (Volk 1987; Brady 1991; Sundquist 1991; White and Brantley 1996). It is probably responsible for long-term climatic trends, such as the global cooling since the Eocene, but may also have a significant influence on glacial–interglacial timescales (Munhoven and François, in press).

Variations in atmospheric CO_2 are known to occur during the Quaternary, both on a glacial–interglacial and shorter timescales. Ice cores indicate that the preindustrial level of atmospheric CO_2 was approximately 280 ppm (Neftel et al. 1985) and it has currently increased to approximately 345 ppm. The ice cores also show that during the LGM the level of atmospheric CO_2 was approximately 195 ppm (Delmas et al. 1980; Neftel et al. 1982; Neftel et al. 1988). The glacial–interglacial CO_2 changes are a major amplifier of the insolation signal. Feedback mechanisms that may affect the concentration of CO_2 in the atmosphere include: changes in vegetation, changes in sedimentation in response to sea level, changes in the concentration of atmospheric CO_2 and changes in ocean currents and heat transport (Broecker and Denton 1989; Broecker 1995).

The increased area of forests implies an increase in global biomass and storage of carbon in wood. Shackleton (1977) interpreted the glacial–interglacial change in ^{13}C as a reflection of the response of tropical rain forests, with significant reduction in their extent during the glacials. The increased interglacial biomass implies a reduction in atmospheric CO_2 by approximately 20 ppm, a negative feedback mechanism acting to stabilize the climate (Adams et al. 1990). However, the interglacial increase in high-latitude bogs in the areas once covered by ice and in coastal swamps produced by the sea-level rise implies an increase in another greenhouse gas, CH_4, a positive feedback mechanism (Broecker 1995).

Changes in the sedimentation system in response to changing sea level may have a significant effect on atmospheric CO_2 content. Terrigenous matter from land supplies the shelf with large amounts of organic carbon (C_{org}) via rivers draining forested areas. Berner (1982) estimated that 130×10^9 kg of C_{org} is buried each year as shelf sediments, and only 10% of this amount is destroyed during diagenesis. This means that approximately 10×10^{12} moles of CO_2 are removed from the atmosphere annually by burial of C_{org} in shelf sea sediments. He also estimated that only approximately one fourth as much, 27×10^9 kg, C_{org} is buried each year in oceanic sediments. Many shelf areas lie near river mouths and estuaries. Nutrients are plentiful, the rate of biologic C fixation is high, and C_{org} burial is enhanced. The net effect should be to lower atmospheric CO_2 through the rapid burial of organic carbon. However, there is another process occurring in shallow water that may affect the flux of CO_2 from and to the atmosphere, the dissolution and deposition of shallow-water carbonates in response to sea-level fall and rise, following the reactions:

$$CaCO_3 + CO_2 + H_2O \xrightarrow{\text{dissolution}} Ca^{++} + 2HCO_3^- \xrightarrow{\text{transport}}$$

$$\xrightarrow{\text{deposition}} CaCO_3 + CO_2\uparrow + H_2O$$

During the glacial low stands of sea level, carbonate shelves and platforms are subaerially exposed and subject to weathering, increasing the supply of Ca^{++} and HCO_3^- to the sea. This process is reversed when sea level rises during the interglacials, flooding the carbonate shelves and platforms (Hay and Southam 1977; Berger 1982; Opdyke and Walker 1992). Carbonate is deposited and CO_2 is returned to the atmosphere. As Hay (1985) observed, at least two thirds of earth's carbon is in the form of carbonate, so that the carbonate dissolution–deposition dominates the cycle and is probably the most important process for removing and supplying CO_2 from and to the atmosphere on glacial–interglacial timescales.

In addition to the two mechanisms listed above which act to change the CO_2 content of the atmosphere, glacial–interglacial changes in seawater would act to affect atmospheric CO_2. According to Broecker (1995), the increased salinity of seawater during the glacial would have reduced its ability to absorb CO_2, a negative feedback increasing atmospheric CO_2 levels by approximately 11 ppm during the last glacial. However, he also estimated that if the surface ocean were 5 °C cooler during the last glacial, as indicated by snow-line depression in mountains and other data, it would have absorbed more CO_2, a positive feedback that would have reduced atmospheric CO_2 by approximately 52 ppm.

Changes in ocean circulation and heat transport are another possibility for amplifying the effect of insolation changes. Broecker and Denton (1989, 1990) proposed that it was a change in the rate of production of North Atlantic Deep Water (NADW), which they considered to be the driving force of the global thermohaline circulation system ("The Great Conveyor"), which has the greatest effect on atmospheric CO_2 content. If the thermohaline circulation system runs rapidly, the deep ocean is better ventilated, but if it is sluggish, CO_2 accumulates in the deep sea at the expense of the atmosphere. Today, a major component of NADW is dense waters overflowing the Greenland–Iceland–Scotland ridge from the Norwegian–Greenland Sea. However, during the low sea level of the last glacial the Greenland–Iceland–Scotland ridge was much shallower and the volumes of water that could have been contributed to NADW production were much reduced. The depth of the Greenland–Iceland–Scotland ridge exerts a strong influence on the rate of deep-water production in the North Atlantic. As the rate of NADW production decreases, CO_2 accumulates in the deep sea at the expense of the atmosphere; this is another positive feedback mechanism affecting the glacial–interglacial climate system.

It has also been found that changes in atmospheric CO_2 content of the order of 30% have occurred on millennial timescales (Stauffer et al. 1985). Ice core records have shown that during the Younger Dryas, a millenium-long return to glacial conditions from approximately 12 500 to 11 500 BP during the last deglaciation, there was a dramatic drop in the CO_2 content of the atmosphere. The most likely explanation of such short-term changes, and probably of the glacial– interglacial changes as well, are that they are the result of changes in the thermohaline circulation and rates of productivity in the ocean. If global upwelling rates were enhanced by increased wind speeds during the Quaternary glacials and the Younger Dryas, the rate of C fixation by plankton would have increased and the flux of particulate organic matter from the surface to the deep ocean would have increased. On short timescales, such as the Younger Dryas, this would result in an increase in the CO_2 in the deep sea. On longer timescales, such as the last glaciation, the rate of C_{org} burial may have increased. These processes would lead to depletion of CO_2 from the ocean surface waters, inducing an influx of CO_2 from the atmosphere and hence causing atmospheric CO_2 levels to decline (Sarnthein et al. 1988; Sarnthein and Fenner 1988).

Climate model simulations with present earth boundary conditions, except for a doubled atmospheric CO_2 concentration, indicate that the increased CO_2 raises the temperature of the polar regions while having little effect on the tropics and equatorial region (Schlesinger 1989). This is because the warm lower atmosphere of low-latitude areas already has a high content of a major greenhouse gas, water vapor. Adding CO_2 to the atmosphere most strongly affects the colder high-latitude areas where the water vapor content of the air is low. The overall effect is to produce strong polar warming. The warmer polar air can then hold more water vapor, creating a positive feedback enhancing the greenhouse effect.

The 30% glacial–interglacial variations in CO_2 content of the atmosphere are minor compared with those between the warm "greenhouse" earth and its present "icehouse" state, thought to be of the order of 400–500%. The present anthropogenic injection of fossil fuel CO_2 into the atmosphere has occurred at a time when the natural glacial–interglacial CO_2 variability is at a maximum. It has already elevated atmospheric CO_2 to a level that is probably higher than any time in the past few million years. Hence, it may be useful to examine a climate characteristic of a time when the earth's atmosphere probably had significantly higher levels of CO_2 than in its recent history.

The Createaceous climate paradox and its solution

The Late Cretaceous was a time when the earth's meridional temperature gradient was much reduced over present (Fig. 8). The polar regions were significantly warmer than at present and the mean annual temperature was above freezing in both hemispheres. A decade ago Barron (1981, 1983, 1984, 1985) and Barron and

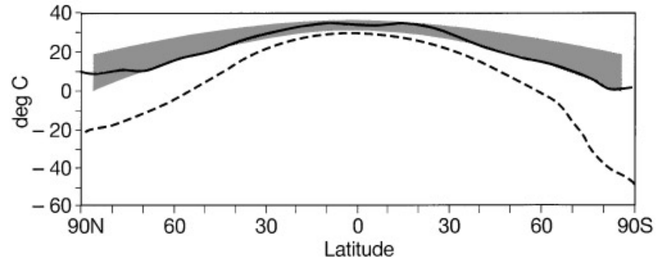


Fig. 8 The present zonally averaged meridional temperature gradient of the earth, the envelope of meridional temperatures indicated by paleontologic and sedimentologic proxies (*gray area*), and the zonally averaged meridional temperature gradient simulated for the Campanian by GENESIS Version 2.0

Washington (1982, 1984, 1985) performed a number of climate model experiments to determine whether the different global climate was a result of the different paleogeography, the high sea level, a different albedo, different ocean heat transport, or elevated CO_2. Those climate model experiments demonstrated that an increased CO_2 level four times present greatly facilitates the maintenance of warm polar temperatures (Barron and Washington 1985; Schneider et al. 1985). Although increased atmospheric CO_2 raises the polar temperatures, it became apparent that this was not a complete answer to the problem of the warm climates of the late Mesozoic because the interiors of the continents remained cold during the winters (Sloan and Barron 1990). Geologic evidence for high levels of CO_2 in the Cretaceous atmosphere continues to build. In addition to the global geochemical arguments for high levels of atmospheric CO_2 cited above, elevated levels of CO_2 have been documented from studies of isotopic fractionation (Freeman and Hayes 1992; Popp et al. 1989), deep-sea sediments (Berger and Spitzy 1988), from paleosols (Cerling 1991), and from surficial deposits (Yapp and Poths 1992).

The Cretaceous climate has been considered an apparent paradox. The problem can be simply stated by three paradigms: (a) both the atmospheric and ocean heat transport systems of the earth are driven by the meridional temperature gradient; (b) during the Cretaceous the meridional temperature gradient was much less than it is presently, implying that the atmospheric and ocean heat transport systems were much more efficient then than they are today; (c) the lesser meridional temperature gradient means that the driving force behind atmospheric and ocean heat transport must have been less. Thus, there has been something quite important about the climate system that we have not understood. To gain further insight into the nature of the warm climate of the Late Mesozoic we prepared a new simulation of Late Cretaceous climate using the GENESIS Version 2.0 Earth System model.

The GENESIS Earth system model

GENESIS is a numerical climate system model developed by David Pollard and Starley Thompson of the U.S. National Center for Atmospheric Research (NCAR) and designed specifically to simulate climates of the earth's past (Wilson et al. 1994; Pollard and Thompson 1995, in press; Thompson and Pollard 1995a, b, in press). GENESIS uses an Atmospheric General Circulation Model (AGCM) as its core component, coupled to a 50-m layer slab ocean model and multi-layer models of soil, snow, and sea ice.

The GENESIS ACGM component is a heavily modified version of the NCAR Community Climate Model (CCM1) described in Williamson et al. (1987). The standard CCM1 code was extensively modified to include new model physics and global arrays instead of temporary disk files. Primary modifications and additions to the original CCM code include a diurnal cycle with solar radiation calculations performed every 1.5 model hours. The solar radiation scheme of Thompson et al. (1987) performs delta-Eddington calculations for all atmospheric layers. Multi-layer, randomly overlapping clouds are included in the solar radiation calculations. In addition to CO_2, the radiative effects of trace gases (CH_4, N_2O, and CFCs) are treated explicitly. The radiative effects of tropospheric aerosols can also be included. Water vapor is advected in grid space by a semi-Lagrangian transport, as described in Williamson and Rausch (1989), Rausch and Williamson (1990), and Williamson (1990). Atmospheric convection and planetary boundary layer mixing is simulated using an explicit sub-grid scale plume model (Anthes 1977). The cloud parameterization is similar to Slingo and Slingo (1991), and uses three types of clouds: stratus, anvil cirrus, and convective. Atmospheric dynamics in GENESIS Version 2.0 include a gravity-wave drag parameterization (McFarlane 1987) and dynamic Courant spectral truncation in the upper stratosphere, which is used for numerical stability. The AGCM uses a Gaussian latitude grid, close to but not equispaced (Washington and Parkinson 1986). The AGCM resolutions for version 2.0 are a spectral horizontal T31 grid (3.75 latitude and longitude) and 18 vertical levels. The resolution of version 1.02, used by us for Triassic simulations (Wilson et al. 1994), was R15 (ca. 4.75 latitude and longitude) with 12 vertical levels. Three of the six additional levels in version 2.0 are in the planetary boundary layer. The Gaussian AGCM grid is independent of the equispaced surface grid, with fields transferred between them by bilinear interpolation (AGCM to surface) or straightforward area averaging (surface to AGCM) at each time step. The equispaced surface grid, used by Land Surface Transfer Scheme (LSX), soil, snow, sea ice, and ocean models has resolution of $2° \times 2°$.

The LSX serves as the interface between the atmosphere and the land surface, including the vegetation.

The LSX is based on the earlier models of BATS (Biosphere–Atmosphere Transfer Scheme; Dickinson et al. 1986) and SiB (Simple Biosphere model; Sellers et al. 1986). It computes the exchanges of momentum, thermal energy, and water mass between the atmosphere and the land surface, accounting for the physical effects of vegetation, soil texture, and snow cover. Two vegetation layers or canopies, such as trees and grass, can be specified at each grid point. The radiative and turbulent fluxes through these layers to the soil or snow surface are calculated. Rain or snow is intercepted by the vegetation and eventually drips or blows off. Given the current AGCM conditions above the upper canopy and the soil or snow conditions below, the LSX predicts vegetation temperatures and canopy air temperatures and specific humidities. Prognostic fields are then passed back to the AGCM, allowing interaction between the earth's surface and atmosphere. The two vegetation canopy heights, leaf area index, fractional cover, leaf albedo, and leaf orientation, are defined by the vegetation type specified at each point on the surface grid. In this simulation the vegetation phenology and physical attributes are defined by the potential plant community structure defined by the Equilibrium Vegetation Ecology (EVE) model.

The EVE model, developed by Jon Bergengren and Starley Thompson at NCAR, predicts plant community structure as a function of temperature, precipitation, relative humidity, and fundamental ecologic principles. EVE can be run "interactively" with GENESIS, so that GENESIS provides the climatic information that drives EVE, and in return EVE provides the vegetation boundary conditions for the land surface component of GENESIS.

A six-layer soil model extends to a depth of 4.25 m. Heat is diffused linearly and moisture non-linearly according to soil texture (Clapp and Hornberger 1986). Soil moisture is removed from rooted soil layers according to transpiration rate. Ice within the soil is predicted, and the latent heat of fusion and amounts of ice and liquid water are accounted for explicitly. Surface runoff and subsurface gravitational drainage are allowed to occur if precipitation minus evaporation exceeds the infiltration rate. Combined runoff and drainage is globally integrated and transferred uniformly to the ocean at each time step. Stochastic precipitation is supplied by single-point LSX values instead of AGCM grid averages. Ponding of water at the surface is also allowed to occur at grid points where the precipitation rate exceeds the infiltration rate. The model also includes an explicit litter layer, non-local downward transport through near-surface microscopic channels, and hydrostatic pressure in saturated soil columns.

A three-layer snow model is used for snow cover on soil, ice sheet, and sea-ice surfaces. The vertical snow column is modeled by a standard finite-difference technique. Total snow thickness is changed according to melting and accumulation rates on the uppermost layer. Fractional snow cover is also accounted for. In GENESIS Version 2.0, snow moisture content, percolation, and refreezing are modeled after Loth et al. (1993).

A six-layer thermodynamic sea-ice model predicts the local melting and freezing of ice according to standard finite-difference techniques like those in Semtner (1976). Heat is diffused linearly through the ice, with changes in the total thickness controlled by melting or freezing of the top and bottom layers.

The ocean model component of GENESIS is represented by a 50-m thermodynamic slab. The slab ocean captures the seasonal thermal capacity of the ocean's mixed layer. Poleward oceanic heat flux is defined as a linear diffusion down the local temperature gradient, according to a zonally symmetric function of latitude based on present-day observations (Covey and Thompson 1989) and the zonal fraction of land and sea at a given latitude. A multiplicative of the diffusion coefficient can be prescribed.

Boundary conditions

As boundary conditions, the new Campanian climate simulation used a solar constant 99.32% present (1355.7 W/m^2), a mean orbital configuration (eccentricity = 0, obliquity = 23.5°), and a prescribed heat transport in the slab ocean model with values similar to today. Atmospheric CO_2 was specified at 1500 ppm (ca. 4.4 times greater than today). Solid-earth boundary conditions were provided by a global paleogeographic reconstruction of the Campanian, based on a new global plate tectonic model for the Cretaceous (Hay et al., in press).

The success of the new simulation depended partly on the detailed representation of the climate system components that are usually generalized or neglected: paleogeography, soil texture, and vegetation. Campanian vegetation was simulated by EVE. Only plant life-forms with known Late Cretaceous analogs were included in the simulation. In particular, water-conserving C4 plants (e.g., grasses), which dominate a large area of the continental interiors today, were not widespread in the Mesozoic. In the simulation, grasses were replaced by more readily transpiring herbaceous C3 plants (forbs). The "grasslands" of today were "fern-forb prairies" in the late Cretaceous (DeConto 1996; DeConto et al., in press).

Results of the simulation of Late Cretaceous climate

As shown in Fig. 8, the recent simulation of the climate of the Campanian stage of the Late Cretaceous (80 Ma) using the GENESIS (version 2.0) Earth System Model satisfies the required low meridional temperature gradients and warm continental interiors indicated by proxy climate data (DeConto 1996; DeConto et al., in press). The results of the simulation fit within the temperature envelope indicated by paleo-faunal and -floral proxy data. The mean annual temperatures in both polar regions are above freezing. The simulation also correctly predicts the occurrence of evaporites (Wold and DeConto, submitted).

The results of the Campanian simulation are compared with a GENESIS simulation of the modern climate in Figs. 9–12, and the results of the proxy formation model for evaporites are shown in Fig. 13. Comparison of model results with observational data have shown that GENESIS closely simulates the modern climate (Thompson and Pollard 1995a, in press). Figure 9 compares the mean annual temperature of the Campanian with that simulated for today. The polar regions are much warmer in the Campanian simulation, with the mean annual North Polar temperature approximately 8 °C (compared with -20 °C today) and the South Polar mean annual temperature approximately 2 °C (compared with ca. -50 °C today). The equatorial and tropical regions are significantly warmer, approximately 32 °C compared with 28 °C today. Because these regions have such a large area, the global temperature of the planet is warmer, as is also indicated in Fig. 7. The increased global warmth implies an increased role for water vapor in the planet's atmospheric dynamics. Figure 10 compares the surface level pressures of the Campanian simulation with those of today. The general features are the same as today, with an anomalously high-latitude high-pressure system over Campanian eastern Asia. The intensity of the polar highs is reduced in the Campanian simulation. The pressure differences between highs and lows are slightly less (20%) in the Campanian simulation than for the present. Figure 11 compares the precipitation for the two simulations. The Campanian earth is obviously a much wetter planet than that of today, with 25% more precipitation and twice as much precipitable water vapor in the atmosphere. Areas of very low precipitation are restricted to the southern hemisphere tropical regions of South America and Africa. Figure 12 compares the cloud cover for the two simulations and shows that the cloudiness of the Campanian simulation is much greater than that of today, especially at high latitudes. The precipitation and cloudiness reflect an intensified hydrologic cycle and significantly increased latent heat transport by the atmosphere. Examination of zonally averaged data show that the major difference between the simulated Campanian climate and the modern climate lies in the latent heat transport.

The use of proxy formation models for verification of a climate model was suggested by Pollard and Schulz (1994) and applied to Triassic simulations of Wilson et al. (1994). Proxy formation models have been further developed by C. N. Wold to determine where the climatic conditions are appropriate for the formation of a variety of climate-sensitive sediments. The Campanian simulation has been validated using proxy formation models for evaporites and bauxites (Wold and DeConto, in press). The proxy model for evaporites calculates the balance between precipitation generated by the AGCM and evaporation from an isolated pool of brine that does not exchange heat with the ocean. Evaporation from a brine is less than from seawater at the same temperature. Figure 13A and B shows the proxy formation model prediction for the occurrence of evaporites and the distribution of evaporite deposits of Campanian age for the northern and southern hemisphere summers, respectively. In this case the proxy model calculated the excess of evaporation over precipitation for brines with a salinity ten times that of seawater; at this salinity further evaporation would deposit halite. Deposition of gypsum and anhydrite would occur at low values of excess evaporation over precipitation. The proxy formation model correctly predicted the potential for existence of evaporites in almost all of the places where Campanian evaporite deposits are known to occur. Introducing a higher atmospheric content of CO_2 to an earth with vegetation having a higher rate of evapotranspiration results in an overall warmer and wetter planet, with warmer continental interiors in winter. The introduction of CO_2, a greenhouse gas which does not depend on temperature, resulted in a much larger increase at atmospheric H_2O both as water vapor and as clouds. Because both water vapor and clouds contribute to the greenhouse effect by absorbing long-wave radiation from the surface of the planet, a powerful positive feedback mechanism for maintaining global warmth is set in place. The role of latent heat transport in the atmosphere is significantly increased.

The answer to the Cretaceous paradox is that one of the paradigms is untrue: the assumption that it is the meridional temperature gradient that drives atmospheric and ultimately oceanic circulation. The results of the GENESIS simulation show that it is possible for the earth to have a state in which the atmospheric high- and low-pressure systems and winds are produced by differences in water vapor content as well as temperature. The Cretaceous meridional temperature gradient is reduced by 40%, but the wind stress is reduced by only 14%. The higher global temperatures increase the vapor content of the troposphere (saturation doubles with every 10 °C increase, as shown in Fig. 7). As Avogadro noted in 1811, equal volumes of gases at the same temperature and pressure must contain the same number of atoms or molecules (Emiliani 1992). The light H_2O (molecular weight = 18) replaces heavier O_2, N_2, and Ar (average molecular weight = 29) in a given volume, and reduces the density of the air, this has the same effect as warming the air. Water vapor is also the most effective greenhouse gas. In the new Cretaceous simulation tropical temperatures reach 34 °C, which allows the atmospheric content of vapor to increase

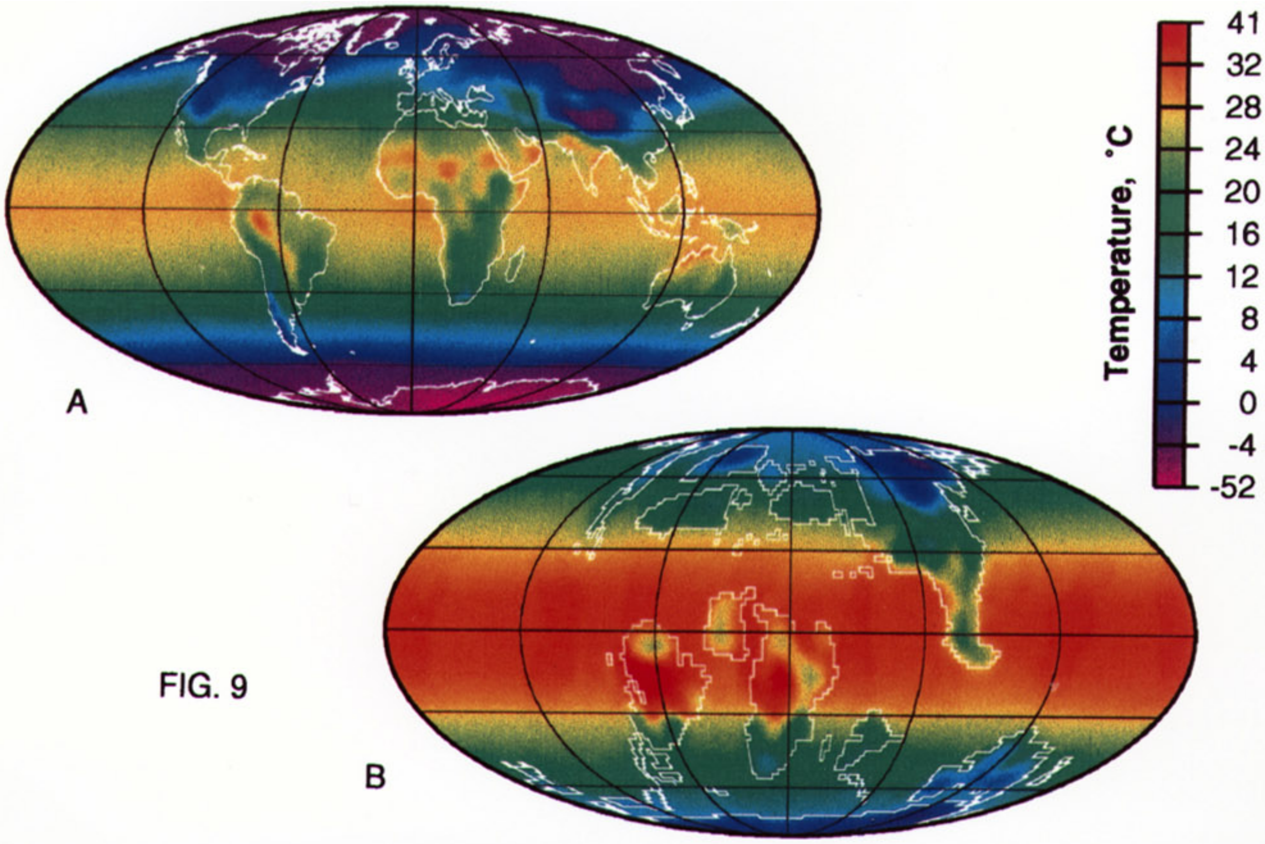

41
32
28
24
20
16
12
8
4
0
-4
-52
Temperature, °C
A
B

FIG. 9

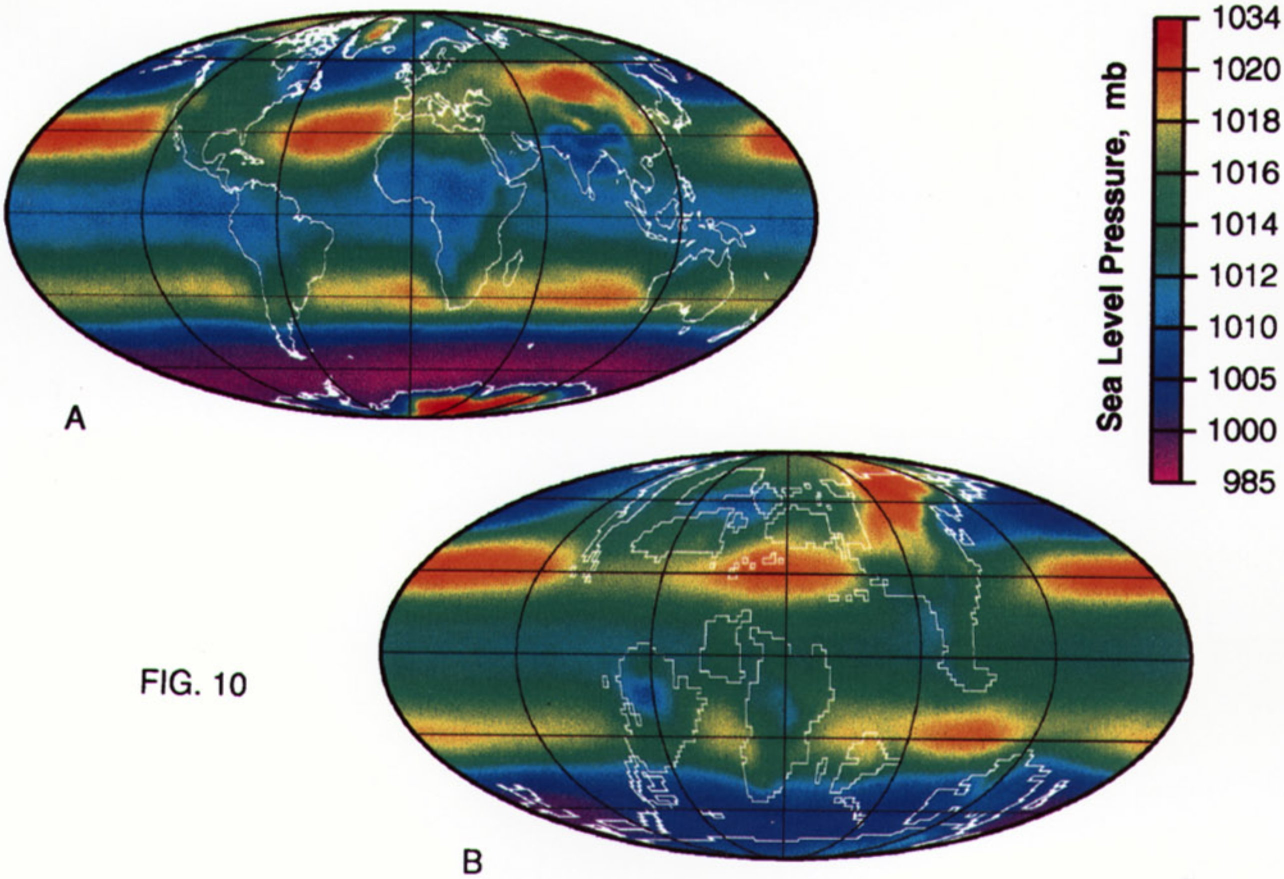

1034
1020
1018
1016
1014
1012
1010
1005
1000
985
Sea Level Pressure, mb
A
B

FIG. 10

locally to almost 150% its present value (Fig. 7). In the polar regions the vapor content increases by 1000%. Even with the reduced meridional temperature gradient, the contrast between atmospheric high- and low-pressure systems is only slightly less than today. The high vapor content allows the planet to utilize efficient latent heat transport from the equator to the poles. Because of the large latent heat of vaporization, latent heat transport is the most efficient form of energy transfer for the atmosphere. Its greatly increased role in meridional heat transport in the Campanian simulation indicates that during the Late Cretaceous the planet had a climatic state quite different from that of today or during the LGM.

The past as the key to the future?

James Hutton's Principle of Uniformitarianism, "the present is the key to the past," has served as the credo of geology for 200 years. If the present is the key to the past, then the past should be the key to the future. Unfortunately, it is becoming apparent that we live in a very peculiar geologic age. Sea level rose 130 m between 24 000 and 7000 years BP and has remained nearly constant since then. Massive extinctions have been a characteristic of the last deglaciation. Weathering, sediment transport, and depositional systems have not caught up with the rapid changes associated with the deglaciation. To make matters worse, the Holocene is unusual in being more climatically stable than previous interglacials, and the last glacial, compared with earlier glaciations, was exceptional in the magnitude of its stages of ice-sheet growth and retreat (Denton and Hughes 1981).

Onto this uncertain scene has come the greatest agent of change the earth has ever seen,"civilized mankind." The human race is performing a major experiment on the planet. The industrial revolution has made humans the primary global agent of weathering, erosion, the major cause of changes of vegetation, and the fastest modifier of atmospheric chemistry since the evolution of photosynthesis Watson et al. (1996). The burning of fossil fuels and deforestation are injecting CO_2 into the atmosphere at an increasing rate. The CO_2 content of the atmosphere has already increased to more than 125% of its pre-industrial level. A doubling of the CO_2 content is expected by the middle of or late in the next century, and a quadrupling, to Late Cretaceous values, could occur by the end of the 22nd century. At the same time, deforestation is changing both the albedo of the planet's surface and the rate of evapotranspiration over land. The replacement of forests by grasslands involves replacement of readily transpiring C3 plants by water-conserving C4 plants. Soil modification and erosion from the expansion of areas devoted to agriculture and ranching tend to increase runoff and reduce infiltration of water into the deeper soil layers and ground-water system. The vegetation cover of the planet is being drastically altered by modern agricultural practices and the use of plant products. Both animal and plant species are being lost to extinction. The changes on the surface of the planet over the past 150 years, but mostly in the past few decades, are so extensive and pervasive that a projection of "climate change as usual" is certain to be untrue. There is no precedent for the rate at which these changes are occurring, except possibly the hypothesized impact of a bolide at the end of the Cretaceous.

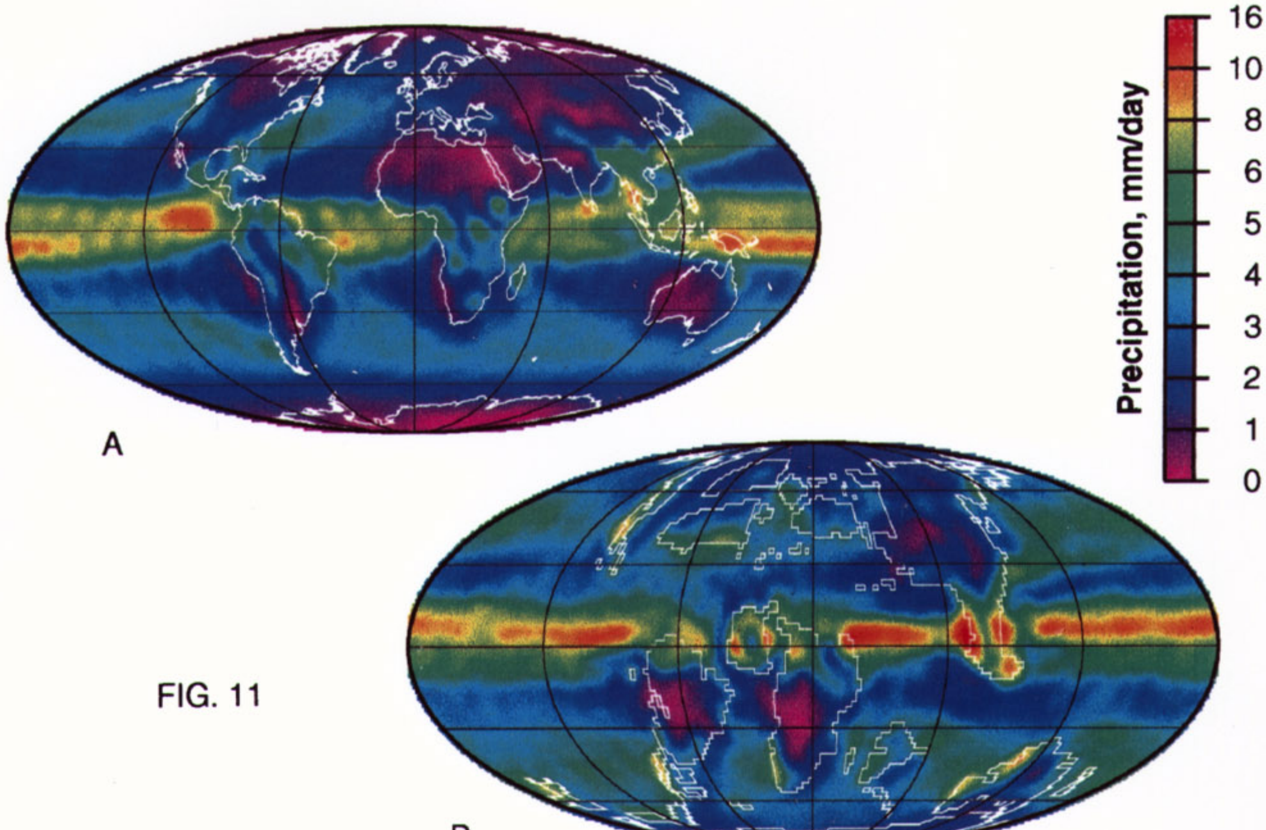
The earth is near the minimum in northern hemisphere and the maximum in southern hemisphere summer insolation. This produces a sensitive situation in the polar regions. The current injection of CO_2 into the atmosphere should reinforce the summer heating in the polar regions. In its current "icehouse" state, the positive ice-albedo feedback plays a major role in the climate of the earth. The highly reflective surface of ice in the polar regions acts as a mirror to incoming radiation ensuring that the poles remain cold. However, in the Arctic, most of the reflective surface is sea-ice only a few meters thick, floating on water. The sea ice acts as a thermal insulator between the water (-2 °C) and the atmosphere (-20 °C). If the Arctic sea ice were to melt, two things would happen: (a) the white surface would be replaced by the much darker and absorbent water; and (b) the air temperature would rise to approximate that of the water. Although at the low sun angles in the Arctic, the water would still reflect some of the incoming solar radiation; much more would be absorbed than at present. The increased air temperature would quadruple the atmospheric content of an important greenhouse gas, water vapor. These two positive feedback mechanisms should force a further rise in the temperature of the Arctic.

In the southern hemisphere, the summer insolation will be at its maximum for the next thousand years or so. Will the increasing CO_2 content of the atmosphere be enough to overcome the ice-albedo feedback effect of Antartica and start the melting of the Antarctic ice sheets before the summer insolation decrease takes place?

A major question about the earth's future is whether the planet will recover from the anthropogenic perturbation before a change in the state of the climate takes place. Will the earth remain in an interglacial in its "icehouse" state, return to a full glacial, or shift back to its long-term preferred "greenhouse" state? Another possibility was suggested by Flohn (1981). He noted

Fig. 9A, B Mean annual temperature (°C). **A** Present climate simulation. **B** Campanian climate simulation

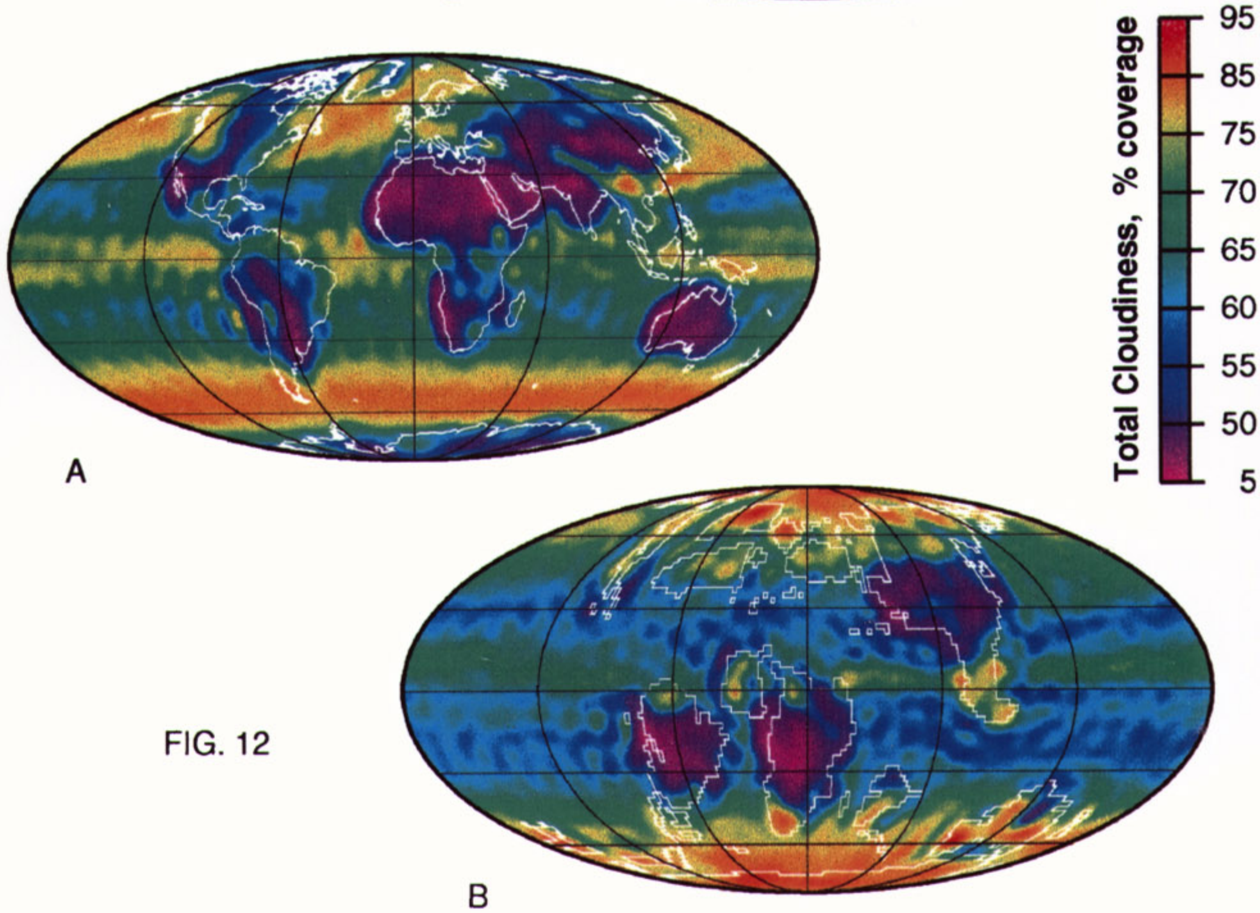
Fig. 10A, B Mean annual surface pressure in hPa (=mb). **A** Present climate simulation. **B** Campanian climate simulation



A

FIG. 11

B



A

FIG. 12

B

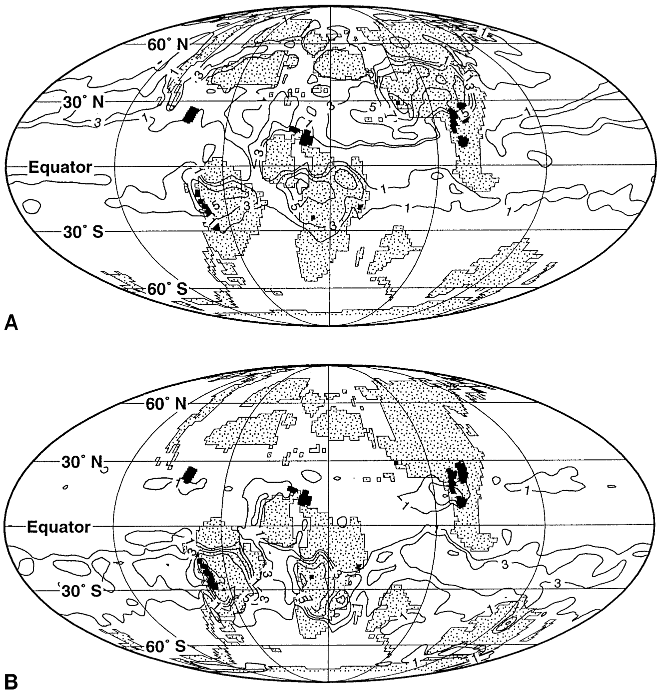


Fig. 13A, B Proxy formation model for evaporites, showing predictions of the occurrence of halite and the known occurrences of halite and anhydrite/gypsum deposits. Contours are excess of evaporation over precipitation (mmday) calculated for a brine with a salinity of 350 ppt. **A** Northern hemisphere summer. **B** Southern hemisphere summer

that during the later Tertiary, the earth had a peculiar climatic state with the southern hemisphere glaciated and the northern hemisphere ice free. The planet remained in this state of unipolar glaciation for much longer (20 million years) than it has had bipolar glaciation (5 million years). He suggested that the unipolar glaciation had very significant climatic consequences, producing asymmetric circulation of both the atmosphere and ocean.

Crowley (1990) has argued that there are no geologic analogs for future greenhouse warming. In this case the past holds no keys to the future. However, the past does offer clues to the future. The Cretaceous simulations suggest that with a high atmospheric CO_2 content and the vegetation that existed at that time, a very different humidity-driven warm climatic state was possible. It is important that we know about this as a possible outcome of the current experiment with the planet, but it is also important to realize that the modern vegetation is different from that of the Late Cretaceous.

Fig. 11A, B Mean annual precipitation (mm/day). **A** Present climate simulation. **B** Campanian climate simulation

Fig. 12A, B Mean annual cloudiness (% area). **A** Present climate simulation. **B** Campanian climate simulation

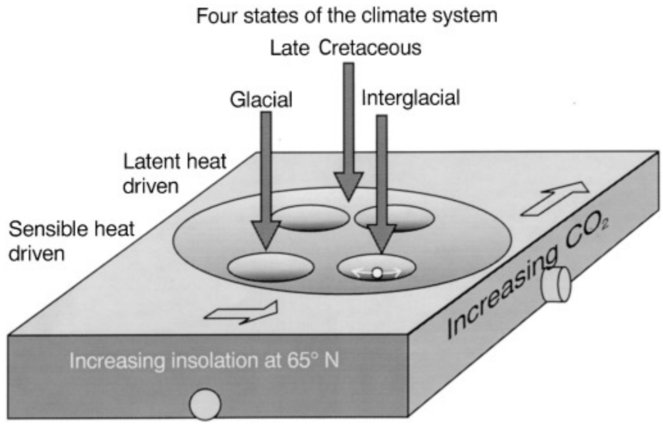


Fig. 14 Four possible states of the climate systems, with the climate represented as a ball on a surface that can be tilted in two directions. The depressions represent stable climate states that allow for climate variation within certain limits. Changes in insolation at 65 °N cause an oscillation between glacial and interglacial states in the "icehouse" mode. Increased atmospheric CO_2 forces the climate to move from the icehouse to "greenhouse" mode. Variations in insolation should cause oscillation between two greenhouse states differing in redistribution of precipitation and evaporation

Humans are simultaneously altering two major components of the climate system, increasing the greenhouse gas content of the atmosphere by burning fossil fuels, and changing the vegetation by replacing C3 with C4 plants. The CO_2 increase drives the planet toward a "Late Cretaceous" condition, but the change in vegetation is in the opposite sense from that of the Late Cretaceous.

Studies of ancient climates, least of all those of the immediate geologic past, will not tell us what the future climate of the earth is likely to be. Studies of ancient extreme climates will tell us more about how the climate system works and give us insight into what the future possibilities for climate change may be. In arriving at a new stable climatic state, the planet may experience extreme climatic events, such as the hottest summer, the coldest winter, and the greatest hurricane, as suggested by Flohn (1988). At present, the climate of the future is unpredictable, but one thing seems certain: it will be different from what it has been in the past.

Summary and conclusions

The climate of the time in which we live, the Holocene, is characteristic of only brief intervals during the past million years. It is an interglacial during which large ice sheets persist in Antartic and Greenland and smaller ice sheets and glaciers in some mountainous areas. It is a time of relative sea-level stability after a rapid 130-m rise from the lowstand during the LGM. The deglaciation has resulted in flooded river valleys forming estuaries and flooding of the continental shelves and carbonate platforms. The Holocene is a short-term climate event in which physical geological processes operate at unusual rates and much of the geochemical system is not in a steady state (Hay et al. 1994).

The 30% of the Phanerozoic time when there was periodic development of large-scale continental ice sheets on the earth is not typical of the planet's "average" state, which is to have a lesser meridional temperature gradient than today, to be free of continental ice sheets, and to have erosional and sedimentation processes operating at rates approximately one fourth of those at present (Frakes et al. 1992; Hay 1994).

Changes in the earth's orbital parameters (Milankovitch cycles) affect the amount of radiation received from the sun at different latitudes over the course of the year. At the LGM and during the subsequent deglaciation, the waxing and waning of the continental ice sheets closely followed the summer insolation changes between 60 and 70 °N resulting from the precession of the equinoxes. There is a local minimum in the summer insolation at 66.5 °N which becomes alternately more and less pronounced as the obliquity of the earth's axis of rotation changes (see Fig. 4). The northern hemisphere ice sheets of the LGM grew as the difference in spatial summer insolation was maximal and the temporal insolation decreased to a minimum at 24 000 years BP. The deglaciation occurred as the spatial summer maximum disappeared and the temporal insolation increased to a maximum at 11 000 years BP. Although the climate changes between 24 000 and 11 000 years BP are closely related to insolation changes, climate changes at other times during the Quaternary are not so directly associated with insolation.

Greenhouse gases are also important in modulating the climate. The atmospheric content of CO_2 during the LGM was approximately half that of the present interglacial. The atmospheric CO_2 content during the Late Cretaceous was probably approximately four times that of the present and produced a strong positive feedback effect with another important greenhouse gas, H_2O. The results of a climate simulation suggest that this positive feedback raised the earth's temperature to a level where latent heat transport became much more significant than it is presently and operated efficiently at all latitudes. Atmospheric high- and low-pressure systems were as much the result of variations in the vapor content of the air as of temperature differences.

There are at least four main states of the earth's climate. They can be visualized as depressions on a smooth surface that can be tilted in space (Fig. 14). The climate is like a ball in one of the depressions; it can roll around inside the depression. These motions represent the natural variability of the climate in a given state. However, when the external forcing becomes too strong, the ball rolls out of one depression and into another. During the earth's younger history it alternated between the glacial and interglacial "icehouse" states. However, at higher levels of atmospheric CO_2 (and in the absence of polar ice) the climate will oscillate between two "greenhouse" states that reflect redistribution of precipitation and evaporation. Future climate change is unpredictable because we are forcing the climate toward the "greenhouse" states when it is accustomed to moving between the glacial–interglacial "icehouse" states that reflect the waxing and waning of ice sheets.

The past climates of the earth cannot be used as a direct guide to what may occur in the future. To understand what may happen in the future we must learn about the first principles of physics and chemistry related to the earth's system. The record of past climate conditions provides us with a catalog of what has happened. It shows us what is possible but offers only indirect clues about the factors controlling climate. The goal of paleoclimatology and paleoceanography is to determine the relative importance of factors producing specific climate conditions and climate change. By understanding the mechanisms that have been important in the past, we gain insight into what may happen in the future. The fundamental mechanisms of the climate system are best explored in simulations of the earth's ancient extreme climates.

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