CLIMATE CHANGE, CAUSES

To summarize evidence discussed elsewhere in this volume, past climate change can be detected on time scales of decades to hundreds of millions of years. Theories as to the causes for such changes extend back almost as far as the observations. James Croll (1867) was the first to seriously examine the role of changes in the Earth's orbit, through their contribution to the waxing and waning of Pleistocene ice ages. In the early twentieth century, Alfred Wegener, in conjunction with the geographer Köppen (Köppen and Wegener, 1924), discussed how continental drift could explain the great Permo-Carboniferous ice age discovered in different parts of Gondwanaland. The tree ring laboratory at the University of Arizona was instituted in part to test hypotheses as to whether changes in the output of the sun may be responsible for decadal scale changes in drought in the western United States. In perhaps the first comprehensive assessment of the problem, Brooks (1926) estimated that there were already 56 different explanations for the ice ages.

Although many of the above ideas are still alive and well, one of the most significant advances in paleoclimatology in the last half century has been a considerable increase in quantifying past climate change, and in determining the chronology of past climate change. This last contribution is exceedingly important and sometimes either overlooked or taken for granted. As John Imbrie once remarked, "Stratigraphy is 90% of geology." By this, he meant that no sound testing of a cause is possible without a precise and accurate knowledge of the time relationships between different sources of forcing and the responses in the climate system.

The testing of hypotheses has also benefited greatly from the development of large-scale models of the atmosphere and ocean circulation and ice sheets, and the coupling of these models with both the biosphere and biogeochemical systems. One of the most significant advances by climate scientists in the last 30 years has been the recognition that not all climate change is related to some external type of forcing (e.g., volcanoes, solar and/or orbital insolation variations, motions of the continents, etc.). Rather, fluid systems can generate their own internal variability because of the different response times of different parts of the system, and this variability can account for a very large part of the entire observed variability in the climate record.

The basic idea behind "internal variability" is that there are different time constants for different parts of the climate system – days to weeks for the atmosphere, months to years for the surface ocean (i.e., ocean mixed layer), centuries to a thousand years for the deep ocean circulation, thousands of years for ice sheets, and millions of years for continental drift. These time scales are not independent. Small, essentially random, variations in weather can sometimes store or remove heat temporarily from the ocean mixed layer. Because the ocean mixed layer has a heat capacity about 60 times that of the atmosphere, the time constant for integrating the atmospheric effects is longer in the surface ocean. Thus, there may be "decadal scale" climate variations driven simply by these random variations. In addition, planetary Rossby waves in the ocean can have time scales of years to a decade, so the propagation of these waves through the upper ocean can generate a more organized type of variability on decadal time scales. The great subtropical ocean gyres also have a time scale of a decade or two with respect to their transport of energy in the different ocean basins.

Given an infinite amount of time, the ocean would return any stored heat to the atmosphere, so that the long-term average exchange would be zero, but for finite periods, temperature can vary by 0.1–0.3 °C with respect to global mean temperature. In fact, all control runs of coupled models of the ocean-atmosphere circulation simulate such variability, which in one case has been extended to more than 10,000 model years. This variability is typically illustrated by variance versus frequency plots, which show increasing variance as the frequency of any forcing decreases (e.g., Figure C43). This pattern is known as a "red noise spectrum" and can be found in virtually all geophysical time series, including climate time series in the geologic record. The slope of the background spectrum is often in the range of –1 to –2 (the greater the slope, the greater the

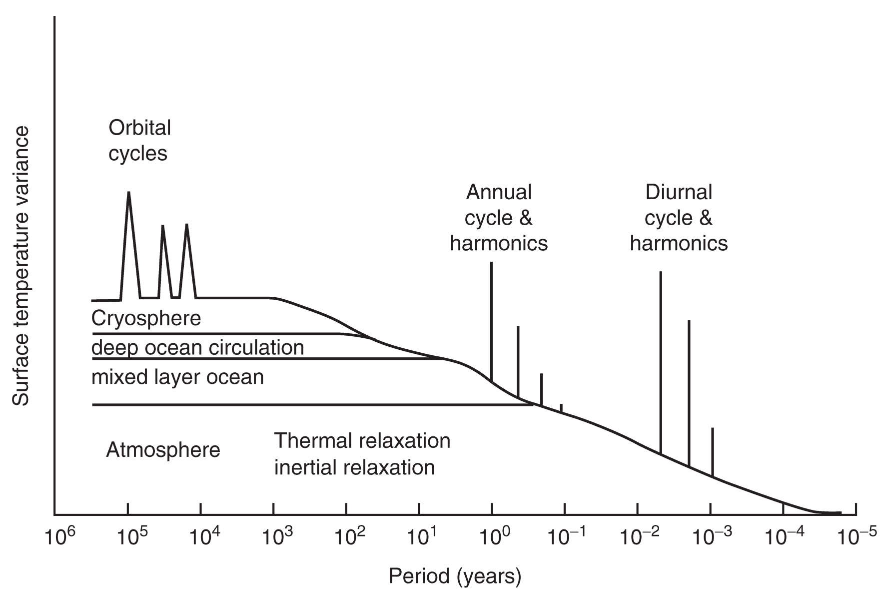

Figure C43 Schematic variance spectrum of the surface temperature versus frequency, *f*, (labeled in terms of period, which equals f^{-1} in years), illustrating the timescale for different components of the climate system and the relation between the background "red noise" variance and externally forced oscillations at distinct periods. (Modified from Crowley and North, 1991).

coupling between different time scales). This is the actual shape and range of slopes observed when high quality geologic observations have been used.

Only spectral peaks exceeding two standard deviations above the local background "red noise spectrum" require some type of additional explanation as to their origin, and even these must be checked with repeat analyses from other records as there is still a 5% chance that, in a fine length time series, a given peak can occur by chance alone above the 2-sigma level. These "stochastic" variations of climate should not be confused with chaos in the climate system. The latter can occur where random perturbations lead to some threshold "state change" in the system, after which there may be an abrupt change in system state. Such changes are inherently nonlinear, but the stochastic processes emphasized above are, to a large extent, linear processes.

The importance of the above discussion cannot be overemphasized, because there seems to be an inherent tendency to attribute any climate fluctuation, past or present, to some change in external forcing. However, the null hypothesis is to interpret the changes as being of internal origin unless there is some compelling evidence suggesting otherwise; for example, a strong correlation between an observed response and an external forcing term. Another, related test would be whether the observed response has a spectrum significantly different from the background climate spectrum. This is clearly the case for the annual cycle of temperatures and some of the climate changes on time scales of tens of thousands to hundreds of thousands of years that have been linked to periodic variations in the planet's insolation.

Tectonic timescale

As indicated in Figure C44, the maximum variance in the paleoclimate system occurs on the tectonic time scale – millions to tens of millions of years. Here, the change is between times of little or no ice and times of major continental glaciation. Direct evidence of glaciations (striated rocks and pebbles, sedimentary deposits of likely glacial origin) indicates that there have been three main phases of major continental glaciation in the last 600 million years – in the late Precambrian (Neoproterozoic, ~600 Ma [million years ago]), the Permo-Carboniferous (~270–360 Ma), and the late Cenozoic (0–35 Ma). There are shorter glaciations (1–10 million years?) in the Late Ordovician (~440 Ma), in the mid-Devonian (~365 Ma) and perhaps in the middle Jurassic (~180 Ma). The magnitude and duration of the latter two is not well established, but it is likely they were less extensive in time and space than the late Cenozoic, Permo-Carboniferous, and Neoproterozoic glaciations. In total, direct evidence for glaciation occurs in about 25% of the record over the last 600 million years.

Changes in geography due to plate tectonic changes have long been explored as a mechanism of causing the "grand cycles" of Phanerozoic climate change (Donn and Shaw, 1977). However, in the early 1980s, paleoclimate-modeling exercises by Barron and Washington (1984, 1985) suggested that, although the climate effects of plate tectonic changes were significant, it was not possible to explain long-term changes in ice cover solely by this process (One exception is Greenland, where model results suggest that cooling could have been due to the northward migration of the landmass through the last 100 million years, plus deceased summer warming due to opening of the Greenland-Norwegian Seas (Crowley et al., 1986)). However, Barron and colleagues discovered that if

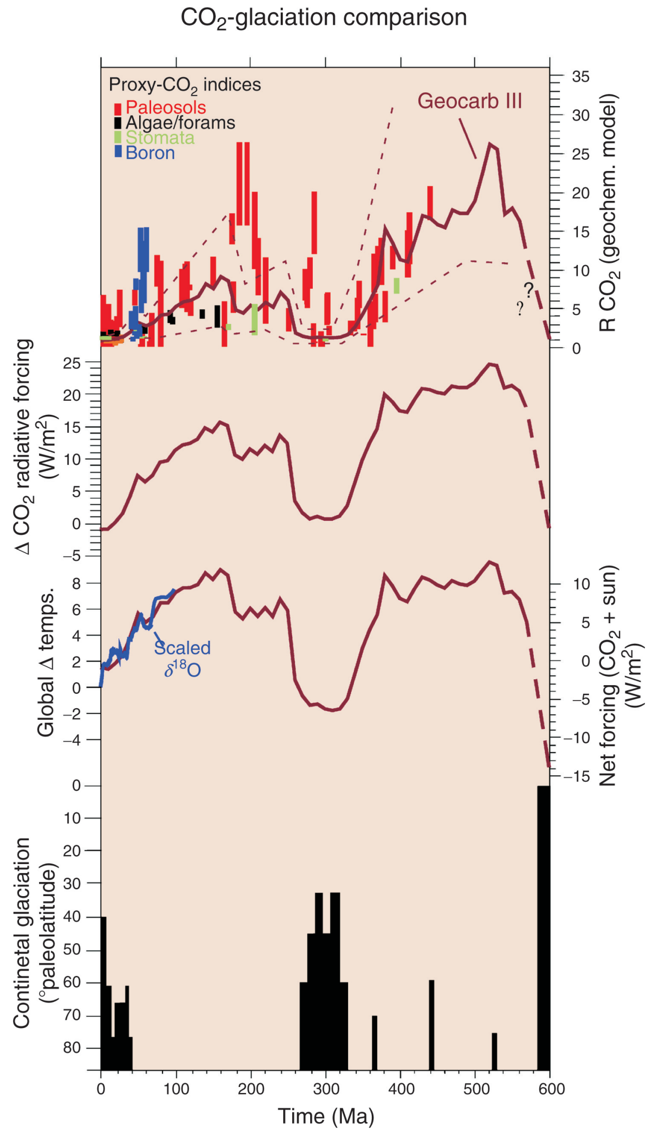

Figure C44 Comparisons of carbon dioxide changes from a geochemical model with various indices of climate change. From the top, comparison with various proxy CO_2 indices of the last 600 million years; next, adjusted radiative forcing after taking into account the logarithmic relation between CO_2 concentration and radiative forcing; second panel from bottom, radiative forcing after factoring in the evolution of solar output over the last 600 million years. On the left hand side of this panel is the oxygen isotope record of climate change for the last 100 million years, scaled to global temperatures. Bottom panel, comparison with best-documented evidence for continental glaciation. (Modified from Crowley and Berner, 2001).

carbon dioxide levels were changed, then a closer agreement between models and paleo-data could be obtained.

The results of Barron and colleagues meshed very well with independent studies of geochemistry. Berner et al. (1983) published a geochemical model suggesting that there could have been major changes in the natural CO_2 content of the atmosphere due to changes in the balance of sources and sinks of atmospheric CO_2 (e.g., outgassing from volcanoes, weathering, and carbon burial). Changes in the latter two draw down CO_2 in the atmosphere. Changes in weathering can be related to uplift of landmasses, CO_2-enhanced increases in weathering, and phases in the evolution of terrestrial life. For example, the present version of this model (Berner and Kothava, 2001; Figure C44) predicts a major period of high CO_2 levels in the early-mid Paleozoic (~300–540 Ma) followed by a significant decline in the later Paleozoic due to the evolution and expansion of land plants (which create an extra carbon sink of reduced carbon and also produce organic acids in the soil that accelerate the breakdown of silicate minerals). A later rise persists into the mid-Cretaceous period (~80–100 Ma) after which there is a slow decline to values at or near present by about 30 Ma.

Although considerable questions have been raised about this geochemical model, a separate line of testing, using geochemical analyses of various sedimentary constituents to derive "proxy" CO_2 estimates, agrees well with the model predictions to the first order. The calculated CO_2 levels also agree (to first order) with the amounts required by climate models to fit the paleo-data. On the 10-million year timescale (the resolution of the geochemical model), there is a good agreement (Figure C44) between the timing of CO_2 lows and major glaciation. On this timescale, it is necessary to factor in the evolution of solar irradiance due to the ever-increasing fusion-related conversion of hydrogen to helium in the sun's core. The estimated increase amounts to about 1% per 100 million years. One also has to consider that radiative forcing from CO_2 changes is logarithmically related to CO_2 concentration because of the increased "saturation" of CO_2 absorption bands at high atmospheric CO_2 levels. Combining these two factors, and assuming for simplicity that the Earth's planetary albedo of 30% remains constant with time, yields an estimate of net irradiance changes versus time that explains ~50% of the variance of continental glaciation on a time scale of 10 million years. There has been a separate but less conclusive line of discussion suggesting that CO_2 levels during the Neoproterozoic glaciation may also have been low. If so, about 60% of the major climatic variance over the last 600 million years can be explained by natural variations in the CO_2 content of the atmosphere.

There are still times when the simple CO_2–ice relationship does not seem to hold – particularly in the Late Ordovician (~440 Ma) and the mid-Jurassic (~180 Ma). However, even these time intervals may not be totally at odds with the CO_2 model, for a number of climate modeling studies (Crowley and Baum, 1995) indicate that there is a small area of parameter space that allows high CO_2 and ice buildup. This parameter space is related to the configuration of the continents. When landmasses are close to the poles, the presence of open water suppresses the summer warming on these landmasses. Even small topographic highs can form permanent ice caps under such scenarios. Some preliminary work also suggests it may apply to the small ice advances in the Jurassic.

One peculiar feature of the above CO_2-climate relationship is that the ocean appears to play a minor role in regulating the long-term global changes in climate. This is not to imply that the ocean did not change. The development of the Antarctic Circumpolar Circulation, after the opening of the Drake Passage (~20–30 Ma?), must have had a significant effect on the ocean circulation – at the minimum causing enhanced mixing between the deep and surface waters as the surface barriers disappeared. Modeling and observational studies (Maier-Reimer et al., 1990) suggest that final closure of the Central American isthmus around ~3 Ma had a very significant effect on poleward heat transport in the Atlantic Basin (Figure C45). However, convincing links to the onset of late Cenozoic glaciation are surprisingly hard to establish. Enhanced poleward ocean heat transport in the North Atlantic since ~3.0 Ma coincides closely in time with the spread of Northern Hemisphere ice, but it is unclear why the ice would grow in the presence of greater warmth (summer temperatures seem more important than winter moisture as a limiting factor for ice initiation).

A more important role for the ocean response to higher CO_2 levels seems to involve the redistribution of heat on the planet. Geological data consistently indicate a very significant reduction in the equator-pole temperature gradient during times of extreme warmth. These reductions cannot be convincingly simulated with the present generation of climate models. This discrepancy represents perhaps the single largest uncertainty with respect to our understanding of how the Earth responded to past changes in forcings, and raises questions as to whether some unexpected changes may occur in the future due to society's emissions of greenhouse gases into the atmosphere.

A related discrepancy between models and observations involves indications that winter warming in high latitudes appears to be greater than simulated by models with increased CO_2 and even a forced change in the polar temperature gradient. However, the disagreements may not be disastrous and could simply be explained by higher CO_2 levels in the atmosphere, or uncertainties in the paleo-latitude of the fossil sites.

In addition to modeling the steady-state nature of warm climates, some work has been done on the changes in climate through the Phanerozoic. In some cases, there are relatively abrupt transitions between states that imply either a rapid change in the forcing or instabilities in the climate system. In addition to the spectacular asteroid impact at the end of the Cretaceous (66 Ma), three noteworthy examples of shorter-term climatic

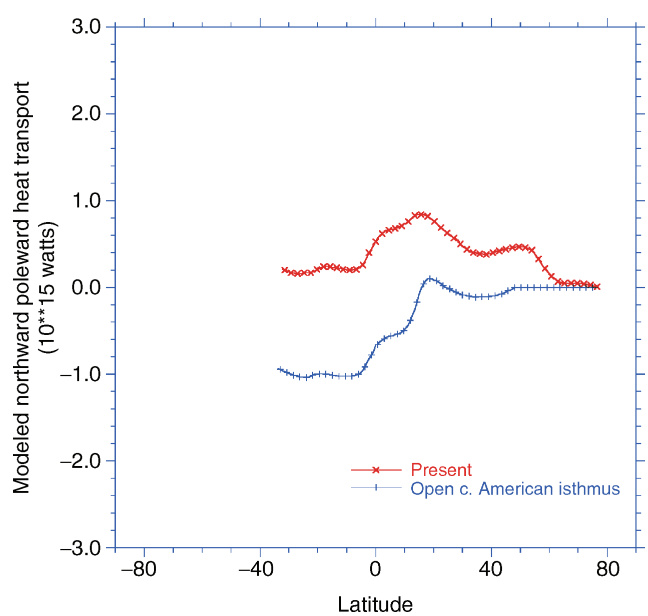

Figure C45 Comparison of polar heat transport in the Atlantic for an ocean model simulation with the present geography and with an open central American isthmus (based on results from Maier-Reimer et al., 1990).

events on long time scales (Zachos et al., 2001) involve an abrupt warming event that appears to have marked the warmest period of the Cenozoic around 55 Ma, the rapid expansion of ice on Antarctica around ~34 Ma, and another rapid climate change around 14 Ma. The first event (Paleocene-Eocene Thermal Maximum, or PETM) is associated (Zachos et al., 2003) with a rapid warming (order 10^3–10^4 year), a poleward expansion of subtropical biota, and abrupt warming of the deep-sea, which caused an extinction of some benthic organisms, an abrupt increase in global weathering rates, and a carbon isotope excursion that seems to be best explained by a sudden emission of methane clathrates buried on ancient continental margins (methane is a greenhouse gas that is rapidly converted to CO_2 in the atmosphere). This signal dissipated after about 200,000 years but may be the closest analog in the geologic record to how the climate system might response to the current anthropogenic CO_2 perturbation.

The abrupt cooling around 34 Ma has long been known. It occurred over about 100,000 years and has been linked to an expansion of the Antarctic Ice Sheet and significant cooling of the deep oceans. Some recent modeling results (DeConto and Pollard, 2003) suggest that the rapid expansion of ice on Antarctica may reflect an unstable system response to slow decreases in atmospheric CO_2. The third abrupt transition at about 14 Ma has been less examined. It has long been known from oxygen isotope records that an abrupt transition, perhaps as short as a few tens of thousands of years, occurred at this time and was associated with a further cooling of deep ocean waters. However, the precise nature of the triggering mechanism has been neither examined nor modeled.

As to reasons for the abrupt transitions, much effort over the last 20 years has been devoted to explaining and modeling abrupt climate shifts as a function of rapid reorganizations in the ocean-atmosphere system. However, for over 35 years, climate scientists have shown, first with simple energy balance models (Budyko, 1969) and later with more complex models, that it is also possible for models to rapidly evolve to a new climate state due to an instability related to the snow/ice albedo feedback. As temperatures cool due to, for example, CO_2 decreases, snow area either increases or (in the case of some regions) may be first preserved in summer. This new snow patch has much higher albedo (reflectivity) and further cools the system until it reaches a new equilibrium with significantly expanded ice area. General circulation model (GCM) experiments for the Permo-Carboniferous ice age (Crowley et al., 1994) provide some support for the idea that slow decreases in radiation (due to, for example, changes in CO_2 levels) result in a rapid increase in snow area at some critical point in the model (Figure C46). Further experiments linking GCMs to ice sheet models suggest that the abrupt change near the Eocene-Oligocene boundary (~34 Ma) may also be explained by this mechanism. Although still not widely accepted in the geological community, the snow-ice instability seems to be a very viable explanation for abrupt changes in ice extent in Earth history.

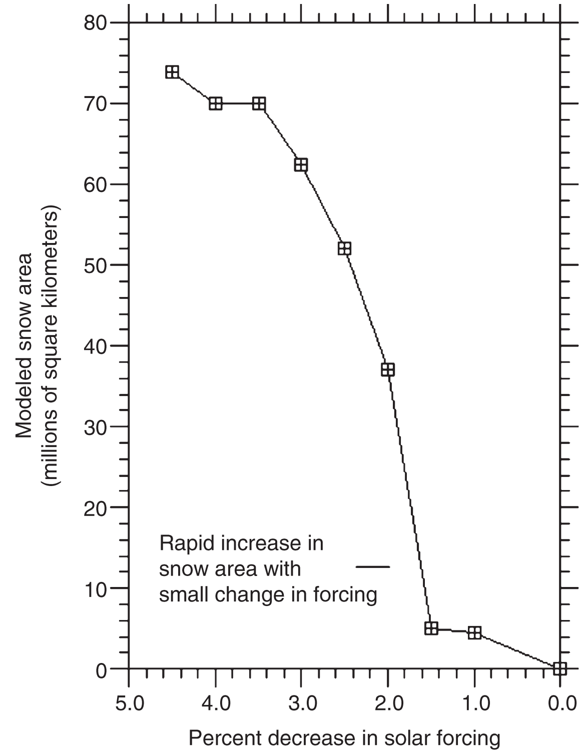

Figure C46 Model result illustrating the snowline instability. The figure shows the response of a snow cover in a general circulation model run for the Carboniferous ice age, versus changes in solar forcing (this is a conventional diagnostic tool for analyzing the response to any change in radiative forcing). Note that a decrease in solar radiation below a certain point results in rapid expansion of snow cover that would be associated with abrupt climate change, and glaciation, in the Earth record. (Modified from Crowley et al., 1994).

Glacial-interglacial timescale

For 50 years, it has been known from deep-sea records that there were numerous glacial-interglacial fluctuations in the late Pleistocene (Emiliani, 1955). With the advent of the Ocean Drilling Program, the record of glacial-interglacial fluctuations, as characterized by the oxygen isotope record of marine planktonic and benthonic organisms, has been extended back millions of years. The records consistently show (Shackleton and Opdyke, 1976) that the expansion of Northern Hemisphere glaciation was a stepwise process, with Greenland glaciating first, then "small" ice sheets fluctuated at a ~41,000 year period, and in the last million years, very large ice sheets fluctuated primarily at the 100,000 year period.

It has now been established beyond a reasonable doubt that the primary factor responsible for the waxing and waning of the major ice sheets has been periodic seasonal variations of the Earth's insolation due to orbital perturbations primarily from the gravitational fields of the Sun, moon, and Jupiter. This is the so-called Milankovitch Hypothesis or the Orbital Theory of Glaciation (Milankovitch, 1930) that was first convincingly demonstrated in a important paper by James Hays, John Imbrie, and Nicholas Shackleton (Hays et al., 1976). A key feature of this paper is that continental ice volume responds almost linearly to the orbital perturbations on shorter periods of ~41,000 years (obliquity or tilt of the Earth's axis) and ~23,000 years (precession), while on the 100,000 year time scale the response to eccentricity variations is nonlinear. Another historic contribution comes from the Vostok (Antarctica) ice core (Figure C47), which indicates that CO_2 and Antarctic temperatures fluctuated almost in parallel for the last 400,000 years, with both strongly influenced by orbital variations (Petit et al., 1999). This result again implicates CO_2 variations as a major amplifying factor of past climate change.

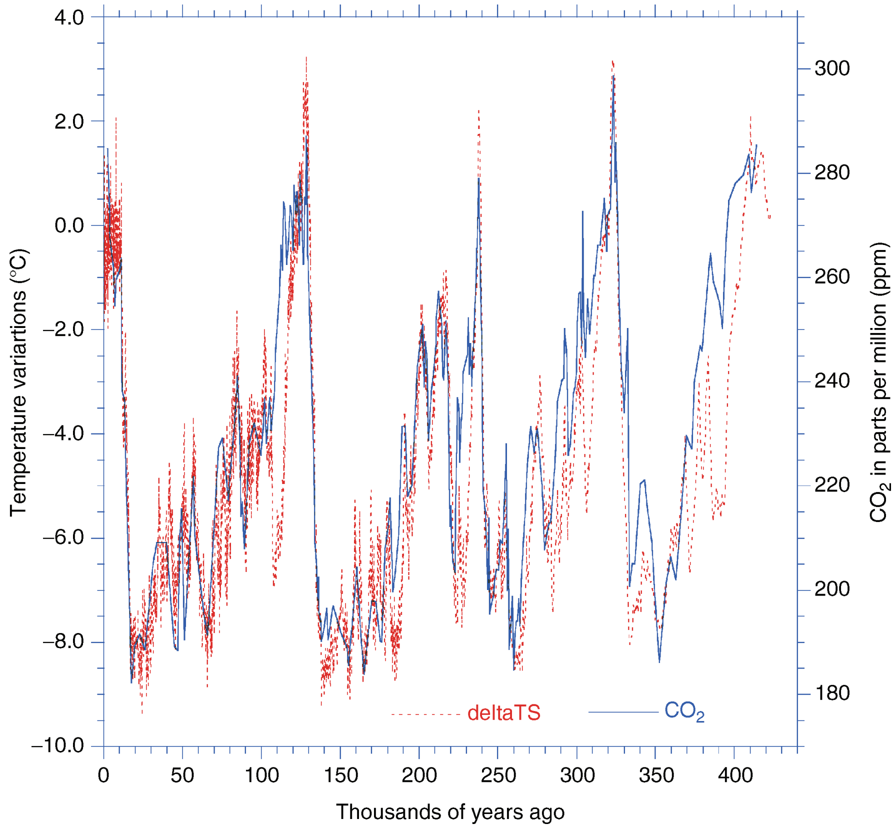

Figure C47 Comparison of carbon dioxide and deuterium temperature record from the Vostok ice core, illustrating a very tight coupling between the two records (the disjoint relationship in the oldest interglacial may reflect sampling problems at the bottom of the core). (Modified from data in Petit et al., 1999).

Since the Hays et al. (1976) paper, the principal modeling efforts have been associated with explaining how the ocean-atmosphere system translates orbital perturbations into ice volume fluctuations of the observed magnitude. A virtual mathematical zoo has been proposed as possible explanations for the 100,000 year cycle. Unfortunately, there has been little effort to cull among the different hypotheses, comparing predictions that can be falsified. Nevertheless, the dominant thinking at present is that the inherent nonlinearities associated with ice sheet dynamics are somehow responsible for the amplified response at the 100,000 period (e.g., Saltzman and Sutera, 1987). One example of how this process works is that, following an interglacial period, low summer insolation during a "cool summer orbit" leads to preservation of permanent snow fields, which over time build up into an ice sheet and flow into lower latitudes. At full glacial maximum conditions, the ice buildup depresses the Earth's crust by as much as 1 km (Figure C48).

During a subsequent "warm summer orbit" configuration, melting of the ice sets in. Because the elastic rebound of the Earth's crust is slower than the thinning of the ice sheet, the ice sheet is essentially "trapped" at low elevations, leading to catastrophic melting. The very rapid wastage in the time domain is translated into more power in the frequency domain at 100,000 year periods. CO_2 represents an important amplifier for the whole process. Application of a model of this type (Tarasov and Peltier, 1997) to the evolution of the last glacial cycle (Figure C49) suggests results in quite good agreement; however, a fuller explanation for Pleistocene climate change requires understanding the origin of the CO_2 changes and further testing of the "ice trapping" model.

As with the tectonic timescale, there is also a great deal of interest in the role of abrupt climate instabilities facilitating the glacial-interglacial oscillations. For example, the first rapid melting of ice starting at about 19,000 calendar YBP seems to have occurred within a few centuries and caused about a 15 m increase in global sea level. A second phase of rapid melting began about 14,500 calendar YBP. This step was preceded by a slow but steady CO_2 increase, to about half of its Holocene value. There was also an abrupt increase in the overturning of the North Atlantic circulation that started at 14,500 YBP. Since the North Atlantic circulation provides substantial heat to the high latitudes in the strong overturning mode, this feedback presumably contributed to the rapid wasting of ice.

Some mechanism is needed to explain the rapid change in the state of the North Atlantic system. As Hays, Imbrie, and Shackleton demonstrated in 1976, some of the first signs of warming at the end of a glacial period occurred around Antarctica – perhaps because Antarctic sea ice has a far lower thermal inertia than the great northern hemisphere ice sheets. A number of recent studies now suggest that changes in the ocean circulation around Antarctica may have altered the production rate of Southern Ocean deep water, which, when it upwells in the North Atlantic, influences the production rate

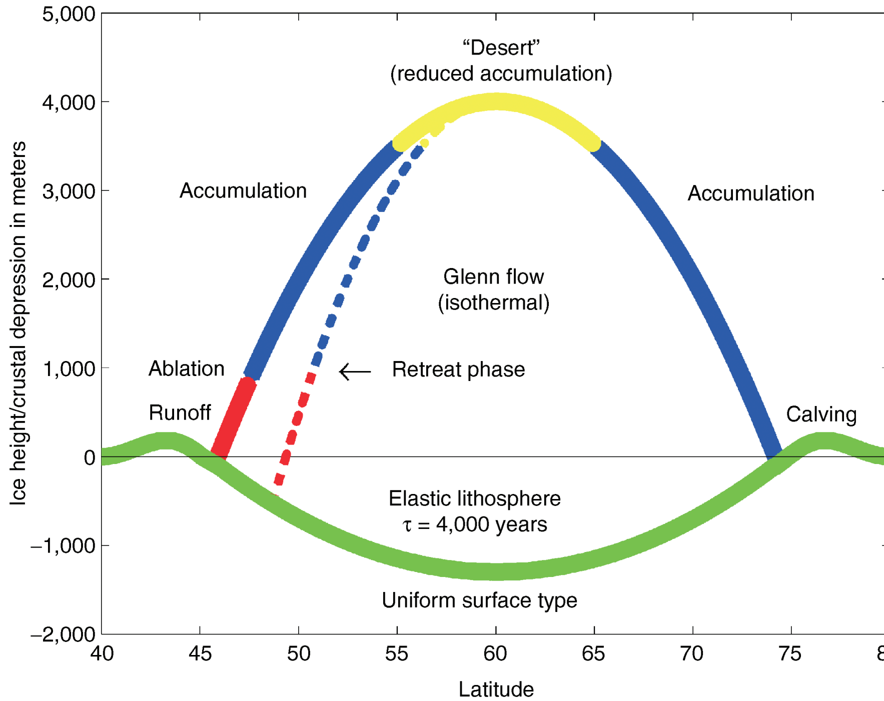

Figure C48 Schematic cross-section of Pleistocene ice sheets, illustrating zones of ablation and accumulation, and isostatic depression of the crust by the ice sheet. During times of rapid melting the ice will lay "trapped" in the depression due to the long response time of mantle rebound, resulting in rapid deglaciation (figure courtesy of William T. Hyde).

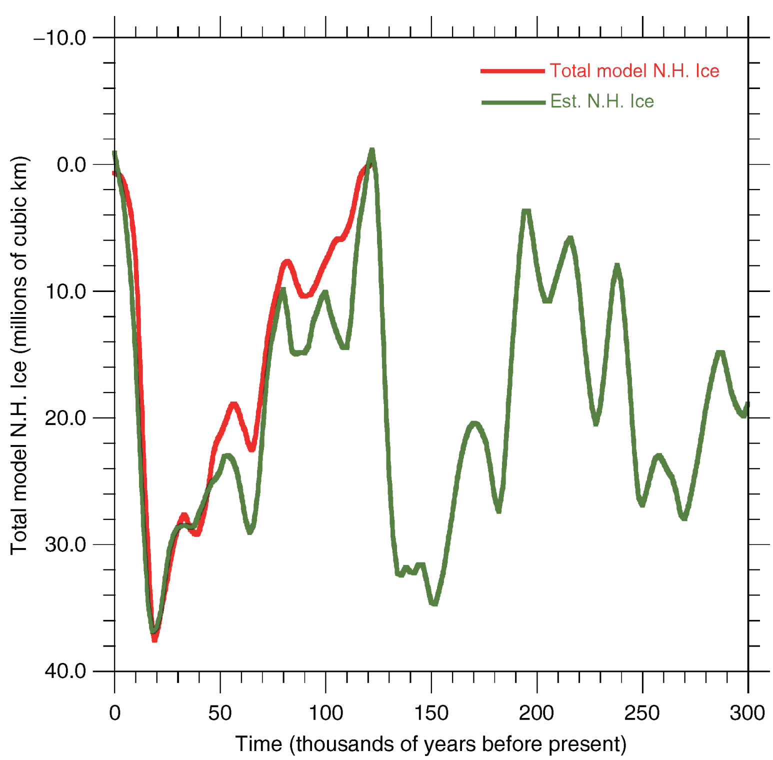

Figure C49 Comparison of modeled and observed Northern Hemisphere ice volume for the late Pleistocene. Observed variations based on marine oxygen isotope measurements converted to ice volume. Model result for the last glacial cycle based on the University of Toronto ice sheet model, which was driven by orbital forcing, CO_2 changes and variations in North Atlantic heat transport (model result courtesy of William Hyde).

of North Atlantic Deep Water. A sudden reduction of deep water formation around Antarctica might then have caused an abrupt "switch on" of the North Atlantic (Mikolajewicz, 1998). It is presently debated whether early CO_2 increases may have triggered the Antarctic changes around 19,000 BP, but the timing of the changes is sufficiently close to suggest such a possibility.

There has also been a great deal of interest in smaller but rapid changes in the ocean-atmosphere system during the "interstadial" period preceding the last glacial maximum. Records from Greenland ice cores, the North Atlantic, Eurasia, North America, and parts of the tropical regions of the South American-Indian Ocean sector indicate a fairly close correlation between the timing of abrupt changes in different regions that may reflect in part rapid and abrupt oscillations of the North Atlantic Deep Water circulation. The triggering link for the North Atlantic changes may involve some episodic outbursts of melted ice-rafted material from the continents that change the ocean salinity and short-circuit the overturning circulation.

The millennial and orbital scales cannot be viewed in isolation. It is clear that orbital forcing is virtually omnipresent in all paleoclimate records of at least the last million years. It is also clear that the system has undergone abrupt transitions. The relation between the two presumably involves the fact that, for glacial and interglacial transitions, slow changes in orbit forcing results in threshold responses in ice growth (e.g., snowline or thermohaline instabilities discussed above) and possibly CO_2. The system then goes through an abrupt transition on its eventual trajectory to a state determined by the longer term forcing. The details of how these steps occur have yet to be elucidated.

Centennial-millennial timescale

Records primarily of the last 10,000 years provide information on shorter timescale climate that enable placement of the twentieth century warming in a longer-term perspective. Such data are also valuable in assessing different mechanisms for decadal-millennial climate change. Reconstructions (e.g., Figure C50) from the last 1,000 years of tree rings, ice cores, and corals provide a general picture of warm Middle Ages followed by a cold "Little Ice Age" that began in the late thirteenth century and persisted until the middle of the nineteenth century. Composites of such fluctuations generally agree with the lower resolution record derived from studies of the advance and retreat of alpine glaciers.

In addition to refining estimates of the magnitude and timing of past climate change, new paleotemperature reconstructions enable more precise estimates of the relative importance of different mechanisms for climate change. It has long been postulated that changes in the frequency of intense volcanic eruptions may have influenced climate on this time scale. Similarly, changes in the output of the Sun have also been postulated. Finally, there were small changes in the CO_2 content of the atmosphere during the Little Ice Age that have been recorded in ice cores, and also a long-term increase in trace gas concentrations for the last few thousand years.

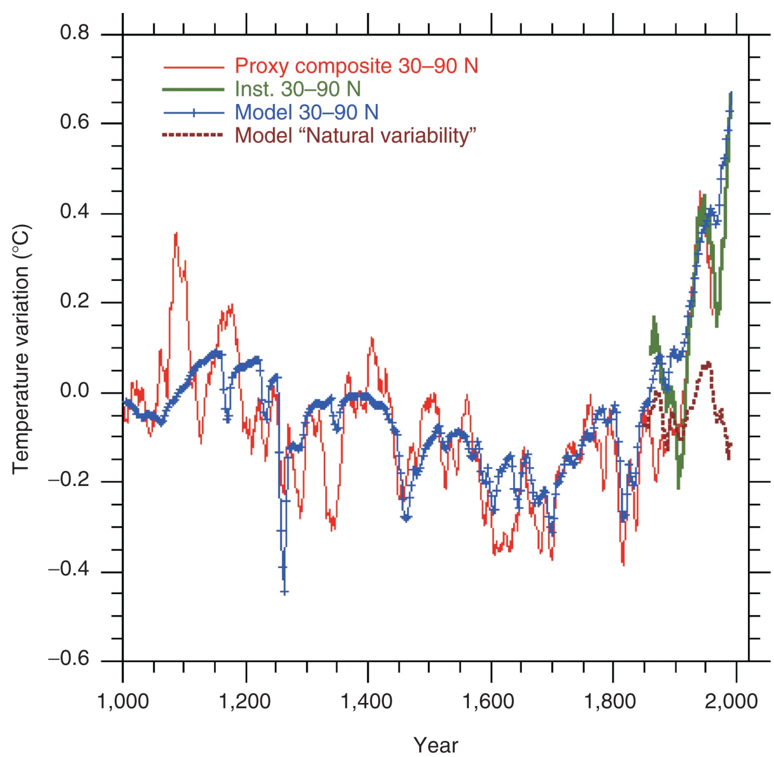

Figure C50 Sample comparison of model simulations of climate change over the last 1,000 years with observations from both the instrument and paleoclimate records. Reconstructed temperatures are for 30–90° N, where most of the long records are preserved. Model results driven by changes in greenhouse gases, volcanism, and output of the sun. Pulses of volcanism primarily account for climate change in the "Little Ice Age" (~1250–1850). Note that although the model does a good job of explaining about half of the decadal variance prior to about 1850, only the addition of greenhouse gases of anthropogenic origin can explain the late twentieth century temperature rise. (Modified from Crowley et al., 2003).

Reconstructions of volcanic, solar, and greenhouse gas forcing have enabled testing of the relative importance of different mechanisms for climate change. The volcanic reconstructions are based on sulfate deposited in Greenland and Antarctic ice cores. Solar variability can be inferred from variations of the cosmogenic isotopes ^{14}C and ^{10}Be. Trace gas concentrations are derived from ice cores. Experiments with both simple and complex climate models indicate that there is a surprisingly large forced response in the decadal-centennial band (Figure C50). More detailed analyses indicate that changes in volcanism can explain about 40% of the variance in the interval 1,000–1,850, i.e., prior to the enhanced disturbance of the system following the industrial revolution (Crowley et al., 2003). By contrast, solar variability and trace gas changes play only a secondary role on the largest scale (Hegerl et al., 2003); although there is some evidence that solar variability may occasionally be proportionately more important on smaller space scales.

The importance of solar variability seems to increase on the millennial timescale (Figure C51). There are a number of known millennial scale climate fluctuations that have long been identified as punctuating the generally warm time of the Holocene. In particular there are changes at about 5,500 BP (calendar years before present), 4,500 BP, and 2,700 BP. In the North Atlantic basin, these and other Holocene fluctuations bear a striking correspondence to solar forcing as inferred from variations of ^{14}C and ^{10}Be. These data suggest that the importance of solar forcing may be timescale-dependent – it is relatively weak on the decadal-centennial scale, but proportionately more important on the millennial scale. The general explanation for such a frequency dependency may involve the fact that there is generally more variance at lower frequencies in geophysical systems. A weak solar signal at decadal-centennial scales may become sufficiently strong at the centennial-millennial scale to leave a clearer imprint on geologic records, especially since there is much less evidence in support of any millennial variability in volcanism.

The above analysis can explain the quasi-cyclical millennial scale oscillations of the Holocene that appear to be influenced by solar activity. However, volcanic activity in the last millennium has had a major effect on the system response during this time and has exerted a great influence on multi-decadal time scale fluctuations. This could explain why the Little Ice Age was the most extreme climate cooling of the last 1,000 years. This analysis therefore suggests that solar forcing may only reach significant levels for climate fluctuations greater than about a century in length.

The clarification of the relative importance of different types of natural forcing has enabled better understanding of the twentieth century trends in the instrumental record. Natural forcing alone, which can explain much of the pre-industrial interval, accounts for only a fraction of the twentieth century record. Viewed from the paleoclimate perspective (Figure C50), the recent temperature increase appears to be much more clearly driven by the anthropogenic greenhouse gas perturbation. Such a conclusion is consistent with an increasing body of analyses of instrumental records and points to the likelihood that the greenhouse perturbation has already manifested itself in the climate system.

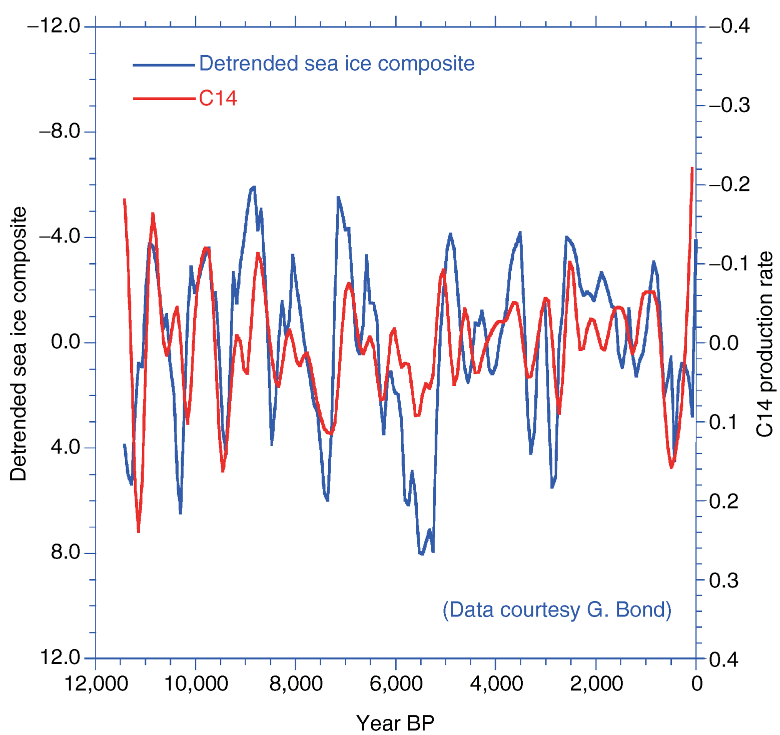

Figure C51 Comparison of atmospheric residual carbon-14 variations of the last 11,000 years with a record of sea ice variations in the subpolar North Atlantic. Positive values on the left axis indicate expansion of sea ice; positive values on the right axis indicates increase in C-14 production rate, which has been associated with a decreased output of solar irradiance. On century-millennial timescales, changes in solar variability may explain a proportionately larger amount of variance than volcanism in climate records (based on results from Bond et al., 2001).

Summary

A great deal has been learned about the causes of past climate change. CO_2 appears to play perhaps the dominant role as the first-order "driver" of climate change on tectonic timescales. However, CO_2 cannot explain everything. In particular, the altered planetary temperature gradient during warm time periods indicates a response of the ocean-atmosphere system that represents perhaps the most prominent difference between models and observations in the paleoclimate record. Understanding this response may enable more confident predictions of greenhouse model simulations of the future.

A second important consideration of climate change on tectonic timescales involves the rapid transitions to ice cover at various times in the Phanerozoic. Models suggest that this transition may be explicable by a snowline instability due to albedo discontinuities at the snow-ice edge. This instability has received much less attention than changes in the ocean circulation, but is fully deserving of equal prominence as a mechanism for rapid climate change.

On ice-age timescales, orbital forcing plays an important role in "pacing" the timing of glacial and interglacial advances. Instabilities appear to play a crucial role with respect to both ice advance and decay; the snowline instability may be more important for ice growth, but ocean changes coupled with ice sheet dynamics may be necessary to explain deglaciations. CO_2 is at the minimum an important amplifier of these responses and for deglaciation may play a fundamental and necessary role in driving the system to full interglacial conditions. Even after almost 25 years since its discovery, the cause of the ice age CO_2 changes continues to elude a satisfactory, consensus explanation.

Volcanism and solar variability appear to play the most important roles on decadal-millennial time scales. Solar variability appeared to have some influence on centennial-scale cooling events in the Holocene. However, the most severe cooling in the last 8,000 years – the Little Ice Age – may have resulted from a wave of volcanism superimposed on a modest cooling of solar origin. Projections of "natural forcing" into the twentieth century indicate that only a fraction of the observed warming can be explained by these processes; anthropogenic greenhouse warming appears to have established itself above the noise level of the geologic record. Future warming projections suggest that conditions comparable to the Pliocene-Miocene warm periods could occur by the end of the twenty-first century. Full utilization of the fossil fuel reservoir could drive temperatures up to levels not experienced since the Eocene warm period, 50 million years ago.

The greatest remaining issues involve:

1. Explanation for the altered equator-pole temperature gradient during past warm time periods.
2. Coupling between low-frequency orbital forcing and abrupt responses in the ocean-atmosphere system on ice age time scales.
3. The origin of ice age CO_2 changes.

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