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Cross-references

Carbon Isotope Variations over Geologic Time
Cenozoic Climate Change
Climate Change, Causes
Climate Forcing
Cretaceous Warm Climates
Faint Young Sun Paradox
Early Paleozoic Climates (Cambrian-Devonian)
Glaciations, Pre-Quaternary
Heat Transport, Oceanic and Atmospheric
Late Paleozoic Paleoclimates (Carboniferous-Permian)
Mesozoic Climates
Mountain Uplift and Climate Change
Neogene Climates
Obliquity
Paleocene-Eocene Thermal Maximum
Paleocean Modeling
Paleogene Climates
Plate Tectonics and Climate Change
Snowball Earth Hypothesis

PALEOCLIMATE MODELING, QUATERNARY

Introduction

Climate models have proven to be very powerful tools in the study of past, present, and future climate. Particular emphasis has been placed on paleoclimate modeling of the Quaternary. The Quaternary is conventionally defined as the Pleistocene plus the Holocene. This modeling has served two basic roles. First, it has helped us to understand the forces driving the diverse phenomena that occurred during this geologic period. Second, by understanding how climates of the recent past differed from those of the present-day, we can both shed light on how climate may change in the future and help to validate our models by seeing how well they simulate a different climate, especially one for which considerable proxy data exist that enable climate reconstruction over much of the globe.

While many diverse paleo-modeling studies have been made for the Quaternary, two major foci can be identified. The first concerns the phenomena for which this period is best known – the cyclical appearance and subsequent disappearance of massive continental ice sheets over much of North America and Europe. Topics here include ice sheet inception, interactions between ice sheets and climate at the Last Glacial Maximum (LGM), and simulation of entire ice sheet cycles. The second major focus is simulation of the mid-Holocene climatic optimum at about 8–6 kyr B.P. While these two themes have drawn the most attention, numerous other facets of Quaternary climate have also been addressed, e.g., the last interglacial at around 120 kyr B.P., the Younger Dryas cold event at around 11–12 kyr B.P., quasi-cyclical Heinrich and Dansgaard-Oeschger events, and the study of past abrupt climate changes in general (e.g., Bradley, 1999). Much attention has recently been paid to climatic changes over the past 2,000 years, for example "mega-droughts" over continental interiors (see *Climate variability and change, last 1,000 years*).

A variety of different types of climate models has been used for these simulations of Quaternary climate. Probably the best-known of these are the so-called "general circulation models," or GCMs (also popularly known as "global climate models"); indeed these types of models will be the primary (but not sole) focus of this chapter. Originally, these only modeled the atmosphere, with the state of the ocean, land surface, and cryosphere specified. More recently, a major push has occurred toward modeling of the entire climate system, with fully coupled ocean-atmosphere GCMs that frequently also include such features as an interactive land surface (including dynamical vegetation components), explicit simulation of sea ice, and most recently, chemistry of the oceans and atmosphere, with particular emphasis on the carbon cycle. These more comprehensive models are frequently referred to as "earth system models," or ESMs, though it is important to remember that their core component is still a GCM.

A number of earlier studies used a much simpler climate model known as the "statistical dynamical model" or SDM. In recent years, a new, hybrid model has been developed that combines features of the GCM and SDM into a robust model that can be used to simulate long periods of time; these are known as "earth models of intermediate complexity," or "EMIC." Finally, a very different type of model, based on the concepts of low-order dynamical systems, has been used to study long term climate changes, such as the Pleistocene ice sheet cycles. These low order paleoclimate dynamical models, or PDMs, have considered the role of such factors as internal non-linear oscillations and external forcings due to Milankovitch orbital cycles (e.g., Berger, 1977) in explaining the ice sheet cycles (as do EMICS).

In the remainder of this entry, we explore in more depth how different climate models have been applied to key problems of Quaternary climate. Since all of these specific Quaternary issues/problems are explored in some detail in other entries of this encyclopedia, key results are summarized rather than explained in detail. The thrust here is rather to explain how one goes about doing this paleoclimate modeling, using an evolutionary time-frame, and emphasizing strengths and weaknesses of the models.

Model descriptions and evolution

The GCM

The core of the GCM is essentially the same type of model that is used for modern day weather forecasting; the major distinction is in how the model is used. For weather forecasting, the model is started from a set of initial conditions and run forward in time for a few days (usually 10–14). For climate studies, the model is used to generate a climatic state for a given set of boundary conditions and forcings. The model must be spun-up for a period of months to centuries, both to remove the effect of what are now arbitrary initial conditions and to come into quasi-equilibrium with the imposed boundary conditions and forcings. The model run is then continued for a period ranging from a few years to centuries – the model at this point is generating a series of daily weather patterns, which are then used to generate the desired "climatic statistics" in much the same way that real climate statistics are generated from daily weather observations.

The original GCMs (dating back to the 1970s) were mostly atmosphere-only models; the state of the ocean was prescribed by imposing known (for present-day) or reconstructed (for past times) sea surface temperatures (SST). The state of the land surface was prescribed through very simplistic formulations that specified a surface albedo and a crude representation of water availability (and hence surface evaporation); snow cover was either specified or simulated using simple models. The cryosphere (that is sea ice and continental ice sheets) were imposed, again based on observations or past reconstructions. These early GCMs were constrained both by lack of sufficient physically-based knowledge (especially how to deal with the ocean, cryosphere, and land surface) and, very importantly, by limitations on computational resources to run these computer-intensive models. Over the past four decades, both our understanding of the physics and computational resources have increased tremendously; as of this writing (early 2006) GCMs that contain fully-interactive atmosphere, ocean, ice, and land surface components are in wide use. It is, however, fair to say that the atmosphere component is still the best understood (and hence best modeled), though the other components are rapidly catching up. Furthermore, while the greatly enhanced computational resources we now enjoy mean that the GCM can include all relevant components of the climate system, they still cannot be run for very long time spans (e.g., thousands to tens of thousands of years). See McGuffie and Henderson-Sellers (2005) and Washington and Parkinson (1986) for a more detailed discussion of the GCM.

Other models (SDM; low order dynamical; EMIC)

Around the time that GCMs were first used to address questions of Quaternary climate, the SDM was also in vogue, and used to address the same questions. Unlike the GCM (which is a daily weather model used to generate climate statistics), the SDM attempts to solve the questions by providing appropriate physical quantities on seasonal to annual climatic time-scales. The problem is that key physical processes involved in describing individual weather systems (especially those responsible for rain and snow at mid and high latitudes) must be heavily parameterized, that is, explained in terms of basic quantities like temperature and large-scale circulation (Figure P10). Thus, these models, as such, contributed little to direct understanding of Quaternary climate, though as described below, they did make substantial contributions to low order dynamical models, and, especially, to the recent develop of the EMIC. Saltzman (1978) provides a review of the SDM.

Low order dynamical models differ from the other climate models discussed here in that the major goal is not to simulate a specific climate state, but rather to directly simulate the way in which climate changes over long timescales. These models attempt to define the important feedbacks involved in long-term climate change and then to show how both linear and non-linear interactions, as driven or modulated by external forcings, account for the known record of climate change, especially when the climate changes are expressed as a time series averaged either globally or over key geographic regions. Saltzman (2001) provides an extensive review and discussion of these models; for our present purposes, it suffices to say that they

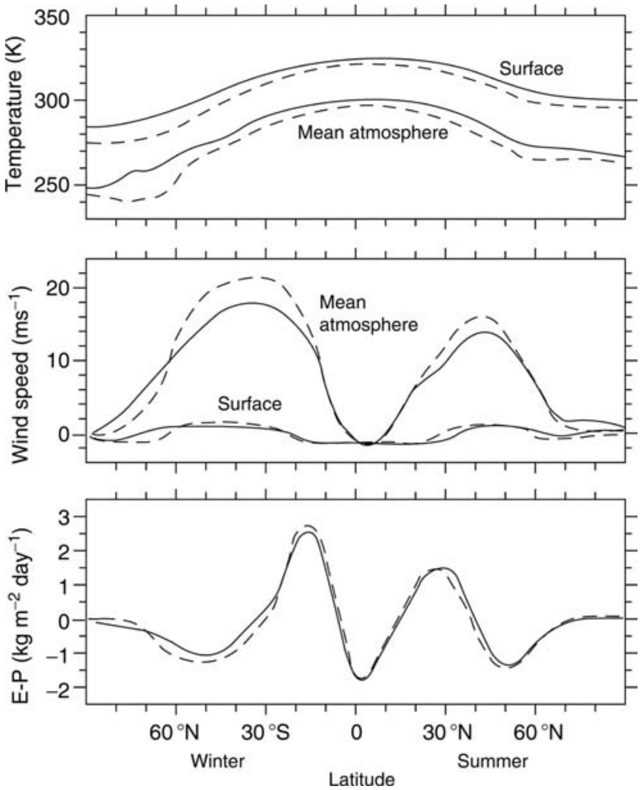

Figure P10 The distribution of zonally-averaged potential temperature (*top panel*), zonal wind (*middle panel*), and evaporation-precipitation difference (*bottom panel*), as simulated by an atmospheric SDM for modern conditions (*full line*) and for 20 ka glacial conditions (*dashed line*) (after Saltzman and Vernekar, 1975).

have demonstrated the important ways in which the state of the oceans, the carbon cycle (i.e., atmospheric carbon dioxide), and the extent and volume of the ice sheets themselves interact nonlinearly to describe how the Pleistocene ice ages occur. Furthermore, they show how such key external forcing agents, especially Milankovich orbital cycles, could act as a pacemaker, that is, phase-lock the otherwise arbitrary ice sheet cycles into the specific time frame given by the paleorecords. An additional key feature of these models is that they are computationally very cheap, and therefore can easily be run for thousands or even millions of years.

The most recent addition to the suite of models is the EMIC. This type of model has been developed specifically to address many of the limitations of the above modeling approaches, and therefore draws upon each of them. These models attempt to explain important physical processes with sufficient rigor (drawing upon concepts adapted from both the GCM and SDM), while at the same time being simple enough that, like the low-order dynamical system models, they can be integrated over geologic timescales (at least those spanning thousands of years, Figure P13). Conceptually these models would seem to offer much, and therefore demonstrate considerable promise. However, since they have only been developed over the past few years, the "jury is still out" on how useful they will ultimately prove to be. One key disadvantage of these models is that they have low spatial resolution compared to the GCM (on the other hand this is a key feature that allows very long runs to be made with them). Claussen et al. (2002) provide an excellent description of one widely used EMIC.

One final modeling approach that has recently been developed and employed is the use of regional climate models (RCM), which have very high spatial resolution (e.g., Giorgi et al., 1990). For many problems, this high resolution is desired or even essential, a good example being the need to resolve mountainous topography (or the full structure of an ice sheet, see Figure P12). Even modern GCMs are typically run for paleoclimate studies at a horizontal resolution no greater than 150 km in latitude and longitude, and many present-day studies are still made with a resolution no greater than 300–400 km. Past studies frequently used even lower resolution GCMs. The drawback to the much higher resolution RCM is inherent in the name; because of computational cost, they can only be run for limited areas, and must be forced at their lateral boundaries, usually from a GCM when conducting paleoclimate studies. Essentially then, the RCM can be thought of as providing a physically based downscaling of GCM results.

With this modeling background developed, focus now shifts to modeling of specific issues of Quaternary climate; emphasizing the use of the GCM, but bringing in other models as appropriate.

Historical development of Quaternary modeling

Some of the earliest GCM and SDM modeling studies involved simulating the impacts of the massive ice sheets of the Last Glacial Maximum (LGM) on the atmosphere (SDM – Saltzman and Vernekar, 1975; GCM – Gates, 1976). Though crude by present-day standards, this work did demonstrate that the climate at the LGM was significantly colder and generally drier than at present, and that orbital forcing played at least some role in accounting for the ice age cycles. Subsequent work generally advanced in two areas: exploration of the physical mechanisms responsible for the relatively cold, dry LGM climate, and snapshot simulations of the climate state every few thousand years from the LGM until the present.

The need to provide specified sea surface temperatures (SST) for the early generation GCM provided the original motivation for the CLIMAP (Climate: Long-range Investigation, Mapping, and Prediction) program, which, in the late 1970s and early 1980s, used all available deep sea core data, especially oxygen isotope data, to develop SST reconstructions for the LGM (CLIMAP group, 1981; Manabe and Broccoli, 1985). These CLIMAP LGM SST became the standard for virtually all GCM work of the LGM, and indeed, with some modification, continue to be used at present. They also engendered considerable controversy when modeling studies using CLIMAP SST yielded significant discrepancies with tropical terrestrial LGM reconstructions from proxy data. Suspicion arose that CLIMAP was flawed over large sections of the tropical Pacific, and much work has gone into resolving this issue, which even at this writing has not been fully resolved (see for example Crowley, 2000; and Toracinta et al., 2004). The controversy does provide an excellent example of the iterative nature by which reconstruction of past environments and paleoclimate modeling work hand in hand.

Another significant development that began in the 1980s was the concept of analyzing GCM time slices through the late Quaternary (especially from the LGM to the present, Figure P11), that is, GCM "snapshots" of simulated climate every few thousand years. The first sets of snapshots

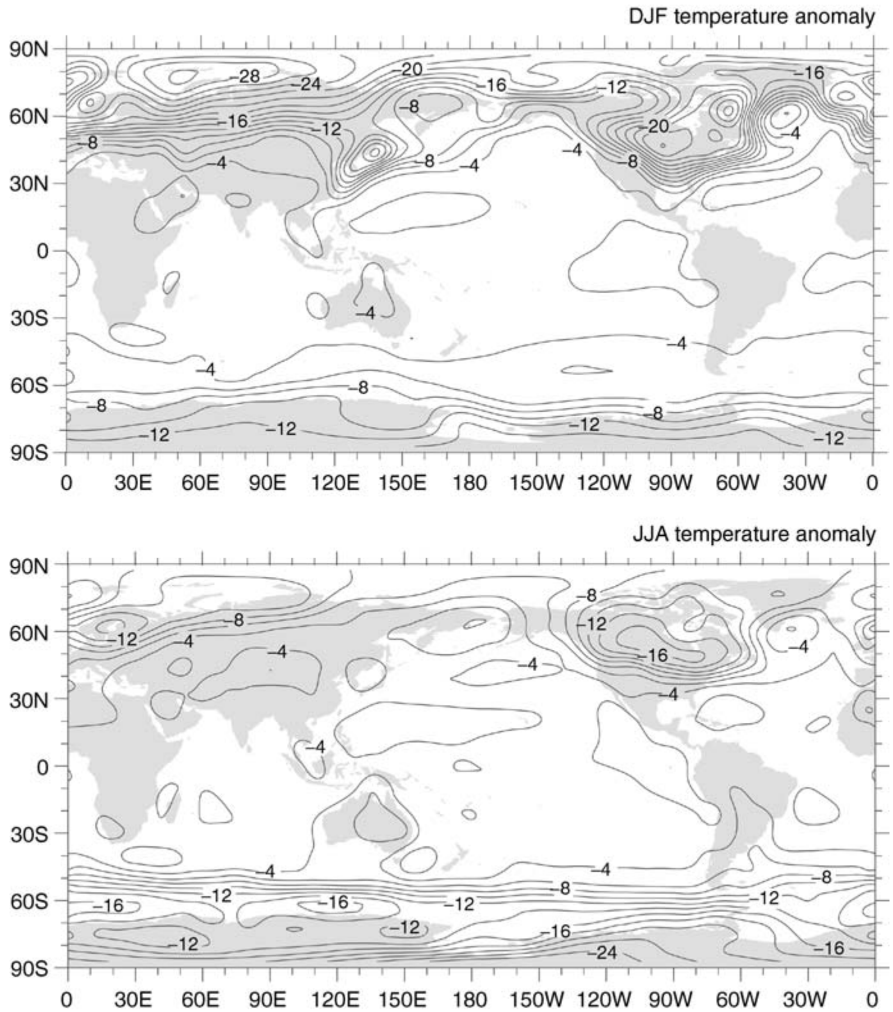

Figure P11 LGM minus present surface temperature anomaly from the NCAR CCSM GCM, averaged over December, January, and February (*top panel*) and averaged over June, July, and August (*bottom panel*). Units are in degrees Celsius (after Shin et al., 2003).

(Kutzbach and Guetter, 1986) were for 18 ka, 15 ka, 12 ka, 9 ka, 6 ka, and 3 ka, or every 3,000 years from what was then thought to be the time of the LGM (18 ka) until the present. Of course, as the difference between "radiocarbon years" and "calibrated years" became known, it was realized that the LGM actually occurred about 21 ka (especially important because it affects the particular configuration of orbital parameters). Thus, subsequent series of model runs had their timings adjusted accordingly. Taken individually, each run of the series can be compared to reconstructions of the Quaternary for that time period. Taken as a group, they can form a description of how climate changed from the LGM to the present, in effect accomplishing, albeit in a different way, a goal similar to that of low order dynamical modeling. These time slice runs have been repeated a number of times, with entirely different models, and with improved versions of the same model. This means that in addition to shedding light on the climate of each of these times, they are also used to describe inter-model differences, and track improvements to individual models.

Related to this time slice approach, the COHMAP (Cooperative Holocene Mapping Project) has focused on reconstructions and modeling of the Holocene, loosely defined as the time after the ice sheets decayed to a point where they (presumably) had little impact (approximately 9–12 ka depending on research group and specific definitions) (COHMAP, 1988). Much of this attention has been focused on the mid-Holocene so-called "climatic optimum" at 6 ka, when, in the Northern Hemisphere at least, orbital parameters should dictate a relatively warm climate. Particular attention has been paid to changes in Asian, African, and North American monsoonal circulations and effects at 6 ka, as these presumably would have been enhanced. Prell and Kutzbach (1987) have also carefully studied monsoon response in simulations earlier in the Holocene as well as during glacial and interglacial times. Not surprisingly, they found that monsoon circulations tend to be stronger during interglacials than during glacials. In part, this is due to the absence of the ice sheets but it is also because interglacials tend to be times of enhanced orbital insolation.

The above modeling studies were primarily focused on model simulation of the overall climate of specific time periods, and comparison to climates of other times, especially the present-day climate. Quite a number of other studies have

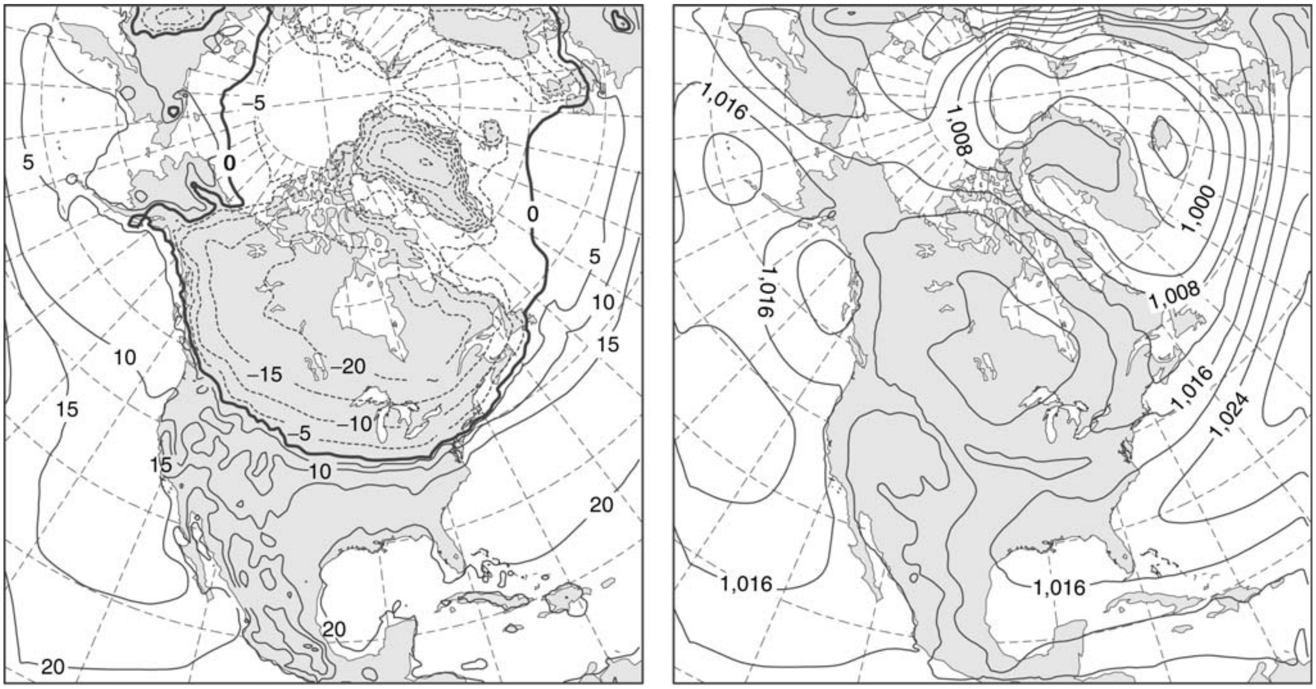

Figure P12 LGM surface temperatures and sea-level pressures as simulated by the PMM5 RCM. *Left panel* is surface temperature averaged over January in degrees Celsius and *right panel* is sea-level pressure averaged over January in hPa (after Bromwich et al., 2004).

addressed how these very different climates have been maintained. These studies fall into two broad categories, the first of which are process-oriented studies for a particular time period. Two key examples here include: (i) the dynamical effects of the ice sheets at the LGM on the circulation of the atmosphere, especially the way in which these very high elevation, white (due to the high albedo of snow and ice) ice sheets impact the circulation (Shinn and Barron, 1989), and (ii) the effect of tropical Pacific SST (especially so-called "permanent La Niña conditions") on the hydrologic cycle and drought over central North America and northern Africa (Shin et al., 2006).

The second category includes sensitivity studies, in which a series of model simulations is made, spanning a range of values for a particular climate component, boundary condition, or forcing. These can be considered individually, or in concert. Key examples include evaluation of: (i) the sensitivity of climate to ice sheet areal extent, height, and "whiteness" (albedo) and (ii) the relative roles that such factors as atmospheric carbon dioxide (CO_2), orbital forcing, and the ice sheets themselves play in accounting for the cooler climate of the LGM. In the first case, Felzer et al. (1996), for example, demonstrated the importance of thresholds in ice sheet elevation – too low and the atmosphere flows over them, but above a certain height the atmosphere must flow around them instead, yielding a very different regional climate, whose effects in turn can be seen over a much larger portion of the Earth. In the second case, Felzer et al. (1999) showed that the ice sheets and lowered CO_2 played approximately equal roles in accounting for the colder LGM temperatures, with orbital forcing playing a much smaller role.

Recently, considerable attention has focused on extending modeling studies further back in the Quaternary. One particular interest has been 115 ka (sometimes taken as 116 ka), which is when the last great Pleistocene ice sheet cycle is thought to have begun (Fig. P13). The primary focus of these studies has been on ice sheet inception, that is, how does the climate system change from little or no perennial snow cover to multi-year perennial snow cover and then to growth of ice of sufficient mass that it begins to flow and thereby leaves a trace in the geologic record (Vettoretti and Peltier, 2002)? This is a question yet to be satisfactorily resolved (Dong and Valdes, 1995). Cold temperatures will certainly help preserve snow/ice, but the colder the atmosphere the less moisture it can hold; the warmer the atmosphere the more moisture can precipitate out as snow (assuming surface temperatures not much above freezing). The other time period of interest has been the time around 125 ka, when the last major interglacial occurred. Evidence from the geologic record suggests this interglacial may have been even warmer than the mid-Holocene; orbital forcing was also somewhat larger at this time. Prell and Kutzbach (1987) indeed found in GCM studies that the monsoon at 125 ka was enhanced relative to 6 ka (and hence also to the present).

A few early attempts were made to use regional climate models (RCM) to address some of the above problems, but neither the RCMs nor the GCMs required for the lateral forcings were adequate. This has changed in recent years; regional model simulations of the Laurentide and Fenno-Scandinavian Ice Sheets at the LGM have been shown to yield much closer overall agreement with paleo proxy reconstructions than does the GCM used to drive the RCM (Bromwich et al., 2004). In particular, the much higher resolution RCM appears more capable of simulating the highly-variable spatial details of precipitation, and the nuances of topography, land surface type and state, and atmospheric circulation than the low resolution GCM, which all too often can only broad-brush these features. On the other hand, occasionally the RCM will provide surprising results that seem at odds with at least

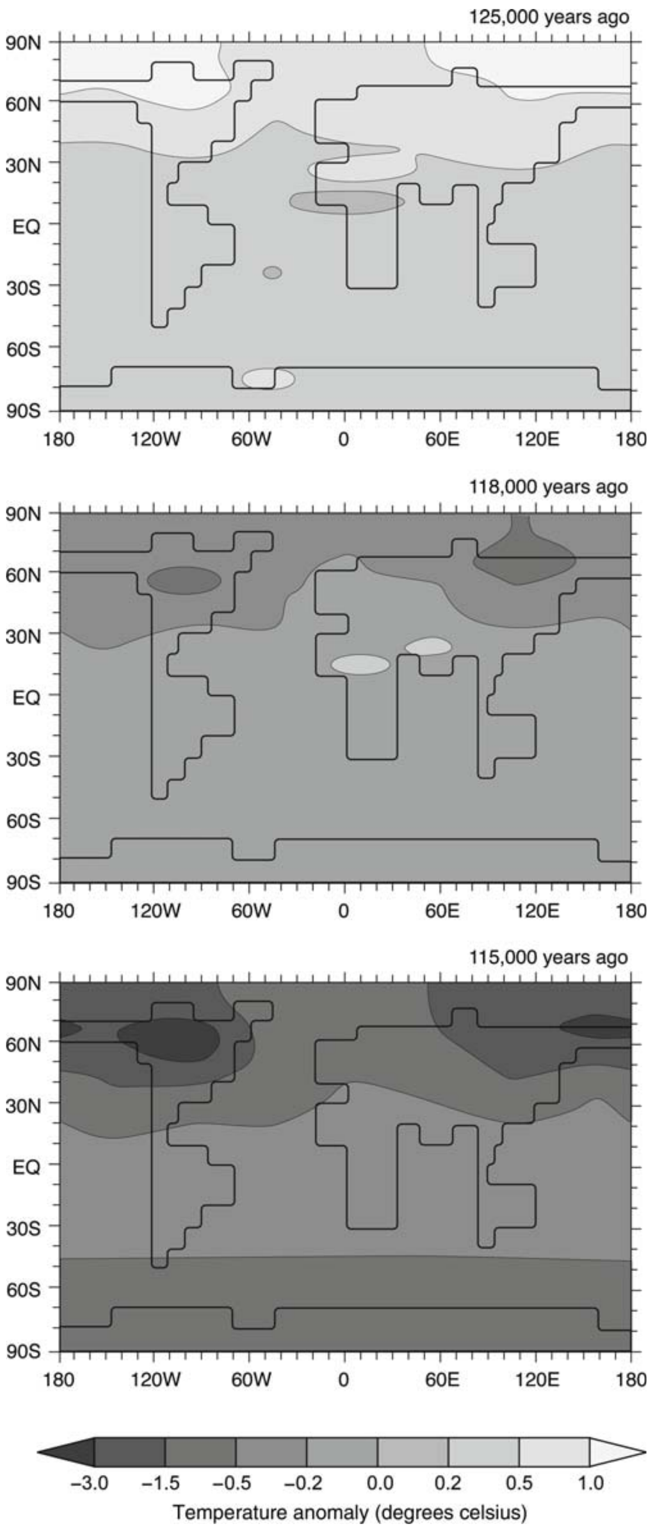

Figure P13 Annually-averaged temperature anomalies, relative to the present, at 125,000 years ago (*top panel*), 118,000 years ago (*middle panel*), and 115,000 years ago (*bottom panel*) from the CLIMBER-2 EMIC. Units are in degrees Celsius. The progression is from full interglacial conditions at 125,000 years ago, to the onset of the next glaciation at 115,000 years ago (after Calov et al., 2005).

the conventional paleo reconstructions. This is yet another example of how models and proxy data together can be used iteratively to provide a much deeper understanding than either one alone. It is likely that GCMs will continue to be used in future paleoclimate studies.

Most recently, the EMIC has been used to address climate problems of the Quaternary. The advantage to these models is that they can be easily integrated over long periods of time. EMICs have been used to simulate changing climate over the past few thousand years (although this is also beginning to be done with GCMs) (Crucifix et al., 2002; Calov et al., 2005). They have also been used to address problems earlier in the Quaternary, e.g., around 400,000 years ago, as well as at the Plio-Pleistocene transition. As described above, it is unclear how informative these models are, largely because of their low spatial resolution (how, for example, can monsoon effects be studied with a model that may only have a 57 degree resolution in longitude?). These models could possibly be considered as an attempt to combine the best of both worlds of low order dynamical models and GCMs; but instead they may actually only capture the worst of both worlds. Again, the jury is still out.

The current state-of-the-art

As climate models continue to evolve, together with our understanding of Quaternary climates, recent efforts have focused on addressing key Quaternary climatic issues with improved models. For GCM studies, this has meant explicitly including other climate components in addition to the atmosphere. Fully-coupled atmosphere-ocean GCMs have been used to simulate the climates of the LGM and the Holocene "climatic optimum" at 6 ka. While somewhat less mature and less well-developed, attention is also being paid to simulating these time periods with interactive vegetation, ice sheet, and biogeochemical cycle components embedded in the GCM (with the model now typically called an ESM). These new, enhanced modeling studies typically have broadly the same results as the more crude earlier models, but do highlight important regional differences and provide new understanding of the relevant physical processes. For example, fully coupled runs at 6 ka have shown the importance of tight atmosphere-ocean coupling in modulating the African and Asian monsoons. This same type of fully-coupled modeling for the LGM-Holocene transition (broadly 9–12 ka) has shown the importance of, and possible bimodality in, the ocean thermohaline circulation, especially the production of North Atlantic Deep Water (NADW). This type of bimodal "switch" or threshold, has profound implications for past climates, and is of potential importance concerning near-term future climate change.

Furthermore, many researchers are now starting to use GCMs not just to study "snapshots" of a particular past time, but instead are actually running the models for periods of thousands of years. A lot of this has already been done for the past 2,000 years, but runs are also underway using a GCM to simulate the past 6,000 years. In addition to the GCM, the EMIC has also been used to peform these simulations through geologic time. By coupling the GCM to high resolution RCMs, models can also commonly be run with local resolutions around 50 km, with as fine as 10–20 km possible. Finally, recovery of higher resolution paleoclimate proxy records in recent years has meant significant improvements in the iterative procedure by which the past reconstructions are used to evaluate the models and, in turn, the model results are used to help understand the implications of the geologic record and guide in the search for more proxy data. Especially important has been the development of high temporal resolution, well-dated, multi-proxy records from ice cores and lake sediments, which have greatly complemented the more traditional deep-sea cores.

Future directions

One direction that has been discussed for years is the development of a super-model; that is, essentially a super-GCM that has very high spatial resolution, can be run for extended periods of time (at least thousands of years) and that incorporates all relevant climate phenomena, regardless of timescale. In other words, such a model would explicitly simulate the motions of the atmosphere on timescales of minutes, and would simulate the waxing and waning of ice sheets, with timescales of tens of thousands of years. Both the recent development of ESMs and of EMICs can be considered as steps towards the development of such a super-model; however, approaching from opposite ends of the spectrum. That is, the ESM attempts to include as many physical processes as possible at high spatial and temporal resolution (increasing the computer resources needed for long runs severely), while the EMIC, which also attempts to consider as many physical procceses as feasible, explicitly uses low temporal and spatial resolution so that long runs can be made. The practical obstacles to developing a super-model are obvious – the need for considerably more computational resources than currently available as well as sharp limitations in our knowledge of the relevant physical processes. In addition, is it not even clear conceptually whether such a model is even possible given the huge range of timescales over which it must be run. Small errors in the short time-scale processes may cascade over longer times, making it impossible to get a satisfactory solution of the long timescale processes.

More use of coupled GCM-RCM studies is likely to be made so that climatic states and phenomena can be studied at much higher resolution. Also, the EMIC could mature as a class of models and continue to provide better ways of making fairly low-resolution but physically-plausible long simulations. Indeed, it may be expected that a "morphing" will continue to take place between the EMIC and low-order dynamical system models. Finally, there will be a continuing need for more and better geologic data to constrain the models, with the models in turn being used to help better understand paleoclimate reconstructions.

Summary and conclusions

The above is intended to provide a concise but necessarily brief and limited overview of how paleoclimate modeling of the Quaternary has developed from the early 1970s until the mid-2000s. Many important problems, concepts, and studies have either been given only a cursory treatment, or even not considered at all. As a glance at the bibliography quickly shows, full treatment of this topic would require at least one, if not several, entire lengthy volumes. All of the issues that have been raised above, as well as those beyond the scope of this discussion, are being actively investigated; none have been satisfactorily "proven," nor, given the simple fact that we will never know precisely what happened in the past (unless someone eventually constructs a true time machine), will they ever be. Nonetheless, they have taught us many things about how the climate system works, which is perhaps the single most important issue to be addressed via climate modeling of any time period, be it the past, the present, or projected future climate states, as well as the climatic changes required to make them. The interested reader is strongly encouraged to use this treatment, and especially the papers and books listed in the bibliography, as a starting point for a more in depth study and analysis of this very interesting and important theme.

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Cross-references

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Atmospheric Circulation during the Last Glacial Maximum
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Climate Variability and Change, Last 1,000 Years
COHMAP
Glaciations, Quaternary
Holocene Climates
Last Glacial Maximum
Last Glacial Termination
Laurentide Ice Sheet
Millennial Climate Variability
Monsoons, Quaternary
Pleistocene Climates
Quaternary Climate Transitions and Cycles
SPECMAP
Younger Dryas

PALEOCLIMATE PROXIES, AN INTRODUCTION

The Earth's climate has changed dramatically over the eons, as the atmosphere continuously interacts with oceans, lithosphere, and biosphere over a wide range of timescales. Efforts to place recent climate observations into a longer-term context have been stimulated by concern over whether the twentieth century global warming trend is part of natural climate variability or linked to increasing anthropogenic inputs of greenhouse gases into the atmosphere. The ability to decipher past climates has expanded in recent years with an improved understanding of present climatic processes and the development of more sophisticated analytical tools. Instrumental records go back only a century or two. To extend the record beyond the instrumental period, scientists turn to "proxies" or "indicators" that are indirect measures of past climates or environments preserved in natural archives, such as marine and terrestrial sediments, trees, and ice cores, among others. Paleoclimatic or paleoenvironmental proxies are materials that are sensitive to a variety of climatic or environmental parameters. These can be grouped into three major categories: (a) lithological/mineralogical, (b) geochemical, and (c) paleontological (Table P2). The types of information on past climates or environments that can be obtained from these proxies are briefly summarized in Table P2 and below. Additional information is provided in the individual entries listed under *Cross references*.

Lithological/mineralogical indicators

Lithological indicators consist of sedimentary deposits or fossil soils (paleosols) that have originated at or near the Earth's surface under conditions characteristic of a particular climatic regime or environmental setting. The paleoclimatic information yielded by terrestrial lithological indicators comes from interpreting the specific environments under which they formed and their spatiotemporal distribution on local to global scales (see Table P2; Parrish, 1998; *Sedimentary indicators of climate change*). Some lithological or sedimentary indicators point to specific climate conditions, such as glaciation (e.g., tills and tillites, moraines, eskers, kames, kettles), aridity (e.g., eolian dunes, evaporites), or warm, humid climates (e.g., laterites, bauxite) (see *Arid climates and indicators*; *Coal beds, origin and climate*; *Glacial geomorphology*; *Glaciofluvial sediments*; *Glaciomarine sediments*; *Laterites*). Others provide more indirect signs of climate change interpreted from the depositional environments of sediments, using classical geological techniques (see *Encyclopedia of Sedimentology*). Examples of depositional environments include fluvial, deltaic, lacustrine, eolian (wind-borne), near-shore, and deep sea settings (see *Coastal environments*; *Deltaic sediments, climate records*; *Eolian sediments and processes*; *Lacustrine sediments*; *Marine biogenic sediments*). Finely laminated sediments, such as varves, preserve seasonal variations in rainfall, streamflow, ice melt, or chemical precipitation in lakes (see *Varved sediments*). Lithological indicators are also closely linked to biogeochemical phenomena, which create additional paleoclimate proxies (see below).

Major shifts in the environment or climate over longer geologic time periods are marked by pronounced lithologic or compositional changes in the stratigraphic column. A beautiful example can be seen in the well-exposed Carboniferous-Permian strata of the upper half of the Grand Canyon, Arizona, where marine limestones of the Redwall Formation were overlain by intercalated reddish mudstones, sandstones, and calcareous sandstones of the Supai Group deposited in a complex coastal plain setting in which the sea repeatedly advanced and retreated. Eolian features within some sandstone units were likely formed by onshore winds (Beus and Morales, 2003). The Supai strata were succeeded by red beds of the Hermit Formation – siltstones, mudstones and fine-grained sandstones – deposited by rivers, showing cyclical alternations possibly related to climatic fluctuations. Desiccated mudcracks and ripples at the top of the Hermit Shale suggest a climatic aridification, which culminated in the vast accumulation of desert sands represented by the Coconino Sandstone. The seas returned toward the end of the Permian period, as exemplified by the thick marine limestone sequence (Toroweap Formation, Kaibab Limestone).

Minerals that form at or near the Earth's surface reflect ambient conditions at the earth-atmosphere interface and can therefore furnish important clues about former climates (see *Mineral indicators of past climates*). Climate-sensitive minerals can be used to infer past climates and changes over time, to deduce changes in atmospheric composition, to act as mineralogical "markers" in provenance studies, and to serve as "hosts" for stable isotopes and trace elements used in paleoclimate studies. The most direct mineral indicators or proxies are those that are generated under relatively narrow climatic ranges or within restricted environmental settings. Examples include chemical precipitates such as evaporites (e.g., halite, or rock salt), clays formed by intense chemical weathering (e.g., kaolinite, smectite), and chemically-resistant minerals concentrated into eolian