Modeling paleoclimates

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Introduction

Data describe, models explain. Both are required to document and understand the past variations of Earth's climate, and to help address the present problem of assessing climate change that may result from human activities. Models (for the most part conceptual as opposed to numerical) have long been applied for understanding climate variations during the Quaternary. Indeed, over a century ago, in a set of papers that contributed to the foundation of scientific method in the geosciences (multiple working hypotheses), T.C. Chamberlin (1897, 1899) provided a comprehensive conceptual model for explaining long-term climatic changes that is remarkably modern in some of its elements. What is regarded as a "climate model" today is generally a computerized numerical representation of the physical processes involved in the climate system, but conceptual models still play an important role in paleoclimate research. Whenever any kind of paleoclimatic data is interpreted, either quantitatively or qualitatively, some kind of model is invoked.

Paleoclimatic data (of the kinds reviewed in this volume) and climate models play a complimentary role in understanding climate change. The data record how climate has changed, but data alone cannot provide an unambiguous explanation of why a particular climate state occurred or changed. This situation arises because most climatic variations recorded geologically have multiple, hierarchial causes (e.g. there is more than one way to create drought in a region) and because environmental subsystems display generally nonlinear responses to climate. Consequently, multiple cause-and-effect pathways can produce the same response in a paleoclimatic indicator. This indeterminacy of the "climate signal" is mitigated somewhat by considering networks of paleoclimatic data and by examining multiple indicators at individual sites, but such "multi-proxy mapping" cannot in itself eliminate the indeterminacy.

Models based on physical principles (or widely accepted empirical representations of those physical principles) do have the potential to provide mechanistic explanations of past climatic variations, provided they are known to work, are applied in an appropriately designed experiment, and (perhaps most importantly) explicitly account for all of the components of the climate system that are involved in a particular climate change. Although comprehensive models of the climate system and its individual components (the atmosphere, oceans, biosphere, hydrosphere, and cryosphere) are evolving rapidly, the development of a comprehensive model that can simulate the temporal and spatial variations of climate on both global and local scales, using as input only the records of the external controls of climate (i.e. an "Earth-system model"), is perhaps a decade away. The indeterminacy of the data and the present limitations of the models thus dictate a synergistic approach for understanding climate variations that relies on integrating paleodata with paleoclimate model simulations.

In this chapter we review the process of climate-system modeling and present a taxonomy of the models recently applied in the study of Quaternary climate change and variation. We also briefly trace the development of climate modeling since the 1965 INQUA volume and its companions were published. A synopsis of climate-modeling results for North America is provided, and we conclude with a discussion of some the emerging issues in the application of models for understanding climatic variations.

Climate-System Modeling

Many conceptual and numerical models that describe the workings of the climate system and its components have been developed, and there probably are as many taxonomies of those models as there are reviews of them. Primary reviews of climate modeling in general include Trenberth (1992), McGuffie & Henderson-Sellers (1997), and Randall (2000). Substantial information for paleoclimate modeling in particular can be found in chapters by Crowley & North (1991, Chaps 1 and 2), Kutzbach (1992), and Peteet (2001). Saltzman (2002) provides a coherent framework for understanding past, present and future climatic variations. Earlier modeling reviews include those by Schneider & Dickinson (1974), NRC (1974), Hecht (1985) and Kutzbach (1985). Because no two sources classify climate models or modeling studies in the same way, the task of providing an overview of the field is complicated. One way to organize a discussion of climate models and their application (climate modeling) is to consider first the nature of the climate system and what controls its variations through time, and then to describe a few large classes of climate models and their applications.

Traditional definitions of climate are typically couched in statistics. For example, climate can be thought of as ". . . a set of averaged quantities completed with higher moment statistics (such as variances, covariances, correlations, etc.) that characterize the structure and behavior of the atmosphere, hydrosphere, and cryosphere over a period of time" (Piexoto & Oort, 1992), or, less explicitly, as ". . . the synthesis of

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weather in a particular region." (Hartmann, 1994). Such statistics-based definitions are being replaced in practice (e.g. IPCC, 2001) by one in which climate is regarded as the collection of individual environmental components (jointly the *climate system*), and the record of their interactions and variations through time.

Although the number of major components of the climate system is relatively small, the number of variables that describe these components is quite large, making a full cataloging of the climate variables that might be represented by models tedious and not very informative. However, the many variables involved in fully describing the climate system generally fall into one of three categories (Saltzman, 2002): those that describe the external forcing of the system (*boundary conditions*), those that describe the slowly varying aspects of the system (e.g. the size of ice sheets) that have traditionally been the focus of Quaternary paleoclimatology (*slow-response variables*), and those that describe the internal variables that are ordinarily thought of as weather (*fast-response variables*). A fourth category of variables, which we call *subsystem variables*, describes the state and function of the many environmental subsystems that are governed by climate and which provide paleoclimatic evidence or "paleodata" (Fig. 1).

Climate-System Variables

Boundary Conditions

In theory, the external controls of climate (or boundary conditions, a term borrowed from numerical analysis) include variables beyond the influence of climate. Such boundary conditions include: (1) the latitudinal and seasonal distribution of insolation (incoming solar radiation), as determined by variations in solar output and the elements of Earth's orbit; (2) the configuration of continents and ocean basins including their topography and bathymetry, and the location of mountain chains and gateways between ocean basins; (3) the abiotic component of atmospheric composition, as determined by volcanic emissions; (4) a small flux of geothermal heat; and (5) human activities not controlled by climate. In practice, what is regarded as an external control as opposed to an internal response depends on both the experimental design of a modeling study and the timescale that it focuses on. Ice sheets, the terrestrial biosphere, and ocean temperature and salinity, for example, are most appropriately regarded as variables internal to the climate system. The areal extent and volume of the major ice sheets are ultimately controlled by

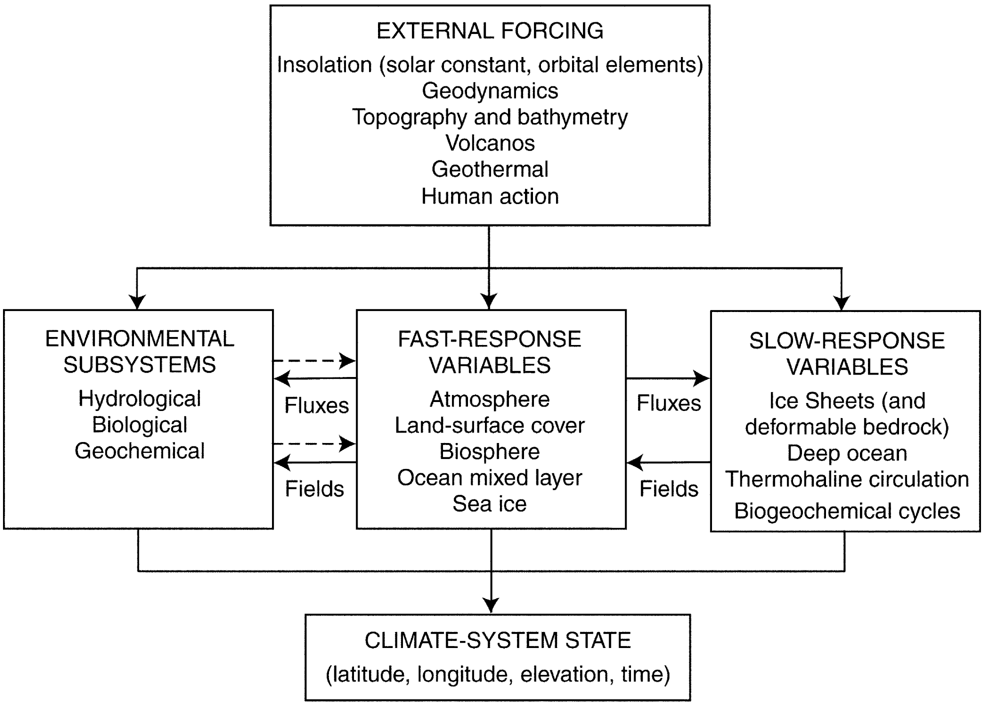

Fig. 1. The climate system (after Fig. 5–3 in Saltzman, 2002). The variables that describe the external forcing of the system (or boundary conditions) directly or indirectly influence the slow-response, fast-response, and environmental-subsystem variables, which in turn influence each other and determine the state of the climate system as a function of longitude, latitude, elevation and time. The arrows labeled "fields" indicate that one set of variables influences the other through patterns of atmospheric circulation, moisture and heat, while those labeled "fluxes" indicate that one set of variables influences another through the transfer of mass and energy. The dashed arrows indicate that the influence of the fast-response variable on environmental-subsystem variables is currently unidirectional in climate models, but that eventually environmental-subsystem variables will interact with the fast-response variables as climate models develop.

external forcing and (over long time spans) can be thought of as an index of the internal state of the climate system. On century-to-annual time scales, however, the sizes of the ice sheets are comparatively constant. In simulations of particular times (e.g. the Last Glacial Maximum) or of sequences of times that are century in length or shorter, the ice sheets can therefore be regarded as one of the external controls that must be "prescribed" (or specified ahead of time) in those simulations. The same is also true for the temperature of the deep ocean and the components of atmospheric composition.

Slow-Response Variables

The slow-response variables of the climate system include ice sheets, large ice shelves, crust and mantle deformable by ice sheets, sea level, temperature and salinity of the deep ocean and the long-term state of its thermohaline and horizontal circulation, and slowly varying reservoirs involved in biogeochemical cycling that determine atmospheric composition. These slowly varying components are most often visualized as time series (as opposed to sequences of maps), and together describe the state of the climate system on century and longer time scales. As is the case for the boundary conditions, the particular role of these variables in climate models can be ambiguous and depends on the specific model and experimental design.

Fast-Response Variables

The three-dimensional states of the atmosphere, land and ocean surfaces are represented by the fast-response variables. For the atmosphere, the key properties that are either observed or simulated include the distribution of temperature, pressure, wind and moisture (including clouds), and its trace-gas and mineral-aerosol composition. At the surface, the fast-response variables include seasonally varying sea-ice extent, soil-moisture content, vegetation cover (including evapotranspiration rate, rooting depth, and albedo), and the temperature, depth and other physical and biological characteristics of the mixed layer of the ocean. On the shortest of time scales (hours-to-days) the fast-response variables can be thought of as describing the weather. In most instances, the fast-response variables are visualized using maps or sequences of maps such as those commonly used in weather forecasts.

Subsystem Variables

A large number of environmental systems and processes respond to variations of climate, and many of these, like those included in the terrestrial or marine biospheres, or surficial hydrologic systems, also provide the principal lines of paleoclimatic evidence that are used to reconstruct past climatic changes (Bradley, 1999). These systems have many variables, including some that play a role in the interaction and feedback between the atmosphere and the surface (and might therefore be thought of as fast-response variables), and some that are dependent on climate but do not feed back to the climate system except in limited ways. There is no common mode for the visualization of these subsystem variables.

Some variables are not easily categorized. Vegetation, for example, plays a key role in the instantaneous coupling of the atmospheric boundary layer and land surface by controlling the exchanges of energy and moisture. The rates of these exchanges depend on the structure of the vegetation and on the states of the atmosphere and underlying soil (including atmospheric humidity, wind, net radiation at the surface and soil-moisture availability) that together influence plant physiology (e.g. stomatal conductance). It was formerly thought that vegetation structure responds slowly to climate changes (on the order of hundreds to thousands of years), placing it in the category of slow-response variables. It is now clear that vegetation structure responds rapidly to climate changes over time spans of years to decades (Tinner & Lotter, 2001; Webb *et al*., this volume). Soils are dependent on climate and vegetation, but also have strongly expressed geological and geomorphic controls. Key attributes of the soil such as water-holding capacity (WHC) may be dominated by parent material (as in arenaceous soils), and so WHC might be regarded as a boundary condition; in other situations WHC is dominantly controlled by soil morphology, and hence acts like a slow-response variable. The particular category a variable falls into is thus largely dependent on context, location and scale.

The Climate-Modeling Problem

The ultimate goal of climate modeling is to consider simultaneously the first three groups of variables listed above, and, as necessary, also to treat the other environmental systems that depend on climate (e.g. those described by the fourth group, the subsystem variables) – all in order to provide both a description and an explanation of the variations of climate through time. The result of modeling may be a single map or a series of maps or one or more time series. One can decompose the basic problem of climate modeling into a sequence of tasks: (1) use the record of boundary conditions to simulate the time history of the slow-response variables, (2) use the boundary conditions and state of the slow-response variables to simulate the fast-response variables, and (3) use the fast-response variables to understand and simulate the environmental subsystem variables.

Climate Models

Climate models can be classified by describing the particular *applications* to which they are put (e.g. simulating the variations of the second-through-fourth set of variables described above), or by describing the *comprehensiveness* of different models – the number of processes and major components of the climate system they include and the (temporal and spatial) resolution at which those processes and components are represented. These classification schemes provide different ways of organizing the various models and are applicable to both conceptual and numerical models. Here we emphasize numerical models, but we do not underestimate the necessity, utility, and power of conceptual models.

Model Applications

Most applications of numerical climate models can be categorized as having one of three general goals: (1) simulating the evolution over time of the climate system or one of its major components; (2) simulating the spatial patterns of climate-system components; and (3) simulating the detailed function of a single component or process. However, the present trends in climate-model development, which are leading to more comprehensive models of the climate system (see below), are in fact aimed at blurring the distinction among these applications.

Time-Evolution Applications

Numerical climate models have been developed to simulate the evolution of climate over a range of time scales from geological (i.e. those that treat Cenozoic cooling or the onset of Quaternary glaciation) to inter- (and intra-) annual variations, as well as the trends in climate over the past several millennia (see Crowley & North, 1991, Chap. 1). The main goal of time-evolution modeling experiments is to simulate some macro-scale feature of the climate system, such as global ice volume or hemispheric-average temperature, using the record of external controls of climate as input (e.g. Birchfield *et al.*, 1994). Models used in simulating time evolution commonly represent components of the climate-system at low resolution, as in box models or energy-balance models that include representations of continental and marine reservoirs or active layers without being spatially explicit (e.g. Harvey & Huang, 2001).

Spatial-Pattern Applications

Models that focus on simulating the spatial patterns of climate include general circulation models (GCMs) and spatially resolved energy-balance models (EBMs) that include realistic geography (Crowley & North, 1991, Chap. 1). General circulation models, which simulate the three-dimensional structure of the atmosphere, ocean and land surface on time steps of minutes to hours, were originally developed for operational weather forecasting. The models continue to evolve and the operational models being run, for example, by the National Oceanic and Atmospheric Administration and the European Center for Medium-Range Weather Forecasts are now also being used for "reanalysis" projects (Kistler *et al.*, 2001) an approach in which observed parameters of global weather (e.g. atmospheric soundings), sea-surface temperatures (SSTs), and ice cover are incorporated into GCMs, which then provide simulations of the 3-D structure of the atmosphere and state of the land surface.

The acronym "GCM" is often being taken to mean "global climate model." A true global model, however, would be one in which all "internal" climate system components (i.e. variable groups 2 through 4 above) are explicitly represented (as opposed to being prescribed). Global climate models now exist in preliminary form as "EMICs" (Earth-system Models of Intermediate Complexity; Claussen *et al.*, 2002). In practice, the extent to which other components of the climate system are included in a GCM (in addition to the atmosphere and land and ocean surfaces) is represented by additions to the GCM acronym. For example, AOGCMs include explicit representation of a three-dimensional ocean, while AVGCMs not only represent the regular physiological variations that must be included in any GCM, but also allow for variations in vegetation structure (Sellers *et al.*, 1997). As more interactive components are added to GCMs, they will gradually evolve toward full Earth-system Models (ESMs).

An important aspect of both GCMs and EBMs is their potential for simulating climate variables that may be crucial for understanding the response of particular paleoclimatic indicators to climatic variations. For example, many terrestrial subsystems (vegetation, lakes) are governed directly by the surface water and energy balances, or by "bioclimatic variables" (e.g. Prentice *et al.*, 1992), as opposed to standard climate variables like temperature and precipitation. The former, mechanistic, variables are not commonly observed, or may indeed be unobservable, especially over regional scales. The potential for GCMs and EBMs, along with process models, to simulate presently unobservable variables also contributes to understanding the mechanistic controls of the variations in paleoclimatic indicators.

Simulation of the time-evolution of the climate system can also be approached by conducting a series of spatial-pattern simulations, or "snap-shots," wherein the boundary conditions at a number of key times are established from the geologic record and are used to initialize models that produce "equilibrium" simulations for those times (e.g. COHMAP Members, 1988; Valdes, 2000; see also Peteet, 2001 for a discussion of the distinction between "snap-shot" and "sensitivity-test" experimental designs).

Subsystem (Process-Model) Applications

Models that attempt to represent the variables that describe individual environmental subsystems are often called "process models" inasmuch as they are designed to incorporate, either explicitly or implicitly, the actual climatic mechanisms that govern a subsystem such as a watershed, lake, or plant. We exclude from this category statistical relationships that are developed by screening a large number of potential predictors of the distribution or variation of some paleoclimatic indicator, but which do include statistical relationships between predictors and mechanistically related responses (i.e. using mean July temperature or growing-degree days as a proxy for the heat and energy requirements of plants). Many process models exist and we do not attempt an exhaustive review here. Process models range in scope (and scale of application) from those that represent the dynamics of ice sheets (e.g. Marshall, 2002) or global vegetation patterns to those that simulate the responses to climate variations within individual watersheds, lakes, or forest stands.

Many subsystem process models are run in a "stand alone" or "off line" mode in which the there is no feedback with the climate model and input for the models is derived from the output of climate simulations. Process models are generally applied to individual points, such as a particular lake or forest stand, but they can also be run over a global network of sites or grid points, thereby producing simulations that are comparable with the spatial-pattern applications of global or regional climate models. Examples include equilibrium vegetation models (e.g. Harrison *et al*., 1998; Prentice *et al*., 1992) and ice-sheet mass-balance models (Pollard *et al*., 2000), applied over a grid, that use the results of a paleoclimatic simulation as input. The individual model grid points do not communicate with one another as they do in an AGCM or AOGCM.

Model Comprehensiveness

A second way to classify climate models is by their comprehensiveness or scope, as was done by Claussen (2001) and Claussen *et al*. (2002) (Fig. 2). Claussen (2001) considers three attributes or axes: (1) the degree of model *integration*, or the number of interacting components of the climate system that are coupled within the model; (2) the number of processes explicitly simulated in the model, which can also be thought of as the cumulative *dimension* of the model; and (3) the detail of description in both time and space, commonly thought of as model *resolution* (Fig. 2). Highly integrated models account for the interactions and feedbacks among multiple components of the climate system, like the atmosphere, ocean, and terrestrial biosphere. In contrast, less integrated models explicitly represent one component (e.g. the atmosphere in an AGCM), and "parameterize" (or represent by very simple, sometimes empirically based relationships) the behavior of others (like the ocean and land surfaces in an AGCM). Models that represent many processes in a spatially explicit way (e.g. multiple-layer soil-moisture storage simulation) have higher cumulative dimensionality than others that include fewer processes in a more generalized way (e.g. the single-layer or "bucket" approach to soil-moisture storage). The third dimension of Claussen's scheme, resolution, which has always been limited by computing resources, is easiest to envision.

When individual models are placed in Claussen's three-dimensional framework, several clusters emerge: (1) conceptual models that are of low spatial resolution (treating, for example, the whole Earth or greatly generalized continents and oceans) and in process dimensionality; (2) elemental (or low-dimensional) models of an individual or small number of the major components of the climate system; (3) EMICs, which are spatially explicit, and often represent multiple components, but generally at low spatial resolution (Claussen *et al*., 2002); and (4) comprehensive models, such as high-resolution "coupled" GCMs (Grassl, 2000). (Claussen *et al*. (2002) recognized clusters 1, 3, and 4, but we found enough differentiation among models to add cluster 2.) We also show a fifth cluster in Fig. 2 (represented by dashed lines) to illustrate the position of a full Earth-system model (ESM).

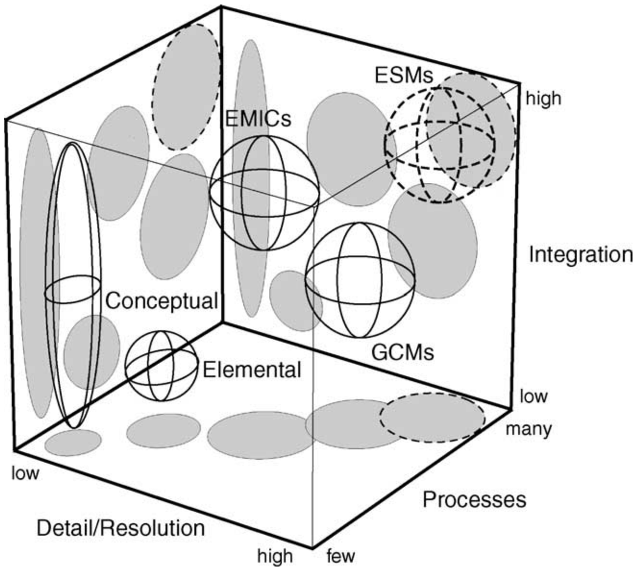

Fig. 2. Classes of climate models plotted in a three-dimensional space that describes model comprehensiveness (after Claussen, 2001; Claussen et al., 2002). The box is defined by the degree of model integration, or the number of interacting components of the climate system that are coupled together in the model, the number of processes explicitly simulated in the model, and the detail of description in time and space, commonly thought of as the resolution of the model. The gray shadows on the wall of the box represent the projections of each cluster of models. ESMs are shown using dashed lines because they currently do not exist.

In a progression of models across the three-dimensional space that defines comprehensiveness, the complexity of the models is measured to a large extent by their resolution and by the number of individual climate-system components described. This progression, however, is not a measure of the worthiness or value of the models. For example, conceptual models, which could be viewed as simple pencil-and-paper "thought experiments," are actually among the more sophisticated of models in use in Quaternary science, whereas GCMs, which appear to be exotic and computationally demanding, are actually familiar to us as the source of day-to-day weather forecasts.

Conceptual Models

Conceptual models include ideas and facts that we know are true (or that we are pretty sure are true, e.g. that Earth has experienced repeated glacial/interglacial variations during the Quaternary, related in some way to orbital variations), but they also include basic statements about how things work, often phrased in terms of hypotheses. Conceptual models are the oldest and most frequently applied kind of model used for understanding past climatic variations. The models are routinely applied by Quaternary scientists when looking at "raw" paleoclimatic data, no matter what kind (geologic, geomorphic, sedimentologic, paleoecologic, isotopic, etc.). Inasmuch as they often consider the Earth system as a whole, conceptual models cover the entire range of integration in the climate-model comprehensiveness space.

As will be illustrated in the next section, conceptual models can take the straightforward form of an annotated list of potential controls of climatic variations (e.g. Mitchell, 1965), but most consist of a description of processes and interactions usually applied to a common sequence of events (e.g. Ruddiman, 2003). The common medium for reporting these models is a commentary in *Science* or *Nature* (e.g. Clark *et al*., 2002) or the summary chapter of a proceedings volume (e.g. Alley *et al*., 1999; Stocker *et al*., 2001). These latter discussions are most always supported by a number of less conceptual, more explicitly numerical modeling studies. Applications of conceptual models span the full range of temporal and spatial scales in Quaternary paleoclimatology and address issues that range from the question of why there are ice ages at all, to what controls individual wiggles in a single time series.

Some conceptual models are expressed numerically. Examples include the Imbrie & Imbrie (1980) or Paillard (1998) models of glacial/interglacial variations in which global ice volume is related to insolation through simple differential equations, with the specific form of the relation determined by the state of the climate system (as represented by ice volume) in a geologically reasonable fashion.

Elemental (or Low-Dimensional) Models

The second cluster includes models that numerically represent one or more components of the climate system in some kind of elemental or single-component fashion, and have lower spatial resolution, integration, or process dimensionality compared with models that are more comprehensive. This simplification results in lower computational demands (again relative to more comprehensive models). The number of models that potentially can be assigned to this cluster is quite large. The models range from highly spatially aggregated energy-balance models – like those of Budyko & Sellers (Budyko, 1982), which attempt to simulate global-average temperature from first principles and can be implemented with spreadsheet software – to spatially explicit energy-balance models like that of Crowley & North (1991). This cluster also includes simulating the slowly varying components of the climate system that must be viewed over relatively long time spans (Saltzman, 2002).

So-called "box models" (e.g. Toggweiler, 1999) in which a few very large-scale geochemical reservoirs (and the flows among them) are simulated are also included in this cluster, as are models that feature coupling between components of the climate system such as the atmosphere and ocean, but for only part of the globe (e.g. the tropics, as in Clement *et al*., 2001). Elemental or low-dimensional models have also been used extensively to assess potential future climate changes (e.g. Houghton *et al*., 1997), and to estimate of the sensitivity of global climate to carbon dioxide variations (e.g. Berger *et al*., 1998; Harvey & Huang, 2001).

EMICs (Earth-System Models of Intermediate Complexity)

The cluster of models described as EMICs occupies an important position in the continuum of climate-model comprehensiveness because it offers a bridge between simple, low-resolution models and more comprehensive spatially explicit models (Claussen *et al*., 2002). In some ways, EMICs are very low-resolution AOVGCMs; in other ways, they are simple, low-dimensional models (like EBMs) to which some kind of simplified depiction of atmospheric circulation dynamics has been added. Fundamentally, EMICs simulate the interactions among more components of interest than can be done with the current generation of AGCMs or AOGCMs. The low spatial resolution of the EMICs, and the "parameterization" of many processes explicitly represented by GCMs, permits very long simulations of the temporal evolution of climate – an advantage over "snap-shot" simulations. Similarly, when used in "sensitivity-test" mode, EMICs allow a large number of combinations of inputs or parameters to be explored.

Comprehensive Models – GCMs

The fourth cluster of climate models includes those that attempt to simulate the three-dimensional structure of the climate system and its variation over time. This cluster is exemplified by general circulation models (Randall, 2000), which in the current generation, include coupling among one or more climate-system components (although not as in as many combinations as the EMICs). In the most common form of application to paleoclimate, GCM experiments are designed by providing a set of boundary conditions of interest (such as insolation, atmospheric composition or the distribution of ice sheets), and the resulting simulations are analyzed as a sequence of gridded observations of a set of climate variables.

In practice, GCMs are less integrated than the EMICs, owing to the smaller number of climate-system components that are directly coupled. They do, however, define the cluster of models that currently have the highest resolution and greatest number of explicitly represented physical processes among the several that we have described. GCMs play a major role in the assessment of potential future climate changes because they are able to provide spatially explicit simulations of climate under different scenarios of atmospheric trace gas and aerosol composition.

GCMs have been applied in sequences of "time-slice" or snapshot simulations (i.e. Charbit *et al*., 2002; COHMAP Members, 1988; Valdes, 2000), with the goal of revealing the mechanisms responsible for the regional patterns of climate change. Suites of models have been run under the same set of boundary conditions (i.e. Joussaume *et al*., 1999) to understand the role (if any) that the structures of individual models play in adequately simulating past climates. Both kinds of studies have featured comparisons with synthesis of paleoclimatic data (Kohlfeld & Harrison, 2000). Such comparisons have implicated the absence of feedbacks among components of the climate system in the mismatches between simulations and observations (Harrison *et al*., 2002).

Regional climate models (RCMs) can be viewed as a subset of the GCMs, and have a relationship to regional or "fine-mesh" weather forecasting models that parallels that of GCMs to global forecasting models. Regional models require "lateral boundary conditions" – a temporal sequence of three-dimensional fields of variables describing the atmosphere and surface (i.e. SSTs) that are usually provided by a GCM simulation. Regional models can be considered to be "nested" within the lower-resolution global model in that the driving GCM fields are ingested by the RCM along the model's boundary. Compared with GCMs, RCMs allow more spatially explicit simulation of the sensitivity of regional climate and subsystems to large-scale atmospheric controls (Hostetler & Bartlein, 1999). GCMs further allow evaluation of surface-atmosphere feedbacks, such as those associated with large lakes (Hostetler *et al*., 2000), that are not resolved in coarser-resolution GCMs.

Comprehensive Models – ESMs

GCMs are evolving toward greater comprehensiveness through the development of coupled models that include, for example, explicit representation circulation of the ocean (i.e. AOGCMs), and the terrestrial biosphere (AVGCMs). Coupled models will eventually fill in the region in model continuum now occupied mainly by the EMICs, and will extend into a presently unoccupied region of highly integrated models that incorporate many processes on a high-resolution grid. However, because of computational limits on comprehensive-model simulations, models that feature coupling between a small number of climate-system components will be the rule for the near term. Ultimately, however, "super-GCMs" (Saltzman, 2002), coupled with models of slowly varying components of the climate system, will form a true climate-system model (CSM), or Earth-system model (ESM).

VII INQUA Congress (1965)

The seventh congress of the International Association for Quaternary Research marked a stage in understanding of climate variations in general, and paleoclimate modeling in particular. The congress took place at an interesting time, because both plate-tectonic theory and the astronomical (Milankovitch) theory of climate change emerged in their present forms and evolved over the following decade, as did the fuller depiction of the climate system and its variations and controls that by 1974 resulted in the National Research Council report *Understanding Climatic Change*, which is essentially modern in its scope and outlook.

The principal materials related to climate modeling from the seventh congress include reviews by Broecker (1965) and Mitchell (1965) in the Wright & Frey (1965) "INQUA volume," and a 1968 volume in the *Meteorological Monographs* series (Causes of Climatic Change; Vol. 8, Number 3), which was edited by Mitchell. Several other proceedings volumes were also published, but the majority of papers or chapters with climate modeling content are found in the volumes edited by Wright, Frey, and Mitchell.

The Wright & Frey (1965) volume, *The Quaternary of the United States*, focused on the paleoclimate of the United States, and as a consequence it does not offer a comprehensive review of the fields of paleoclimatology or climate modeling of the time. It can be supplemented, however, by nearly contemporaneous books by Lamb (1966) and Budyko (1982, a summarization of his earlier work). With the organization of the Intergovernmental Panel on Climate Change in 1990, the publication of proceedings from NATO Advanced Study Institutes (e.g. Berger, 1980), and joint U.S./USSR syntheses (e.g. Porter, 1983; Velichko *et al*., 1984; Wright, 1983) and reports (MacCracken *et al*., 1990), the study of global climate change was shown to be truly global in perspective and participation.

Climate Modeling in the VII INQUA Congress Materials

With the exception of EMICs, it is possible to see the same classes of models we described above both in the INQUA publications, and in journal articles not part of the formal proceedings but related to the scientific threads of the meeting.

Conceptual Models

Mitchell's review of the causes of climate change in the chapter "Theoretical Paleoclimatology" in the Wright & Frey (1965) volume represents a comprehensive listing of the conceptual models of Quaternary climate variations that were current at the time (see Mitchell's Tables 1 and 2). The particular "causative factors" and the mechanisms through which they control climate reviewed include:

(1) Autovariation, or internal variations of the climate system stemming from its highly nonlinear nature.
(2) Air-sea interaction, including the role of the thermohaline circulation in transporting heat throughout the climate system.
(3) Continental drift, which Mitchell viewed as an indirect cause of Quaternary glaciation.
(4) Orogeny and continental uplift, and their potential effects on large-scale atmospheric circulation patterns.
(5) Carbon-cycle variations, in which the potential for human action to have a significant impact on climate was discussed.

(6) Volcanism, and the effect of dust and aerosols on incoming solar radiation.
(7) Solar variability, including long-term and periodic variations of the solar constant.
(8) Orbital variations, including the potential role of land-surface feedback in amplifying insolation changes.
(9) Feedbacks, in which Mitchell reviewed a number of hypotheses that attempt to explain glacial/interglacial variations from combinations of internal variations and external forcing, including the one advanced by Chamberlin in 1899.

Chamberlin's hypothesis, which we would regard today as one expressed in terms of biogeochemical cycles, is particularly interesting in its consideration of the above controls (although not necessarily in modern terms), as well as the interactions among them. Interactions were referred to by Chamberlin as "intercurrent agencies," an idea now usually described as "coupling" among systems.

The only large gap in Mitchell's list, though filled implicitly, is the potential role of land cover in controlling climate. Changes in land cover, on both the Quaternary and historical time scales, have the potential to influence significantly the emission of dust and mineral aerosols to the atmosphere (Harrison *et al*., 2001; Mahowald *et al*., 1999) and to change surface energy balances (DeFries *et al*., 2002) and consequently other components of the climate system (Chase *et al*., 2001).

Elemental Models

Several elemental or low-resolution models were discussed in the INQUA proceedings. In the Wright & Frey (1965) volume, Broecker (1965) used a number of elemental models while reviewing the isotopic record of paleoclimatic variations. The chapter by Schumm (1965) included discussion of several elemental geomorphic and hydrologic models to examine the impact of climate changes while Meier (1965) presented an analysis of the response of glacier mass-balance and flow to variations in climatic controls.

In the *Meteorological Monographs* volume, elemental models were used in the discussion of the thermohaline circulation (Weyl, 1968), and the surface energy balance (Ericksson, 1968). Saltzman (1968) considered the surface forcing of atmospheric circulation, and Kutzbach *et al*. (1968) examined the effects of changes in the latitudinal temperature gradient on atmospheric circulation. Both these latter studies examined with simple models the sensitivity of one component of global climate (atmospheric circulation) to changes in forcing in a manner that anticipates those authors' later work.

Comprehensive Models

GCMs appeared in a chapter in the *Meteorological Monographs* volume by Mintz (1968), which suggested how AGCMs might be used to investigate paleoclimatic questions. Although not explicitly part of the INQUA materials, the importance of contemporaneous work by Smagorinsky (1963), and Smagorinsky *et al*. (1965) to later work with GCMs is evident in subsequent publications. In the decade following the VII INQUA Congress, routine application of GCMs in paleoclimatic studies emerged (e.g. Gates, 1976; Williams *et al*., 1974).

Subsequent Developments

It is apparent that many of the questions and issues that were raised in 1965 the INQUA Congress are still relevant today. Moreover, the specific contributions of the congress and its proceedings contributed to the foundation of the U.S. National Research Council (1974) report *Understanding Climatic Change* and its successors. These reports initiated research agendas for the study of global change (e.g. Malone *et al*., 1985) that remain relevant today (National Research Council, 1999).

Synopsis of Results from Modeling Quaternary Paleoclimates of North America

Climate models have been applied to advance understanding of many of the aspects of Quaternary climate changes in North America. The presence of the Laurentide Ice Sheet (LIS) makes climatic variations over North America a key component of the general description of long-term climatic variations. As a spatially heterogeneous region subject to the influence of the major northern hemisphere atmospheric circulation mechanisms, the patterns of regional climate changes across the continent have also been of interest. Paleoclimate modeling studies that have focused on North America fall into two general groups: those that focus on the slow-response components of the climate system like the LIS, and those that focus on the spatial patterns of the fast-response components at key times.

Temporal Variations of Climate

Studies of the temporal variations of the climate system have addressed the onset of glaciation over the Cenozoic, as well as the nature of individual glacial cycles, and have also been used to examine the potential controls of glacial/interglacial variations and the genesis of millennial-scale variability. The long-term cooling during the Cenozoic, which ultimately led to Quaternary glacial/interglacial variations, and the higher-frequency variations superimposed on them, present several features or "targets" for which explanations have been attempted using various classes of models. These targets include:

(1) the cooling itself, and the reorganization of the ocean, atmosphere, and cryosphere that is implied.

(2) the non-reversing steps toward more extensive glaciation, such as those around 35 myr B.P., 12 myr B.P.; and within the past 5 myr.
(3) the onset of extensive northern hemisphere glaciation around 2.8 myr B.P.
(4) the changes in periodicity and amplitude of global ice volume variations during the last 3 myr.
(5) the sequence of global climate changes during a single glacial cycle.
(6) "sub-millennial"-scale variations in climate.

Cenozoic Cooling and the Quaternary Ice Age

The long-term cooling of the Cenozoic, leading ultimately to the onset of extensive glaciation in the northern hemisphere around 2.8 myr ago, has been examined using a variety of approaches, which have generally featured conceptual models supported by syntheses of data, elemental models of particular components of the climate system, or more comprehensive models used to simulate key times or to explore particular combinations of controls (using "snap-shot" simulations). Examples of the first application include the examinations of isotopic records by Miller *et al.* (1987) and Zachos *et al.* (2001) for the entire Cenozoic, or by Driscoll & Haug (1998) and Haug & Tiedemann (1998) for the past 5 myr. The transition to a more glacial state described by the latter two studies was also examined in simulations with Saltzman's model of paleoclimatic dynamics (Saltzman, 2002; Saltzman & Verbitsky, 1993) and with the LLN 2-D model (Li *et al.*, 1998), both of which are sophisticated elemental models. In another example of a general conceptual model supported by simulations with a more comprehensive model, sensitivity tests by Kutzbach *et al.* (1997) contributed to the evaluation of the tectonic hypotheses of Cenozoic climate change (Ruddiman, 1997). In a similar fashion, the role of the changes in paleogeography from Cretaceous times to present have been explored with coupled AOGCMs (Huber & Sloan, 2001; Otto-Bliesner *et al.*, 2002), which account for the effects of changes in ocean basins and gateways on global climates. Further applications of GCMs and related models to pre-Quaternary climates are described by Parrish (1998).

A number of studies have focused on the onset and maintenance of glacial/interglacial variations, again using a combination of modeling approaches. These include the conceptual (but mechanistic in character) model of Imbrie *et al.* (1992, 1993), and the aforementioned models of Imbrie & Imbrie (1980) and Paillard (1998). In these latter two applications, data analyses or relatively simple numerical models are used to illustrate the features of "thought experiments" that attempt to explain, for example, the features of the oxygen isotopic record.

The inception of a single glaciation, as occurred around 115,000 yr ago, has been examined in several GCM-focused studies. Rind *et al.* (1989) found that the insolation changes between the time of the northern hemisphere summer maximum around 126,000 yr ago, and the relative minimum around 115,000 yr ago were insufficient to initiate permanent snow cover in northeastern North America in their model. In contrast, subsequent simulations by Dong & Valdes (1995), Gallimore & Kutzbach (1996), and deNoblet *et al.* (1996) were able to simulate the accumulation of permanent snowfields, particularly if the models included feedback from climate-induced changes in land cover.

Millennial-Scale Variations

Millennial-scale climate variations have also been examined with combinations of conceptual models, data analyses, and comprehensive models, in particular time-evolving elementary models and EMICs. The conceptual models, which include those described by Alley *et al.* (1999), Stocker *et al.* (2001) and Clark *et al.* (2002), have developed or attempted to test hypotheses for millennial-scale variations that generally involve reorganization of the circulation of the atmosphere and ocean, including the thermohaline circulation, and the global transmission or propagation of climate variations in the North Atlantic.

The kinds of modeling studies used in the development and testing of those hypotheses span the entire continuum of model comprehensiveness. Saltzman (2002) (see also Saltzman & Verbitsky, 1995) showed how millennial-scale variability, like that associated with the Heinrich events, emerged from a dynamical model of the slowly varying components of the climate system. Similar variability emerges in simulations using EMICs (e.g. Crucifix *et al.*, 2002; Ganopolski & Rahmstorf, 2001), which add some spatial specificity to the simulated climate variations. Simulations with GCMs and RCMs that examine the sensitivity of the climate and subsystems at the LGM to imposed changes in North Atlantic sea-surface temperatures reveal further details of the spatial patterns of millennial-scale variations (Hostetler & Bartlein, 1999; Hostetler *et al.*, 1999).

The integrated modeling studies and data analyses of the temporal variations of climate across the different timescales described above support make several generalizations about the temporal variations of the climate of North America leading up to and during the Quaternary:

(1) changes in paleogeography, including changes in mountain belts and oceanic gateways, explain much of the pattern of climate change over the Cenozoic, if the synergistic effects of changes in atmospheric composition and ocean heat transport are considered.
(2) the ice sheets are active components of the climate system, and no realistic account of the temporal and spatial patterns of Quaternary climate change can be made without considering them.
(3) the thermohaline circulation of the ocean seems involved in climate variations across all time scales.
(4) feedback from changes in the land surface and in ocean circulation appear to be involved in amplifying or attenuating the climatic effects of changing boundary conditions such as insolation and the arrangement of continents.

Spatial Patterns of Fast-Response Variables – LGM to Present

The LGM-to-Present "Natural Experiment"

Various modeling studies have focused on the interval between the LGM (Last Glacial Maximum, 21,000 yr ago) and present. During this interval, nature performed experiments with the climate system (Webb & Kutzbach, 1998), and recorded the results in paleoclimatic data sets like those reviewed in this volume and elsewhere (Kohlfeld & Harrison, 2000). Both the nature of the boundary-condition changes over the interval and our knowledge of them has facilitated numerous application of elemental models, EMICs, and, particularly, GCMs.

Comparing the climates of the LGM and 6000 yr ago with present provides an optimal experimental design in which only a few controls are changed from their present settings. At the LGM, there were extensive continental ice sheets, low concentrations of greenhouse gasses in the atmosphere, high aerosol loadings, relatively cold sea-surface temperatures, and land-cover characteristics that featured reduced areas of forest, but the latitudinal and seasonal distribution of insolation was similar to that at present. After the LGM, the amplitude of the seasonal cycle of insolation increased, reaching a maximum around 11,000 yr ago, so that at 6000 yr ago, insolation during the northern summer was greater than at present, while the remainder of the boundary conditions were close to their present (or pre-industrial) values. Because of the elegance of this natural experiment, many simulations have been done for 21,000 and 6000 yr ago, including those in PMIP (Harrison *et al.*, 2002; Joussaume *et al.*, 1999; Palaeoclimate Modeling Intercomparison Project). These two times have also been the focus for simulations with coupled AOGCMs (Braconnot *et al.*, 2000; Harrison *et al.*, 2002; Hewitt & Mitchell, 1998; Hewitt *et al.*, 2001; Shin *et al.*, 2002). Relatively few sequences of simulations with GCMs over this interval have been able to exploit the full natural experiment. The published sequences of experiments include simulations conducted with an early version of the NCAR CCM (National Center for Atmospheric Research, Community Climate Model) (COHMAP Members, 1988; Wright *et al.*, 1993), a subsequent version of the CCM (CCM 1, Webb & Kutzbach, 1998), and with the UGAMP GCM (U.K. Universities Global Atmospheric Modelling Programme General Circulation Model; Valdes, 2000), and the LMD5.3 model (Laboratoire del Météorologìe Dynamique; Charbit *et al.*, 2002), models similar to CCM 1 in the degree of coupling among systems.

These sequences of simulations, along with the suites of simulations for 6000 and 21,000 yr ago, jointly show that much of the variation in global and regional climate over this interval can broadly be explained by the influence of the ice sheets on atmospheric circulation and the influence of insolation on circulation and surface water- and energy-balances. Comparisons of model simulations with paleodata demonstrate that, as is the practice of the Intergovernmental Panel on Climate Change (Houghton, 2001), it is indeed feasible to simulate climates different from that at present using the kinds of models reviewed here. The detailed data-model comparisons organized by PMIP do show, however, that the present generation of global models may underestimate the magnitude of the responses of the climate system to changes in its controls (Harrison *et al.*, 2002).

LGM-to-Present Simulations for North America

The sequence of simulations conducted with CCM 1 (Fig. 3), although obsolete by today's standards in terms of model resolution and interactivity of the ocean, still provide the only complete sequence of simulations performed using a coherent experimental design that have been extensively analyzed for North America (see Bartlein *et al.*, 1998; Webb *et al.*, 1998). Figure 3 shows the simulated sequence for several variables for January and July, expressed both as the actual values for each time in the sequence and as anomalies, or differences between each "paleo" simulation and the present-day or "control" simulation. Table 1 summarizes some of the main features in Fig. 3 that were discussed by Bartlein *et al.* (1998) and Webb *et al.* (1998).

The variables in Fig. 3 appear roughly in a sequence that represents cause-and-effect. The top row of maps shows insolation (and anomalies) over the sequence of simulations, along with the outlines of the Laurentide ice sheet in the model – the two major controls of the sequence of regional climatic changes. Net radiation and surface air temperature illustrate the direct effects of insolation and ice-sheet size on the surface energy balance and temperature. The latitudinal and continental-marine contrasts in temperature, in concert with the topographic effects of the ice sheet, influence atmospheric circulation as represented by 500 mb horizontal wind speed and vertical velocity, and sea-level pressure. In turn, atmospheric circulation, in particular the large-scale patterns of vertical motions, and moisture availability (determined mainly by temperature) jointly influence the patterns of precipitation and thus precipitation minus evaporation.

The principal features of the simulated climate over North America include:

(1) displacement by the Laurentide Ice Sheet of the band of fast upper-level winds to the south of its present location in both winter and summer during the LGM and afterward.
(2) development of a "glacial anticyclone" over the ice sheet in eastern North America, and consequent generation of large-scale sinking motions in the eastern and southern quadrants of the ice sheet.
(3) existence of generally drier-than-present conditions during glacial times (when it was colder than present), giving way to wetter-than-present conditions as the continent warmed.
(4) changes in the strength of surface atmospheric circulation features that follow the trends in the boundary conditions: weakening of the Aleutian low

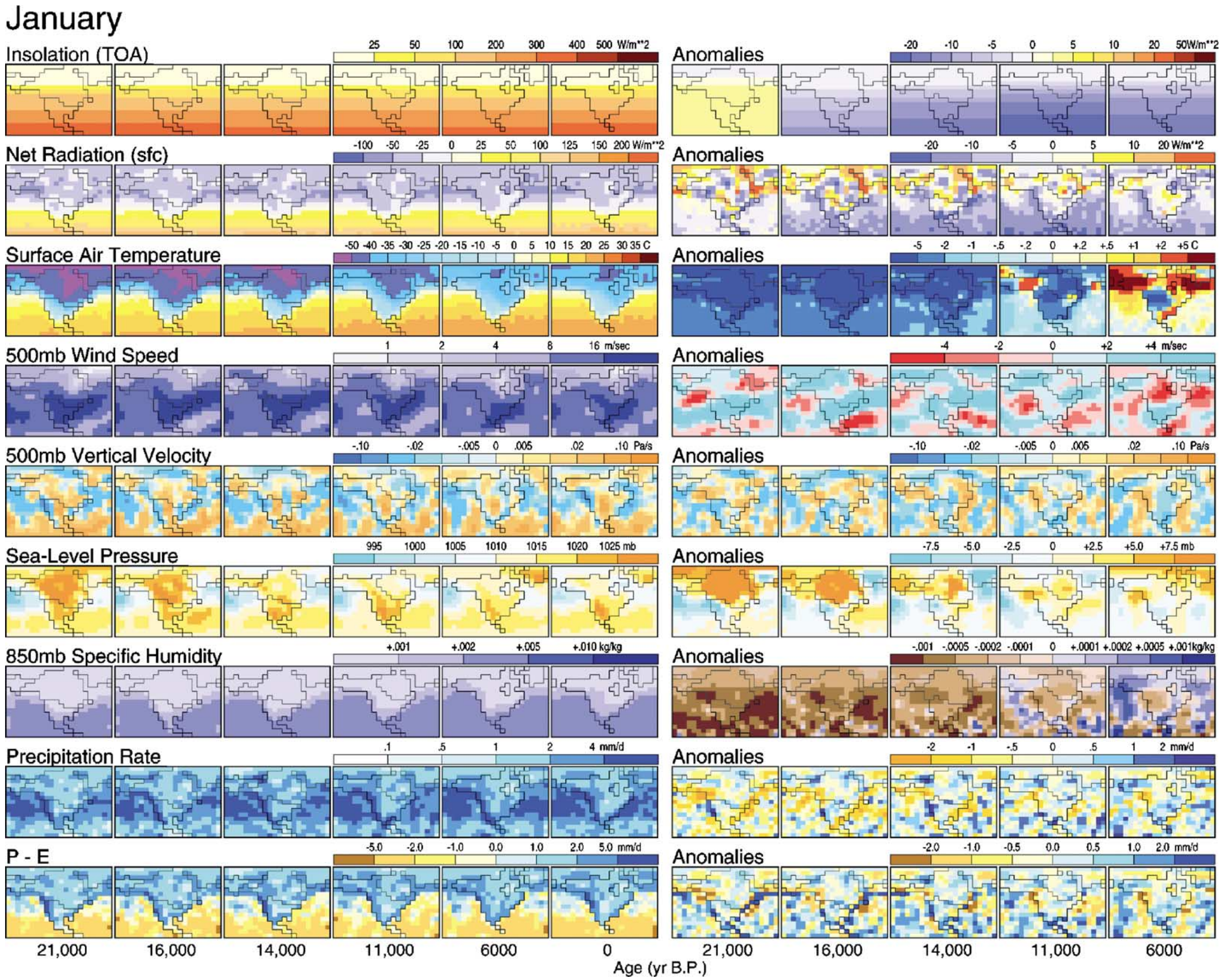

Fig. 3. Sequence of CCM 1 simulations for North America from the LGM to present, for January (top) and July (bottom) (Bartlein et al., 1998; Kutzbach et al., 1998). The simulated values for each experiment are shown on the left-hand side of the figure, while the anomalies ("paleo" experiment minus present "control") are shown on the right. For 500 mb vertical velocity, positive values (orange) on the left-hand panels indicate large-scale sinking motions, while negative values (blue) indicate large-scale rising motions. For 500 mb vertical velocity anomalies, negative values (blue) indicate more rising or less sinking than present, while positive values (orange) indicate more sinking or less rising than present.

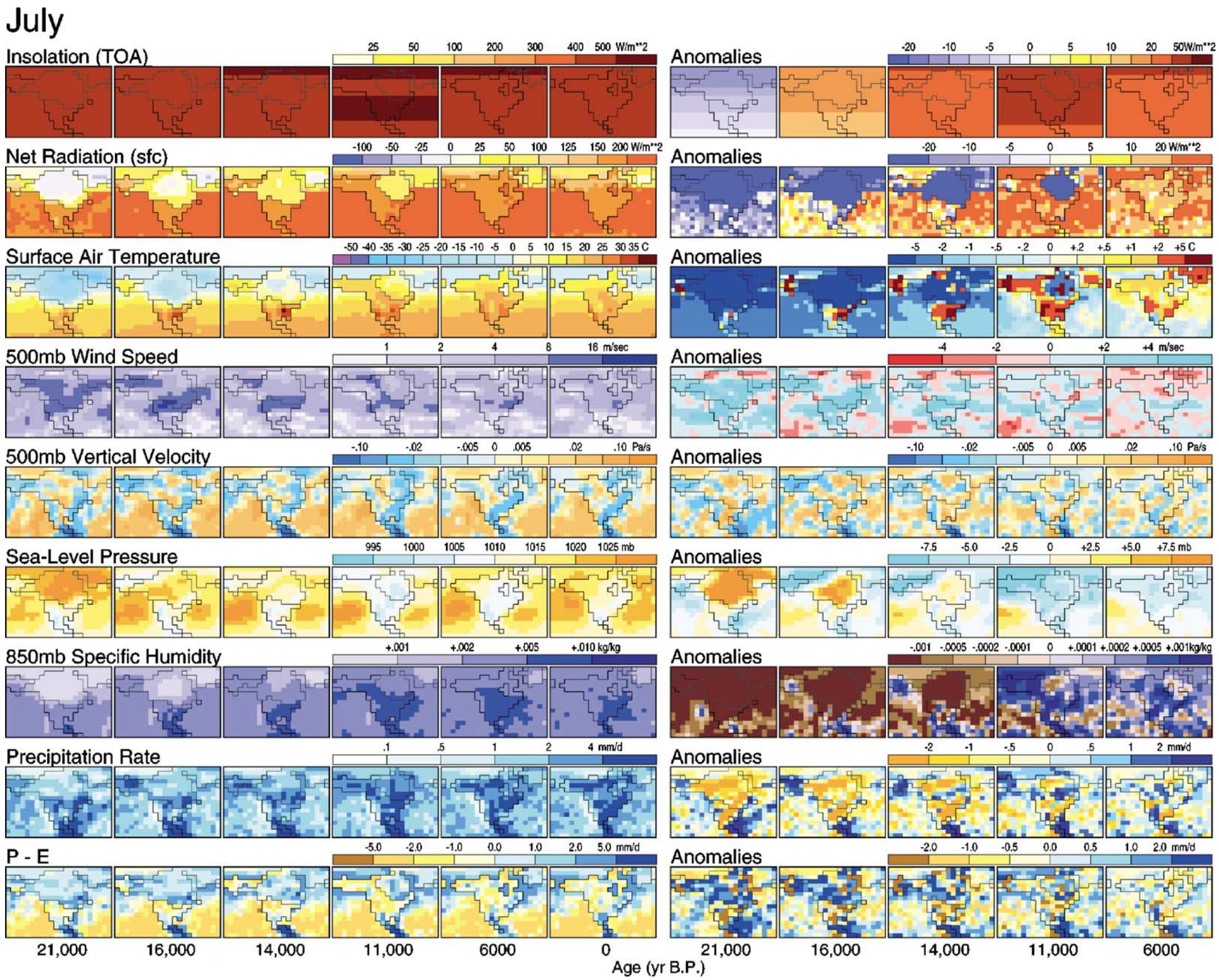

Fig. 3. (Continued)

Table 1. Features of the simulated climate of North America, LGM to present.

Feature	CCM 1 Simulation[a]
Last Glacial Maximum 21,000 cal yr B.P. experiment	
Upper-level winds	Southward displacement and strengthening of the jet stream in both January and July
Sea-level pressure and surface winds	Glacial anticyclone over ice sheet; prevailing easterlies in PNW, strong onshore flow in SW; strong Aleutian low in January, southerly flow into Alaska in January
Large-scale vertical velocity	Strong rising motions in SE in July, and in SW in January
Net radiation	Strong negative anomaly over ice sheet in July
Atmospheric moisture	Much drier than present throughout
Surface climates	Greatest cooling near ice sheet ($\Delta T \sim -10\,^{\circ}$C); less cooling farther away; generally dry to south of ice sheet; wet in SW
Late-Glacial 14,000 cal yr B.P. experiment	
Upper-level winds	Jan. and July jet stream at present latitude, and stronger than present
Sea-level pressure and surface winds	STHs in July as strong or stronger than present
Large-scale vertical velocity	Stronger-than-present rising motions in continental interior in January
Net radiation	Continued strong negative anomaly over ice sheet in July, with positive anomaly along southern edge of continent
Atmospheric moisture	Continued dryness
Surface climates	Continued cold near ice sheet; July temp. near or higher than present in SW U.S., SE U.S., and Alaska; Jan. temp. below or near present throughout
Early Holocene 11,000 cal yr B.P. experiment	
Upper-level winds	Upper-level circulation generally near present configuration; ST ridge over SW U.S. in July
Sea-level pressure and surface winds	Strong STHs in July; strong onshore flow into SW US
Large-scale vertical velocity	Rising motions in the SW and sinking in PNW and eastern North America in July
Net radiation	Continued strong negative anomaly over ice sheet in July, with strong positive anomaly over continental interior in July
Atmospheric moisture	Continued drier than present in Jan; wetter than present over much of continent in July
Surface climates	July temp. higher than present everywhere except along edge of ice sheet; Jan. temp. near present; dry in PNW and Alaska; wet in SW US
Mid-Holocene 6000 cal yr B.P. experiment	
Upper-level winds	Upper-level circulation generally near present configuration; ST ridge over SW U.S. in July
Sea-level pressure and surface winds	Strong STHs in July; strong onshore flow into SW U.S. and S US
Large-scale vertical velocity	Rising motions in continental interior and sinking in PNW in Jan., rising motions in the SW and sinking in PNW and eastern North America in July
Net radiation	Strong positive anomaly at high latitudes and negative in interior in Jan., strong positive anomaly throughout in July
Atmospheric moisture	Generally moister than present
Surface climates	Wetter than present in SW U.S. in July; warmer than present in July throughout

[a] Abbreviations: cal (calendar years before present); PNW (Pacific Northwest); SW (Southwestern U.S.); SE (Southeastern U.S.); STH (subtropical high-pressure system); ST (subtropical).

and the glacial anticyclone as the ice sheet retreated, and strengthening of the East Pacific and Bermuda subtropical high pressure systems in summer as the (positive) insolation anomaly increased, followed by weakening as the insolation anomaly decreased.

(5) increases in summer temperature earlier in the sequence in regions distant from the ice sheet.

(6) development of a thermally induced low surface pressure over the continent in summer when the insolation anomaly was at its maximum, and consequent enhancement of the summer monsoon in the southwestern U.S.

(7) concurrent increases in effective moisture in the southwestern U.S. and decreases in the Pacific Northwest and continental interior when the monsoonal circulation was amplified during the time of summer insolation maximum (Harrison, 2003).

(8) generally lower-than-present winter temperatures over the continent throughout the sequence of simulations.

These responses are quite robust, appearing in most simulations or partial sequences of simulations, and suggest that a substantial part of the regional-scale patterns in paleoclimatic data that have been reviewed in this volume are explainable in terms of the direct and indirect effects of insolation and the direct effect of the ice sheet (see also Bartlein *et al.*, 1998; Thompson *et al.*, 1993; Webb *et al.*, 1993, 1998). More recent simulations and their comparisons with paleoclimatic data have attempted to show how secondary climatic variations across different regions may be mechanistically linked. For example, simulations for 6000 yr ago show a decrease of surface low pressure and an increase in the height upper-level ridge over the western U.S. These changes induce large-scale subsidence (or sinking of air) in the interior of North America (Harrison *et al.*, 2003), thereby linking climate anomalies that are opposite in sign across different regions.

Existing and Emerging Issues in Paleoclimatic Modeling

Comparison of paleoclimatic observations with the conjectures of conceptual models or simulations from numerical models have long been part of the practice of Quaternary science. The rapid development of the different classes of models and syntheses of paleoclimatic data, presented either as maps for key times (e.g. Kohlfeld & Harrison, 2000), or time series at key locations (e.g. Alley & Clark, 1999), ensure that formal comparisons between simulations and observations in data-model comparisons will continue to increase in frequency. There are a number of issues that arise in such comparisons in specific and in paleoclimatic modeling in general that when addressed will enhance the effectiveness of those activities.

Model and Data Resolution

One issue that frequently arises in data-model comparisons is disparity in the spatial and temporal resolutions of paleoclimatic data and model output. Spatial-resolution mismatches are probably most evident in the comparisons of EMIC and GCM output with networks or syntheses of paleoclimatic data. Most present-day GCMs (Fig. 4) have grid-cell resolutions coarser than 2 degrees of latitude or longitude (about 200 km at the equator) while EMICs are still coarser (10 degrees or more). Topography in EMICs and GCMs is highly generalized, and much smoother than the real terrain – topographically complex regions like the Cordillera may be represented as broad featureless domes in a GCM. RCMs mitigate this issue somewhat, and can represent features such as the Sierra Nevada, Cascade Range, or Columbia Basin, but resolutions in RCMs are still fairly coarse (grid cells greater than 25 km on a side).

Paleoclimatic data, in contrast, is often site specific, and a given indicator may represent the environment of a watershed or of a smaller area. Consequently, some kind of “downscaling” of the simulations is necessary, even for RCMs, if the object is the direct comparison of observations and simulations at particular locations. The current approach (Harrison *et al.*, 1998) is to apply the model’s “anomalies”

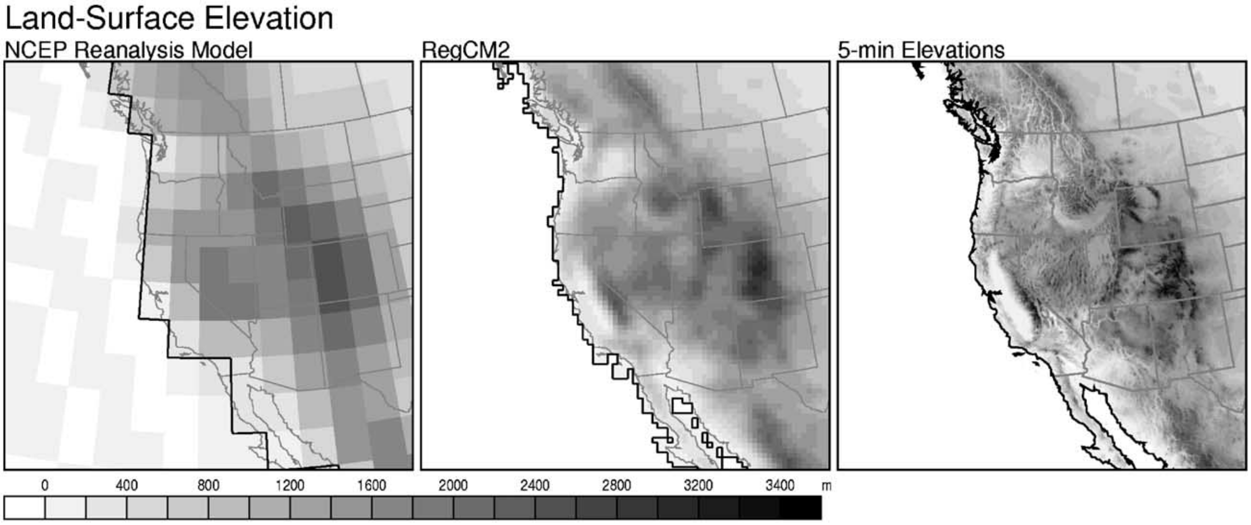

Fig. 4. Land-surface elevations for two climate models and for the western U.S. on a 5-min latitude by longitude grid for comparison. The NCEP Reanalysis Model (Kistler et al., 2001) is a GCM with a rectangular resolution of 2.5 degrees, and represents the topography of the western U.S. as a broad dome centered over western Colorado. Varying elevations over the Pacific Ocean are an artifact of the spectral representation of the atmosphere in the model. RegCM2, a regional climate model (e.g. Hostetler & Bartlein, 1999), as depicted here for the western U.S. has a resolution of 36 km. Viewed at arm’s length, the RegCM grid captures much of the physiographic detail for the region, such as the Sierra Nevada and Cascade Range, and the Snake River Plain and Central Valley, that is evident in the actual 5-min elevations.

(differences between a paleoclimatic and modern "control" simulation) to either a gridded higher-resolution observed data set for the present day, or to data for a specific location, both derived by spatial interpolation within a network of modern climate stations. This approach necessarily assumes that the models have sufficient resolution to describe adequately those anomalies, and that mediation of large-scale anomaly patterns does not change over time. Increases in computational capacity, which in turn will allow finer model resolutions, should ultimately minimize this issue.

Simple spatial averaging of the paleoclimatic data to approximate the resolution of a model does not suffice to reduce the mismatch. A topographically complex region, for example, may vary from place to place in its paleoclimatic response to localized physiographic effects on atmospheric circulation (Whitlock & Bartlein, 1993). Paleoclimatic data may also be quite sparse in some regions, and simple interpolation among sites may not be appropriate (Broccoli & Marciniak, 1996).

Mismatches in resolution also arise between time series of climate simulations and observations. Chronological and sampling issues that limit the "downcore" resolution of paleoclimatic data can make comparisons with model output of annual- (or shorter-) timescale resolution difficult. Conversely, there may be limitations in the temporal resolution of a model simulation related to an inability to specify changes in boundary conditions frequently enough.

In both the spatial or temporal cases, some thought must therefore be given to placing the simulations and observations on a similar framework or timescale by appropriate filtering or aggregation. An example of such an approach involving comparisons among time series of data with differing resolutions is given by Tinner & Lotter (2001).

Variables

Another potential mismatch in comparing simulations and observations arises when considering the variables that can be simulated or reconstructed. Climate models such as EMICs and GCMs can be quite specific in what they simulate, including variables (like atmospheric vertical motions) that cannot be directly observed. In contrast, a specific paleoclimatic record may require some kind of transformation in order to be interpreted in quantitative terms, and by themselves, the interpretations cannot discriminate among multiple controls. For example, the observation of a positive glacier mass balance can signify either increased winter precipitation or decreased summer temperature. This ambiguity can be removed, however, through the application of process models (e.g. Hostetler & Clark, 2000) that explicitly quantify the dependence of mass balance on a number of controls.

Experimental Design

The design of a modeling experiment is an important issue that must be considered in comparing simulations and observations. From the paleoclimatic data perspective, this includes the specific protocols that are used to synthesize data, and the scheme for describing chronological control (Kohlfeld & Harrison, 2000). It should be possible for the reader to trace the development of a particular interpretation or reconstruction (see Farrera *et al*., 1999, for an example; Harrison, 2003).

From the perspective of a model, experimental design is for the most part synonymous with the choice of which boundary conditions are changed and by how much, though it also includes selection of the length of a simulation in the case of spatial-pattern applications of models. Recall that there are two approaches to the design of an experiment – the sensitivity test in which one or more boundary conditions are changed, and the full simulation in which all of the boundary conditions are changed (Peteet, 2001). In the sensitivity-test approach, leaving a boundary condition (say, land-surface cover, or the size and location of ice sheets) unchanged from its present value is the same as assuming that it does not vary over time, or if it does vary, that it does not have any influence on climate. The comparison of a sensitivity-test simulation with observations must therefore consider the extent to which the simulations should be expected to resemble the observations in the first place.

Paleoclimatic Diagnostics

Although it is satisfying when a simulation agrees favorably with some observations, that situation may not be the most informative one – it is the mismatches that indicate something is wrong or needs improvement. There are three sources of apparent mismatches between simulations and observations: inadequacy of the climate model, misinterpretation of the data, and shortcomings in the experimental design, as discussed above. (Note that incorrect "false positive" comparisons could also arise from the same sources.) From a distance, it might be perceived that the goal in data-model comparisons is simply to discriminate among the three sources, but a better way of thinking of the general exercise is as paleoclimatic diagnostics. Analogous to its shorter-timescale cousin climate diagnostics (apart from its longer temporal focus), paleoclimate diagnostics could use almost the same description of its objectives, which are: ". . . to identify the nature and causes of climate variations on time scales ranging from a month to centuries . . . [and] to develop the ability to predict important climate variations on these time scales (NOAA Climate Diagnostics Center Web Page)." If we extend this definition to longer time scales, data syntheses and model simulations can be viewed as complementary tools that can be used to understand past climatic variations.

The motivation for understanding past climatic variations is now stronger than ever, in light of the realization that humans may be producing Quaternary-size changes in climate. The full range of climate models is being used in making projections of future climate, and those models need testing, something that can be done using syntheses of paleoclimatic data and paleoclimatic "natural experiments."

Paleoenvironmental observations also demonstrate that no environmental system is completely insensitive to climatic variations, which raises questions about the magnitude of that sensitivity and how specific systems respond, questions that modeling approaches are well suited to answer. Together, climate models and paleoclimatic data are bringing scientists closer to the goal of understanding climate well enough to predict its future course.

Summary

The synthesis of paleoclimatic data sets and the simulation of past climates using climate models are a complimentary set of activities that lead to better understanding of the climate system. The objective of paleoclimate modeling is to quantify the behavior and variations of the components that describe the climate system. These components include:

(1) boundary conditions or external controls, such as solar irradiance.
(2) slow-response variables that characterize the general state of the climate system, such as continental ice sheets.
(3) fast-response variables that comprise what is ordinarily thought of as weather, such as the configuration of the jet stream and location and strength of surface high- and low-pressure centers.
(4) variables that provide the forcing for the many environmental subsystems that depend on climate, such as lakes.

Climate models can be classified according to the applications to which they are put, which include simulating the temporal evolution and spatial patterns of the climate system, and the attendant responses of environmental subsystems. They may also be classified by their comprehensiveness into several clusters, which include conceptual models, elemental models, Earth-system models of intermediate complexity, comprehensive models represented by coupled general circulation models, and ultimately, full Earth-system models. With one exception, the classes of climate models and the manner in which they are applied were evident in the publications of the INQUA Congress in 1965.

Example simulations of the Quaternary climates of North America illustrate regional patterns of climate. These respond directly to continental ice sheets, and both directly and indirectly to changes in insolation.

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