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A framework for regional modeling of past climates

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Summary

The methods of reconstructing ancient climate information from the rock record are summarized, and the climate forcing factors that have been active at global and regional scales through Earth history are reviewed. In this context, the challenges and approaches to modeling past climates by using a regional climate model are discussed. A significant challenge to such modeling efforts arises if the time period of interest occurred prior to the past ~3–5 million years, at which point land–sea distributions and topography markedly different from present must be specified at the spatial resolution required by regional climate models. Creating these boundary conditions requires a high degree of geologic knowledge, and also depends greatly upon the global climate model driving conditions. Despite this and other challenges, regional climate models represent an important and unique tool for paleoclimate investigations. Application of regional climate models to paleoclimate studies may provide another way to assess the overall performance of regional climate models.

1. Introduction

Geologic records of past climates indicate that climate conditions have varied frequently and widely throughout Earth history; past climate states were, at times, very different from current and recent climates. For example, during some periods in Earth history global climate appears to have been much warmer, such that ice sheets did not exist and global sea level was substantially higher than at present (“greenhouse” climate states). In contrast, there also have been periods during which vast ice sheets covered large areas of the land surface and climate was generally colder than at present (“icehouse” climate states) (on both topics, see summaries in Crowley and North (1991), and Zachos et al., 2001). The records not only indicate dramatic variations in global climate, but also demonstrate large variations in regional climates through time. While such records are incomplete both spatially and temporally, they are pervasive and indicate climate variations of sufficiently large magnitude to present enigmas about how climates have changed through time, why the changes occurred, and what climatic and environmental conditions existed in various regions through time.

Records of past climates, known as proxy climate indicators, take the form of various sedimentary, geochemical, and biologic elements. These indicators can be recovered from rock records in both marine and terrestrial environments. For example, sedimentary records can indicate desert environments, the presence of glaciers, changes in global sea level, or other types of general environmental conditions that can be associated unambiguously with a particular climate state. Geochemical proxy climate indicators are also valuable in reconstructing past climatic conditions. Most importantly, stable isotope ratios, particularly oxygen, but also including carbon, nitrogen, strontium, and other isotopes, can be used to quantitatively estimate past climate conditions. Measurements of stable isotope ratios have been used to interpret past temperature parameters, precipitation, and evaporation, as well as other environmental and climatic characteristics (e.g. Baker et al., 1998; Parrish, 1998; Zachos et al., 2001; Fricke, 2003). Finally, biologic proxy climate indicators, in many forms of preserved flora and fauna, can also be used to determine both qualitative and quantitative information about past climates (e.g. Jackson et al., 1997; Markwick, 1998; Thompson and Anderson, 2000). For a more comprehensive summary of various types of paleoclimate proxy indicators, see Bradley (1999) and Parrish (1998).

It is important to note that records of past climates derived from geologic evidence contain information about the influence of both global climate forcing and regional climate forcing factors upon climate in the area of the proxy data. Unlike present day observational data, where a large network of spatially distributed data can be processed and analyzed to produce a coherent and large scale representation of climate, paleoclimate proxy data are less numerous for any given period of time and often, as a result, the past climate state can only be interpreted for a region. The main reason for the regional nature of paleoclimate records is that rock outcrops that potentially contain proxy climate information do not occur uniformly, and researchers who recover and study such records tend to focus their studies in particular areas with the proper geologic attributes. This leads to areas with a relatively high density of geologic information for a given period of time, and other areas where no information has been recovered. This may result in an interpreted climate record that is representative only for a region, and therefore most strongly influenced by regional climate forcing, relative to global climate forcing.

Examples of significant regional climate change through Earth history are numerous and include: the widespread existence of large pluvial lakes in western North America during the Last Glacial Maximum (LGM; approximately 18,000–20,000 years ago) (e.g. Street-Perrott and Harrison, 1985; COHMAP, 1988); the decreased aridity and northward expansion of semiarid savanna vegetation, as well as the expansion of lakes, in sub-Saharan Africa, during the period of ∼10,000–4,000 years ago (Street-Perrott and Harrison, 1985); the intensification of the south Asian monsoon during the last 10,000–6,000 years (e.g. Ruddiman, 1997); the repeated desiccation of the Mediterranean Sea between 5.9 and 5.3 million years ago (Duggen et al., 2003); and the large-scale cooling and drying of the western interior of North America over the past 20 million years (Ruddiman et al., 1989; Ruddiman and Kutzbach, 1989). All of these regional climate changes were the product of both global and regional climate forcing, due to combinations of factors discussed below.

2. Climate forcing mechanisms and timescales

There is a range of climate forcing factors acting on the planet at all times. These forcing factors act across a spectrum of temporal (and spatial) scales, from hundreds of millions of years to less than decades (Table 1). Most of these forcing factors can generate large, and often unique, regional climate changes, as indicated by the examples provided above.

The luminosity of the sun has varied throughout its lifetime, due to natural processes of stellar evolution. Some of this variation has had a long-term secular trend; over the past 500 million years, solar output has increased approximately 5%, and over the past 4.5 billion years it has increased approximately 25–30% (Newman and Rood, 1977). On shorter timescales (decades to centuries), solar luminosity has varied as a func-

Table 1. Climate forcing factors and timescales of operation to consider in investigations of pre-historical climates

Factor	Characteristic timescale
Solar luminosity	10^9–10^0 yrs
Distribution of solar insolation (Milankovitch effects)	10^4–10^6 yrs
Tectonic processes	
Changes in land/sea distribution	$>10^6$ yrs
Topography	10^5–10^6 yrs
Volcanism	10^0–10^2 yrs
Atmospheric composition (greenhouse gases)	10^0–10^2 yrs
Land cover/vegetation characteristics	10^1–10^4 yrs
Glaciers and ice sheets	10^4–10^5 yrs

tion of solar flare activity (sunspots). These result in minor (<1%) fluctuation in short term solar output (Lean et al., 1995). Variation of solar output directly affects climate by influencing the amount of solar radiation that reaches the top of earth's atmosphere.

Due to gravitational interactions between celestial bodies, Earth's position and orientation relative to the sun has varied through time. These changing orbital characteristics lead to continuos variation in the amount of solar radiation that reaches the top of Earth's atmosphere at any given latitude and time of year; thus there can be very strong regional climate responses to these factors. There are three primary aspects of Earth's orbital motion that have changed more or less rhythmically through time. The first is eccentricity, which is a measure of the elliptical degree of the orbit of the Earth around the sun, which influences the distance between the Earth and the sun at different points throughout the year and thus, to a minor degree, can influence the total amount of insolation received through the course of a year. Eccentricity varies on timescales of 100,000 and 400,000 years. The second aspect is obliquity; this is the degree of tilt of Earth's rotational axis with respect to the plane of the ecliptic. The degree of tilt affects the seasonal contrast of insolation, especially at high latitudes. Obliquity varies on a timescale of approximately 41,000 years. The third aspect of Earth's orbital motion is referred to as precession of the equinoxes, which is most simply described as the motion or "wobble" of Earth's rotational axis that describes a circle in space; precession has a period of 26,000 years. As a result of these individual and combined motions, the distribution of solar radiation across space and time has varied through geologic time. Changes in incoming solar radiation drive many different climate responses at regional levels, including seasonality characteristics, and ice sheet dynamics. For more information on Earth's orbital parameters see Berger (1976, 1978), Crowley and North (1991), and Berger and Loutre (1991).

Tectonic processes occur on and within the Earth as a result of the compositional and rheological properties of the planet. The surface layer is constantly in motion, with crust being created and destroyed, uplifted and eroded. This means that the land–sea distribution and topography are constantly changing, although at relatively slow geologic rates (Table 1). On very short timescales of years to decades, volcanic eruptions, which are a manifestation of tectonic processes, also can occur with varying levels of severity.

All of theses tectonic forcing factors can lead to significant regional climate changes, as well as global climate changes. Changes in land–sea distributions can influence climate via variations in surface albedo (total and areal distribution), atmospheric and oceanic heat transport, meridional heat transport (via changes in oceanic gateways and circulation systems), possible formation of ice sheets (themselves a major climate forcing factor), and other factors. For a comprehensive assessment of these topics, see discussions in Ruddiman (1997). Changes in topography, which includes mountain building, have the potential to influence climate via the influence upon atmospheric circulation (including planetary wave patterns) with associated cloud formation and precipitation processes, the impact of lapse rate upon regional temperatures, the potential formation of mountain glaciers, and the geochemical effects of the weathering of newly uplifted and exposed silicate rock upon atmospheric pCO_2 levels (Raymo et al., 1988; Raymo and Ruddiman, 1992). The effect of volcanic eruptions upon climate may include a reduction in solar radiation absorbed at the surface, via atmospheric aerosol injection, and changes in atmospheric composition (e.g. Briffa et al., 1998).

The other two factors listed in Table 1, atmospheric composition and land cover characteristics, can influence climate, and are themselves influenced by climate, via feedback processes. The amount of greenhouse gases in the atmosphere has changed due to tectonic, geochemical, and biological factors. Evidence of atmospheric CO_2 and CH_4 through geologic time suggest that concentrations of these trace gases has varied more than 10-fold at various times throughout Earth history (Pearson and Palmer, 2000). For example, approximately 56 million years ago, pCO_2 may have been on the order of 2000–3000 parts per million (ppm) (Shellito et al., 2003), and atmospheric CH_4 concentrations could have been 10 times higher than current levels (Sloan et al., 1999). In contrast, during the LGM, pCO_2 was approximately 180 ppm (Jouzel et al., 1993). The rate of change of greenhouse gas concentrations has been as rapid as on the order of thousands to tens of thousands of years, and as slow as millions of years. The effect of this forcing is to cause cooling or warming of the atmosphere as well as associated feedback effects.

Changes in the character of land cover occur largely in response to climate changes and, more recently, as a result of human activities. The changes are most typically the replacement of vegetated terrain with other types of vegetation, or with desert, water, or glacial ice. These changes occur at a relatively rapid scale (100s–10,000s of years). Land cover characteristics can influence regional climate via albedo, evapotranspiration, surface roughness, and soil moisture, among other feedbacks (Bonan, 2002; Snyder et al., 2004). One special type of land cover is glaciers; these can influence climate via albedo, temperature, atmospheric circulation perturbation, and other processes.

3. Why investigate pre-historical past climates at a regional scale?

There are three main motivations for applying climate models to paleoclimate investigations. The first is to understand how past climate states came to exist. In these efforts, scientists investigate what possible combination(s) of forcing factors was (were) the most likely cause of a climate state that is indicated by proxy climate data for a particular time interval. The second motivation is that the use of climate models to investigate past climates helps to fill the spatial gaps in paleoclimate information reconstructed from the proxy record; while the proxy data are spatially incomplete, a climate model will produce results everywhere. This may be particularly important at the regional scale, since proxy climate records indicate, to a large degree, the effects of regional forcing factors upon climate. Third, in the case of global climate models (GCMs), paleoclimate modeling has been viewed as one way to evaluate model performance; the same models that are used to investigate possible future climate changes and associated impacts are used to model past climates. In this manner, the model performance under different forcing conditions can be assessed (Kutzbach, 1992). The same may be true for regional climate models (RCMs).

Up until the past several years, only GCMs were used to investigate past climates (e.g. Barron and Washington, 1984; Crowley et al., 1986; Kutzbach et al., 1990; Sloan and Pollard, 1998). As RCMs have become more widely used, a limited number of regional paleoclimate modeling studies have been carried out. As noted by Giorgi (1995), RCMs describe and investigate climate at scales more consistent with regional processes. In addition, RCMs permit the explicit description of high-resolution processes that link the various component of the Earth system, and they capture mesoscale processes that are not explicitly included in GCMs. A final advantage of using a RCM to investigate past climates is that the finer spatial resolution of climate dynamics described in the model and of the RCM results is more compatible with the distribution and nature of the geologic record of paleoclimates, as discussed in the Introduction. As a last consideration related to this idea, RCM results can potentially be used to drive coupled ''proxy models'' such as vegetation or hydrology models at regional resolution, and these results can be directly compared to geologic data (e.g. Alfano et al., 2003; Huntley et al., 2003).

4. Paleoclimate studies using RCMs: A summary

All of the paleoclimate RCM investigations that have been published to date have focused upon climates of the past 100,000 years. One advantage of addressing climate questions within this time range is that the land–sea distribution does not have to be changed substantially in the RCM from that of the present day. Specifying boundary conditions of land–sea distribution and topography for time periods significantly different from present is the largest challenge facing paleoclimate modelers, especially those using RCMs. This is discussed in more detail in the following section.

The majority of paleoclimate RCM studies that have been carried out to date have focused upon climate of the most recent 20,000 years, and most of those studies have examined the region of North America. Over this time period, geologic records indicate that the LGM had reached its end, and climate evolved into the most recent interglacial phase. A major forcing factor during this time was the change in solar insolation distribution due to changes in earth's orbital motion (Table 1). Other trends through this period relevant to model boundary conditions include the increase in global sea level and decrease in continental ice extent and volume, and increasing atmospheric CO_2 and CH_4 concentrations. In RCM studies within this time interval, all of these forcing factors have been considered, typically in combination; several studies have also considered the presence of extensive pluvial lakes in western North America.

For example, Hostetler et al. (1994) investigated the impact on regional climate caused by the presence of ancient pluvial lakes Bonneville and Lahontan in western North America during the LGM. They applied a RCM to the problem because they wanted to distinguish between local climate forcing and feedbacks, and global controls on climate. Hostetler et al. used the RCM RegCM, coupled to an interactive lake submodel. They used the National Center for Atmospheric Research (NCAR) GCM CCM0 to produce the LGM lateral boundary conditions. RCM boundary conditions included reconstructed LGM land cover types, glacial ice extent, and lake extent. They ran two LGM cases with the RCM, one including the lakes and one without the lakes. The results demonstrated that the lakes, primarily via surface-atmosphere moisture feedbacks, exerted a strong regional climate forcing in the region.

Bromwich et al. (2004) used the polar MM5 RCM, driven by an NCAR CCM3 LGM case, to investigate the winter climate of North America that may have existed during the LGM. In this case the investigators specified the entire host of LGM boundary conditions in their RCM case, including LGM ice cover, orbital forcing, atmospheric pCO_2 of 180 ppm, LGM land cover (including lake extents), sea surface temperatures, and continental configurations that reflected a global sea level lowering of 120 m (Bromwich et al., 2004). They found large differences between the results from the polar MM5 model and the GCM, and saw generally better agreement between the proxy data and MM5 results than between the proxy data and the GCM results.

In another study using a RCM coupled to an interactive lake model, Hostetler et al. (2000) investigated the impact of a large lake in central North America upon regional climate at 11,000 years ago. They used RegCM2, driven by a GENESIS GCM case for 11,000 years ago. Both models included orbital parameters for 11,000 years ago and atmospheric pCO_2 concentration of 270 ppm; in addition, sea surface temperatures were calculated with a mixed layer ocean in the GCM. Hostetler et al. (2000) found that lake–atmosphere interactions, primarily in the form of enhanced or reduced precipitation, affected moisture delivery to the adjacent ice sheet, and affected ice sheet mass balance dynamics. Also focusing on the period of approximately 11,000 years ago, Renssen et al. (2001) examined the regional climate of Europe, using the RCM REMO driven by ECHAM4 GCM output. The objective of that study was to evaluate the performance of a RCM relative to that of a GCM, for a past climate state. Their results showed that the higher resolution results of the RCM were better for comparison to proxy climate data.

Two studies have examined the regional climate response to orbital forcing at approximately 6,000 years ago. At this time, orbital forcing resulted in a ~6% increase in summer insolation and a ~6% reduction in winter insolation in the Northern Hemisphere. The basic hypothesis of these investigations was that the orbital forcing could explain much of the paleoclimate data recovered from western North America and the adjacent ocean for this period of time (Diffenbaugh and Sloan, 2004; Diffenbaugh et al., 2003). Both studies used the RCM RegCM2.5, driven by the NCAR GCM CCM3.6. Results from Diffenbaugh and Sloan (2004) showed that orbital forcing at a regional scale can explain much of the proxy climate data which indicated increased summer warming for large regions of western North America at 6,000 years ago; in addition, the results suggested that orbital forcing was not the sole forcing agent affecting the moisture regime of this area, a conclusion not reached by GCM studies. A related study examined the influence of orbital forcing upon wind-driven upwelling along the west coast of North America at 6,000 years ago (Diffenbaugh et al., 2003). This study could only be carried out using an RCM, due to the high spatial resolution needed to adequately represent this coastal region and to capture the processes of interest (coastal upwelling). Results from this work indicated that orbital forcing could explain the geologic records of a change in the intensity and seasonality of coastal wind-driven upwelling at that time, relative to the present (Diffenbaugh et al., 2003).

A study by Barron and Pollard (2002) investigated an older period of climate change, a period known as Oxygen Isotope Stage 3 (approximately 60,000–25,000 years ago). Barron and Pollard used the GENESIS GCM to drive RegCM2, in an effort to reproduce the climate of Europe during this time. In a series of sensitivity studies they examined the roles of orbital forcing, atmospheric CO_2 concentration, the size of the Scandinavian Ice Sheet, and sea surface temperature values upon the climate of Europe at 30,000 and 42,000 years ago. Results from this study suggested that variations in the orbital forcing, atmospheric CO_2 concentration, and ice-sheet size were of little significance in explaining the observed climate variability through this time interval; rather, the results suggested that millennial-scale variations in North Atlantic sea-surface temperatures were a major factor in explaining the climate.

5. Requirements and methods for modeling past climates with a regional climate model

Applying a RCM to paleoclimate issues requires some information that is similar in form to that needed for investigations of future climate, and some information that is unique to paleoclimate studies. There are four main issues that must be addressed in a RCM paleoclimate study. The first issue is the existence and synthesis of sufficient paleoclimate proxy data for the time period and region of interest. Without this geologic and paleoclimatic information, there is little context or motivation for a focused modeling investigation. There must be sufficient geologic information to constrain the GCM boundary conditions, and there must be a relatively greater density of proxy data in the RCM region of interest. The proxy climate data are used for two purposes with the RCM. Proxy climate data (as well as other geologic data) are needed to create boundary conditions and to frame the climate problem or hypothesis. Additional proxy climate data are needed for comparison to the RCM results, to evaluate the model's performance and the climate issue in question. Due to the fact that geologic information is not uniformly available across space and time, and that paleoclimate interpretations of proxy data have not been carried out with equal effort and detail everywhere, some time periods and regions are more readily addressed with RCM modeling efforts than others.

Second, lateral boundary conditions must be generated for the past time period of interest. This means generating or obtaining GCM output that is compatible with the RCM paleoclimate focus. While many GCM studies investigating possible future climate change have been carried out and can potentially be used to provide the lateral boundary conditions for corresponding RCM investigations, there are not as many corresponding GCM paleoclimate studies that are readily applicable to paleoclimate RCM studies. This is mostly due to the fact that paleoGCM studies are very rarely archived at the proper time frequency to be applied to RCMs. Also, given the approximately 4.5 billion year history of Earth, there is a vast amount of geologic time, and a very large number of different climate/earth system scenarios represented during that time, to be investigated. Many time periods have yet to be explored with even a single GCM, for a variety of reasons; see Sewall et al. (2000) for further discussion on this topic.

Third, boundary conditions of land cover types (including glaciers and ice sheets), topography, and land–sea distribution, as well as the initial conditions that are required by the land model of the RCM, must be generated for the RCM domain, at the RCM resolution. Unlike the present day, for which numerous digital elevation databases exist to guide the creation of model topography and land–sea distributions, the geologic past has not been as systematically described in unified databases and at resolutions appropriate for climate modeling. Creation of these boundary conditions typically must be carried out by the individual RCM investigators; this effort requires detailed knowledge of the past geologic and environmental conditions as well as tectonic processes. This task can represent a significant challenge if the time period of interest is in the deeper past (e.g. greater than $\sim$3–5 million years ago). As one looks progressively further back in geologic time, the information that is available to create such boundary conditions becomes increasingly more scarce, making the challenge that much more formidable.

Lastly, the boundary condition of incoming solar radiation at the top of the atmosphere may need to be changed, depending upon (1) the forcing factors of interest in the RCM study (e.g. the solar forcing appropriate for the time interval of interest (e.g. Barron and Pollard (2002); Diffenbaugh and Sloan (2004)), and (2) how far back in time the RCM time period of interest is (i.e. a change in total solar luminosity may be required) (Table 1). To do this, the RCM user may need to adapt the RCM code to include the appropriate solar forcing. Note that it is also important that the driver GCM case also includes the same solar insolation distribution.

6. The future of regional paleoclimate modeling

There are several current and pending future developments in regional climate modeling that may be particularly useful for paleoclimate modeling. These include regional nesting capabilities in RCMs, stretched or zoomed grid capabilities (e.g. Krinner et al., 2004), the incorporation of more fully-coupled lake and ocean model components, dynamic vegetation, and isotope tracers. All of these model developments have the potential to help investigators gain additional insights into past climate dynamics and climate states, by providing improved comparisons between model results and paleoclimate proxy data, and by providing more realistic components of the climate system to RCMs.

As a final consideration, there have been several coordinated regional modeling collaborations and intercomparisons focusing on present and future climate states (e.g. Takle et al., 1999; Christensen et al., 2002; Mearns et al., 2004). As has been done in GCM intercomparisons, the inclusion of paleoclimate modeling to evaluate RCM performance in such future intercomparison projects may prove to be insightful for the RCM community.

7. Summary

Climate forcing though time can generate very large regional responses that may be recorded in geologic records of past climates. Investigation of these regional past climate changes is difficult to address with GCMs, due to their relatively coarse resolution. Thus, the application of RCMs is a welcome new tool for paleoclimate studies. Despite the small number of paleoclimate RCM studies carried out to date, results from those studies have indicated that RCM investigations of past climate can play an important role in understanding the regional versus global climate controls that have influenced past climates. In addition, RCM spatial resolution is better suited to the nature of paleoclimate proxy data, since such information must be extracted from geologic records, which tend to be regionally concentrated.

The primary challenge for RCM modeling of climates prior to ~3–5 million years ago is to create the necessary boundary conditions – most notably the land–sea distribution and topography – for the RCM (and possibly the GCM as well). This challenge is unique to investigations of past climates and requires a level of geologic understanding not necessary for investigations of present and future climates. Despite the high degree of difficulty in setting up RCM investigations for climates older than ~3 million years, the results of such studies will help to reveal new insights into past climates that are not accessible with a GCM approach.

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