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What Do We Know about Potential Modes of Operation of the Quaternary Earth System?

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ABSTRACT

The problem of Earth system stability during the Quaternary, approximately the last two million years, is addressed from a global perspective. Despite efforts over the last 160 years to obtain geological evidence of ice ages, we conclude that the question of which potential modes of operation impacted the Quaternary Earth system is as yet unsolved. However, there are some clues as to which elements should be included in a theory of the Quaternary Earth system. The search for direct paleo-analogues is unlikely to answer the question of potential modes in a physically meaningful manner. Assessment of a number of conceptual models — ranging from models in which forcing is necessary to yield observed climate variability to models of free climate oscillations — does not favor any particular model because of the difficulties of tuning each model to the time series of global ice volume. Hence, geographically explicit fully coupled climate system, or natural Earth system, models are required to analyze the system's response to geographically varying forcing and internal feedbacks. Evidence emerges that much of Quaternary climate variability was due to internal feedbacks involving ice sheets and biogeochemical cycles as critical elements and orbital forcing as the pacemaker.

PALEO-ANALOGUES VERSUS PALEO-SYSTEMS ANALYSIS

In 1795, the Scottish scientist James Hutton published his two-volume "Theory of the Earth," which established him as one of the founders of modern geologic thought. In brief, one could summarize his novel approach with the phrase "the present is the key to the past." Today, it has become popular to reverse this phrase by saying "the past is the key to the future" in order to highlight the value of paleoclimatology and possible paleo-analogues for the discussion of recent, present-day, and possible future climate change.

Numerous papers have put forth the idea of paleo-analogues. For example, Petit-Maire (1990) asked the question of whether the Sahara will become greener in a warmer climate, thereby proposing a paleo-analogue of potential modern climate change to the early and mid-Holocene wet phase in Northern Africa. In their model of the natural Earth system, Claussen et al. (2003) found indeed a possible greening of Northern Africa in a greenhouse gas climate warming scenario. However, they state that the early and mid-Holocene greening of the Sahara is not a proper paleo-analogue as the processes involved appear to have different weight.

The duration of the Holocene has been subject to controversial debate. From statistical interpretation of interglacial–glacial cycles, it has been suggested that the present interglacial is likely to end in only a few hundred years, whereas from the astronomical theory of glacial cycles, a rather long interglacial is expected (Berger and Loutre 1997). According to the astronomical theory, the interglacial associated with the Marine Isotope Stages 11 (MIS11) would be a dynamical paleo-analogue of the Holocene. However, it is unclear whether MIS 11 could serve as analogue of Anthropocene climate dynamics, that is, climate dynamics in the presence of strong perturbation of land cover and atmospheric chemistry.

There is general consensus that the current anthropogenically induced increase of atmospheric greenhouse gas concentrations is unprecedented in terms of the last 420 thousand years (ka), or perhaps even the last 20 million years (Ma) (Prentice et al. 2001). Hence, no direct paleo-analogue exists of present-day climate change when considering similar tectonic forcing, that is, land–sea distribution and natural outgassing of CO_2, water, and other substances from the Earth's interior, and total carbon of the fast pools (atmosphere, ocean, and biosphere). Perhaps we could construct paleo-analogues in a more general sense, that is, paleo-analogues for the identification and testing of functional mechanisms determining the potential modes of operation of the Quaternary Earth system. A recurrent theme directly relevant to concerns about future climate change is whether the Earth system is robust or highly sensitive to small forcings. In this respect, time periods prior to the Quaternary would also appear useful for study. For example, the Late Paleocene Thermal Maximum (LPTM), some 55 Ma ago, could be such a time period. During the LPTM, a dramatic increase in (natural) CO_2 emission occurred and was presumably of comparable magnitude as the anthropogenic greenhouse gas forcing (Schrag and McCarthy 2002; Watson et al., this volume). There is, however, one major caveat: some cases (e.g., the thermohaline ocean circulation discussed by Rahmstorf and Sirocko, this volume) indicate that the stability of the system depends on the state of the system and, hence, on the boundary conditions.

Therefore, we surmise that the search for paleo-analogues is unlikely to answer the question of potential modes of operation of the Quaternary Earth system and suggest that exploration of the phase space, through the implementation of numerical climate system models, would yield an answer. Accordingly, in this chapter, we focus discussion on dynamical models of the natural Earth system, or climate system; we use the terms "natural Earth system" and "climate system" interchangeably. We will summarize existing theories of Quaternary dynamics, from the perspective of conceptual models and comprehensive models, and explore possible conclusions to be drawn from modeling studies.

REVIEW OF THEORIES FOR QUATERNARY EARTH SYSTEM DYNAMICS

A Brief History of the Theories of Ice Ages

In 1842, shortly after L. Agassiz proposed the existence of ice ages on the grounds of geological evidence, J. A. Adhémar suggested the first astronomical theory of climate change based on the known precession of equinoxes. Over the following decades, glacial geology became strongly tied to the astronomical theory that was advanced by J. Croll in the 1860s. Since Croll's theory appeared to be increasingly at variance with emerging geological evidence, his theory was eventually refuted. In 1896, S. Arrhenius concluded that

> It seems that the great advantage which Croll's hypothesis promised to geologists, viz. of giving them a natural chronology, predisposed them in favor of its acceptance. But this circumstance, which at first appeared advantageous, seems with the advance of investigation rather to militate against the theory, because it becomes more and more impossible to reconcile the chronology demanded by Croll's hypothesis with the facts of observation (Arrhenius 1896, p. 274).

Perhaps it would be useful to cite this classic statement more often in the light of present-day orbital tuning of data.

Arrhenius was convinced that changes in atmospheric transparency (due to changes in atmospheric CO_2) would "prove useful in explaining some points in geological climatology which have hitherto proved most difficult to interpret" (Arrhenius 1896, p. 275). The astronomical theory was modified and advanced by R. Spitaler, M. Milankovitch, V. Köppen, and A. Wegner at the beginning of the last century; however, it was disputed again, in 1955, after C. Emiliani detected that there were more glaciations than the "traditional four" (Günz, Mindel, Riss, and Würm glaciations, which were discovered by A. Penck and E. Brückner in 1901–1909). The astronomical theory saw a strong revival after new geological evidence, presented by J. D. Hays, J. Imbrie, and N. J. Shackleton in 1976, appeared to corroborate many of the predictions advanced and refined by A. Berger in the late 1970s.

The theory of ice ages, in which geochemical reactions and CO_2 play a major role, is perhaps as old as astronomical theory. Early work dates back to J. J. Ebelman in the 1840s, J. Tyndall in 1861, and S. Arrhenius in 1896. In addition, there are present-day models (e.g., by G. Shaffer, developed in the 1990s) that could be described as biogeochemical oscillators in which ocean biogeochemistry is the key player.

Overview of Conceptual Models

Climate archives, which reveal climate variability over the last several million years, display four striking features (Figure 7.1):

1. Prior to 3 Ma ago, relatively small climate variations (with a period of approximately 20 ka) are observed.
2. Next, there appears to be a gradual transition to colder conditions until some 2 Ma ago.
3. Thereafter, until some 900 ka ago, that is, the so-called early Pleistocene, climate variations (with respect to temperature and ice volume) are seen with a dominant periodicity of approximately 40 ka.

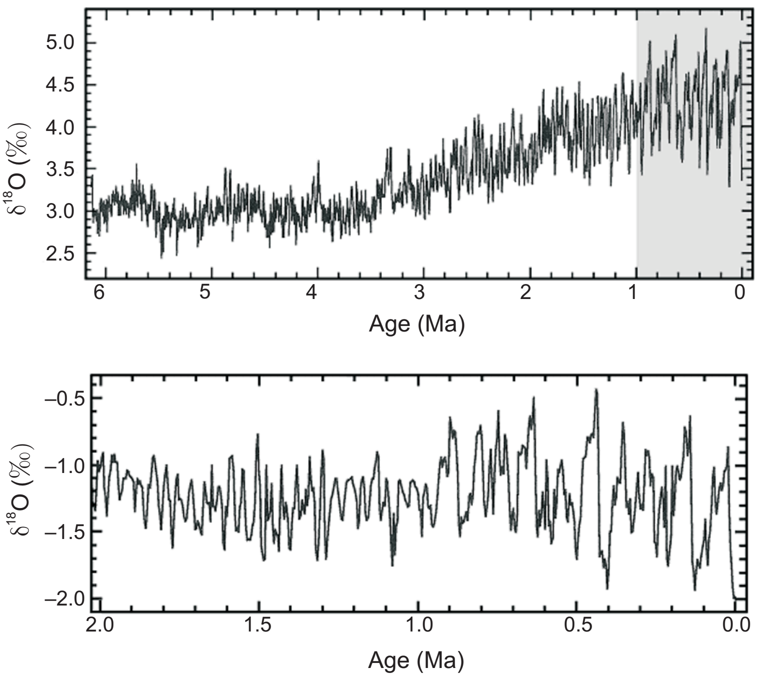

Figure 7.1 Changes in δ^{18}O reconstructed from marine sediment cores for the last 6 Ma and the last 2 Ma, respectively. These changes are interpreted as changes in global ice volume where increasing δ^{18}O values indicate increasing ice volume. The upper curve represents data from the tropical western Pacific sedimentary core ODP 806; the lower curve is from the same core, but using pelagic foraminifera. Figure from Saltzman (2002) and used with permission from Academic Press.

4. The last period, the late Pleistocene, is characterized by a predominant 100-ka periodicity with relatively large amplitude of temperature and ice volume. The time around 900 ka (or in other archives, around 700 ka) is often referred to Mid-Pleistocene Transition (MPT).

To explain these phenomena, a plethora of models has been developed over the past decades. These models can be categorized (see Saltzman 2002) into "forced" versus "free" models, that is, models in which astronomical forcing is necessary versus instability-driven, auto-oscillatory models.

Astronomical, or orbital, forcing consists of meridional and seasonal changes of insolation as a result of changes in the eccentricity of the Earth's orbit with dominant periods of 400 ka, 125 ka, and 95 ka, in the obliquity with a dominant period at 41 ka, and in the precession of equinoxes with a bimodal period at 23 ka and 19 ka. Models employing astronomical forcing need to resolve the "100-ka paradox": whereas the late Pleistocene time series displays a strong frequency component at 1/100 1/ka, astronomical forcing does not. Hence, within the astronomical paradigm, one has to conclude that the climate system responds in a strongly nonlinear way to the forcing. Muller and Macdonald (1997) proposed an alternative by suggesting that near-100-ka period fluctuations in the inclination of the orbital plane, in conjunction with the location of cosmic dust bands, might be able to generate the observed 100-ka oscillations. Again, the radiative forcing implied by this astronomical forcing appears to be rather small, and thus some additional amplifier is required to elevate the 100-ka period above the others.

From the viewpoint of systems theory, the forced models suggest different mechanisms in order to reproduce the observed features:

1. The simplest models are just a linear combination of the three astronomical tones.
2. Then, there are a number of more comprehensive models — energy-balance models, ice-sheet models, and atmospheric energy-balance/statistical dynamical models coupled to ice-sheet models — that are capable of reproducing the approximately 20-ka and 40-ka response to astronomical forcing, but do not show a 100-ka response.
3. A third class of models is based on the assumption that the near 20-ka precessional variations could produce 100-ka relaxation oscillations of ice sheets. Such behavior is well known to engineers and physicists from the paradigmatic van der Pol's oscillator or from aeroelastic fluttering (Guckenheimer and Holmes 1997). Relaxation oscillations are characterized by self-sustained periodic motion, where each period consists of sharp switching between small amplitude (energy gain) and large amplitude (energy loss) episodes.
4. Other forced models allow for internal oscillations, which are entrained by combination tones of precessional forcing (overtones within insolation) or produced by climate system's nonlinearity.

5. A more sophisticated class displays dynamics that result in multiple equilibria. If certain thresholds in forcing are reached, the system would jump from one equilibrium to another.
6. If, in addition, stochasticity is present, the periodic forcing can be less pronounced and yet can induce synchronized jumps as the result of stochastic resonance.

In general, one source of variability would be a random walk process. This idea was originally proposed by Hasselmann (1976), who assumed that the annual cycle of insolation generates variability in the fast climate components, which could be randomly accumulated by the more sluggish climate components. Recently, Wunsch (2003) pursued this idea by demonstrating that most long-term climate archives reveal a red-noise spectrum, that is, a spectrum with an amplitude of variance that decays with larger frequencies. Superimposed on the red spectrum are weak structures, which correspond to the frequency bands of orbital forcing (see Figure 7.2). To explain the dominant 100-ka climate variability, Wunsch suggests a stochastic forcing of a system with a collapse threshold, which yields a transition in the spectral domain from red to white, that is, a flat spectrum with amplitudes independent of frequency. This way, variability on

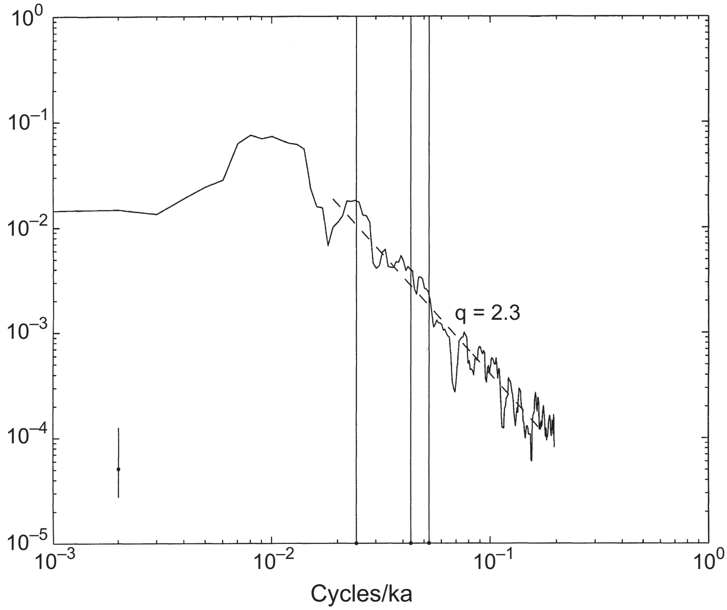

Figure 7. 2 Power spectrum normalized to sum to unity, for the tropical (Panama Basin) core ODP677 (planktonic $\delta^{18}O$ of the last 1 Ma). Also shown are an approximate 95% confidence interval and a least-square fit to the high-frequency range of the power spectrum (dashed line). Vertical lines indicate periods of astronomical forcing, i.e., 41, 23, and 19 ka. This figure is taken with modification from Wunsch (2003) and used with permission by Springer-Verlag.

the 20- to 100-ka timescale, as well as on shorter timescales, can be explained in a combined way (Table 7.1).

If astronomical forcing is removed, forced models would not reproduce the major 100-ka period seen in most paleo-archives of the late Pleistocene. In contrast, free models do not rely on astronomical forcing at all; instead, the 100-ka period appears as an internal (free) oscillation once the system crosses critical boundaries in the parameter space. In other words, the 100-ka oscillation is the consequence of a bifurcation (i.e., a qualitative change of the system's state caused by a change in a control parameter, be it a key, internally generated slow variable or an external forcing) to a self-sustained oscillation (a so-called Hopf bifurcation) that is driven by an instationarity of the Earth system. Such free oscillators can be composed of ice masses interacting with another variable: ice-sheet location, bedrock depression, or thermohaline circulation. The free oscillator is forced by steady long-term variations, for example, by a tectonic forcing associated with a slow variation in CO_2 outgassing. The long-term forcing tunes the oscillator or switches it on or off in a Hopf bifurcation. An essential point is that the free models do not require amplification of small forcing and explain the relatively large climate changes over the Pleistocene as simply the

Table 7.1 Overview of models that try to explain Pleistocene variability, in particular the 20-, 40-, and 100-ka periods. *Any* of them performs well for the 20- or 40-ka frequency component.

1. Forced models: Orbital forcing is necessary
   a. Models with remarkable 100-ka response
      i. Astronomical forcing in conjunction with location of cosmic dust bands (Muller and Macdonald 1997)[1, 2]
      ii. Linear combinations of the three astronomical tones; extreme necessity of 100-ka forcing[1, 2]
      iii. Multiple equilibria; complicated threshold paths (Paillard 1998)[2]
      iv. Internal oscillations, entrained by combination tones of precessional forcing[1, 2]
      v. Ice-sheet inertia[1, 2]
      vi. 20-ka precession-induced relaxation oscillations[1]
      vii. Stochastic resonance and related effects; also produces higher-frequency variability (> 10 ka) in a red spectrum[1] (Wunsch 2003 expanded from Hasselmann 1976)
   b. Models without dominant 100-ka response:
      i. Some energy-balance models
      ii. Ice-sheet models
      iii. Coupled energy-balance/statistical dynamical models[1]
2. Free models: Orbital forcing is not necessary
   a. Free internal oscillation — limit cycle made up from a nonlinear combination of positive feedback loops[1, 2]

[1] Examples for the model class are given in Saltzman (2002)
[2] Indicates a model that is included in the Roe and Allen (1999) intercomparison

response of relatively large internal oscillators that could in some cases even resist additional forcing over a variety of timescales.

Rial and Anaclerio (2000) demonstrated that the interplay of astronomical forcing with the Earth system's nonlinearity is not pure speculation. At a 95% level of statistical significance, by bispectral analysis, they showed that the 29-ka and 69-ka spectral peaks in the Vostok ice core time series are phase-coherent sidebands from the 41-ka obliquity and an overtone of the 413-ka eccentricity. This finding, based purely on time series analysis, without model assumptions, strongly supports nonlinear models.

The existence of switching behavior around 0.9–0.7 Ma B.P. provides further evidence for the system's nonlinearity, as the character of the astronomical forcing remained constant. Saltzman and his coworkers (cited in Saltzman 2002) assume tectonic CO_2 as a slow, steady external driving force, which causes their model to switch to the late Quaternary mode. According to their model, atmospheric CO_2 concentration decreases linearly in time over the last 5 Ma. Unfortunately, this assumption seems to be at variance with recent evidence from carbon isotopes of biomarkers by and from boron isotope reconstructions of seawater pH (see Pagani et al. and Pearson and Palmer, cited and referenced in Prentice et al. 2001). Paillard (1998) circumvents the problem of identifying a particular external forcing, but assumes a long-term linear shift in one of the thresholds defined in his model. An alternative hypothesis explains the mid-Pleistocene transition by the removal of regolith (i.e., more loosely aggregated soil till and sediment material) over several ice age cycles. According to that hypothesis, ice sheets would easily slide on regolith. After removal of soft sediments by early Pleistocene ice ages, ice sheets could eventually grow without the sliding effect of the soft sediment layer in the late Pleistocene. This hypothesis, however, seems to be at variance with Antarctic inland ice dynamics, where sliding can occur without significant disturbance of regolith mass.

Saltzman (2002) also suggests a switching behavior at the onset of the Quaternary ice age some 2.5 Ma ago, which, again, was triggered by steady reduction in tectonic CO_2 forcing according to his model. However, there is no unequivocal evidence for a switch of natural Earth system dynamics. At least some geological evidence (see Figure 7.1) suggests a more gradual transition into the Pleistocene. Although tectonic CO_2 forcing is disputed, the formation of the Isthmus of Panama (Haug and Tiedemann 1998), which lasted from 13 Ma to 1.9 Ma ago and which has led to a major reorganization of Atlantic ocean circulation, has been suggested as a candidate for triggering the onset of the Pleistocene.

The categorization of models of Quaternary climate system dynamics as "forced" and "free" can be complemented by ordering them by means of complexity in terms of physical processes involved. According to Saltzman (2002, p. 276) climate system models aim at "ever more complete representation of the full slow-response climate system"; hence the center manifold. Saltzman (2002,

p. 276) suggests that "ice sheets and their bedrock and basal properties, coupled with forced and free variations of carbon dioxide, operating on an Earth characterized by a high-inertia deep thermohaline ocean that can store carbon and heat ..." encompass the center manifold. (In the "vicinity" of a bifurcation (see above), one can identify slow and fast processes. Then the center manifold characterizes the interplay of the few slowest variables with the collective effect of all the other variables, and therefore allows the study of a complex system's long-time behavior by just a few degrees of freedom; hence by a conceptual model (see Guckenheimer and Holmes 1997). Behind this lurks the idea that few slow climate variables exist, which enslave the fast variables, and that this list of slow variables could be completed.

After several models had been suggested to explain the climatic time series, Roe and Allen (1999) investigated the performance of six representatives of these classes. They tuned each model to the time series (the last 900 ka) of global ice volume and also the time rate of change for the ice volume, while modeling the residuals as first- (and second-) order autoregressive process. They found that within 95% error bars one cannot favor any model over its competitors. This demonstrates that it is necessary to obtain further insight into the physical mechanisms underlying the paleo-time series and then to ask whether a hypothesis at hand would be consistent with the latter.

SOME LESSONS FROM COMPREHENSIVE MODELS OF THE EARTH SYSTEM

What Is the Appropriate Level of Model Complexity?

Thus far we have mainly considered conceptual models that dealt with relatively simple dynamic systems theory, in terms of the degrees of freedom. Saltzman (2002) called these models inductive models, that is, models based on the cross-understanding of the feedbacks that are likely to be involved. From these zero- or one-dimensional models, one gains valuable insight into possible feedback mechanisms. However, the predictive value of conceptual models is limited because of the large, in comparison with the degree of freedom, number of tunable parameters. Moreover, validation of conceptual models is difficult (see above). Some assumptions that form the basis for various conceptual models are oversimplified and, thus, could be misleading. For example, the assumption that orbital forcing is identified with summer insolation at high northern latitudes overemphasizes the ice-albedo feedback at high northern latitudes while neglecting the fact that other components of the climate system can react to varying insolation in a different way than Northern Hemisphere ice sheets do. Therefore, it seems sensible to explore the role of geographically varying forcing and feedback processes in geographically explicit models.

The degree of spatial and temporal resolution necessary for paleoclimate simulations is disputed. Comprehensive, "state-of-the-art" coupled models describing the general circulation of the atmosphere and the ocean (AOGCMs), in some cases including models of biosphere dynamics (referred to as "climate system models" or "Earth system models" — or quasi-deductive models, according to Saltzman) are supposed to be the most realistic laboratory of the natural Earth system. However, their applicability to long-term simulations is limited by high computational costs. Therefore, it has been proposed (Claussen et al. 2002) that Earth system models of intermediate complexity (EMICs) be used which operate at a higher level of spatial and temporal aggregation. In the case of CLIMBER-2 — an EMIC developed at the Potsdam Institute for Climate Impact Research — it was argued that the optimum degree of aggregation would be a spatial resolution finer than hemispheric scale, thereby resolving the distribution of continents and oceans, but larger than the correlation radius of the most energetic synoptic (weather) pattern, which is of the order of several 1000 km (Petoukhov et al. 2000). Temporal resolution and the degree of parameterization follow from that requirement. As a consequence of this aggregation, many processes resolved in AOGCMs have to be parameterized in EMICs. The advantage gained by this reduction is computational efficiency. Moreover, many EMICs are designed to include explicitly biogeophysical and biogeochemical processes, which makes them a useful tool for integrated paleoclimate modeling. Presumably, neither EMICs nor AOGCMs alone offer the best modeling tool, but rather it requires the appropriate use of the full spectrum of conceptual models, EMICs, and AOGCMs.

Some Results: Factors Contributing to Climate Differences between Glacial and Interglacial Climate

Most comprehensive model simulations have addressed the question of which processes could have contributed to the difference between glacial and interglacial states during the late Quaternary, more precisely between the Last Glacial Maximum (LGM) and the preindustrial, or even present-day, climate. For example, within the framework of the Paleoclimatic Modeling Intercomparison Project (PMIP), a number of atmospheric circulation model (AGCM) simulations were undertaken, in which oceanic characteristics were either prescribed on the basis of paleoclimatic reconstructions or simulated using a simple slab-ocean model with prescribed modern oceanic heat transport. It was shown that two major factors — the buildup of large ice sheets in the Northern Hemisphere and a lowering of CO_2 atmospheric concentration — could explain a global cooling at the LGM compared to the present in the range of 2°– 6°C. One observation that appears to be more difficult to reconcile with most model results is the large (~3°C) cooling of the Western Pacific Warm Pool (e.g., Stott et al. 2002), as this region is relatively insensitive to ice-sheet emplacement and may suggest a somewhat higher sensitivity to atmospheric CO_2 or oceanic heat transport than most models currently employ.

Although ice-sheet cover and atmospheric CO_2 indeed may be the most important factors contributing to LGM–Holocene climate differences, several others may be relevant. In particular, paleo-data indicate that vegetation cover at the LGM was considerably different from the present one, with a much smaller forest area in Eurasia and in the tropics. Experiments with AGCMs have demonstrated that such changes in vegetation cover could have a pronounced regional impact, but show little global-scale influence (e.g., Kubatzki and Claussen 1998). This is not surprising, since it has been shown in several studies that models with fixed ocean characteristics considerably underestimate the impact of vegetation changes outside the regions where these changes occur.

Another important mechanism, which might have affected the glacial climate state, is related to changes in the ocean circulation. Data suggest a weakening and shallowing of the upper branch of the thermohaline circulation and northward penetration of the Antarctic bottom water. Model experiments, however, yield diverse results. Ganopolski et al. (1998) have demonstrated that a reorganization of the ocean circulation would have a profound impact on the climate. Other AGCM studies (e.g., Hewitt et al. 2001) show an intensification rather than weakening of the glacial thermohaline circulation. Hence the "thermohaline circulation riddle" is still not solved.

By using the Potsdam EMIC CLIMBER-2, Ganopolski (2003) made the first attempt to analyze geographically explicit factors that contribute to the difference between a fully glacial and an interglacial climate. (Actually, Ganopolski did not perform a complete factor analysis, because he did not differentiate between pure feedbacks and synergisms, i.e., feedbacks between feedbacks.) His results, shown in Figure 7.3, can be summarized as follows. Changes in ice-sheet distribution and elevation give the largest contribution to the glacial cooling, namely, about 3°C in globally averaged annual surface temperature. Regional cooling due to this process is strongest at high northern latitudes. Lowering of CO_2 by 80 ppm is a global process, which, according to CLIMBER-2, causes a global cooling by 1.2°C. These results are obtained in experiments with prescribed modern vegetation. The inclusion of vegetation dynamics leads to a drastically reduced forest area over Eurasia and some reduction of forest area in the tropics and subtropics. Hence, the strongest cooling associated with the biogeophysical feedback occurs at high northern latitudes (Figure 7.3c). In this region, the impact of vegetation changes is as large as the direct effect of CO_2. The global cooling due to changes in vegetation cover, however, is smaller than the CO_2 contribution, only some 0.7°C according to the model. The effect of a reorganization of the thermohaline ocean circulation is estimated as a difference between two equilibrium climate states corresponding to "cold" (stadial) and "warm" (interstadial) modes of the glacial thermohaline circulation discussed in Ganopolski and Rahmstorf (2001). Although reorganization of the thermohaline circulation does not have a pronounced global effect, due to the compensation between the Northern and the Southern Hemispheres, it has strong regional impact (Figure 7.3d). The near-surface temperature is more than 5°C lower over the Northern Atlantic in the cold mode than in the warm mode. To the contrary, the Southern Ocean and Antarctica are warmer by 1°–2°C in the cold (stadial) mode due to the seesaw effect.

Transient factor analyses have been undertaken by Berger (2001) using a two-dimensional model of the Northern Hemisphere. Berger finds that factors contributing to glacial–interglacial climate change are not constant in time. For example, biogeophysical feedback — in particular the feedback between near-surface temperature and expansion or retreat of highly reflecting snow-covered tundra on the one hand, and darker, more insolation absorbing tundra on the other hand — enhances the glacial inception, that is, the transition during MIS 5. Once the ice sheets have grown, at the end of MIS 5, this feedback appears to become negative.

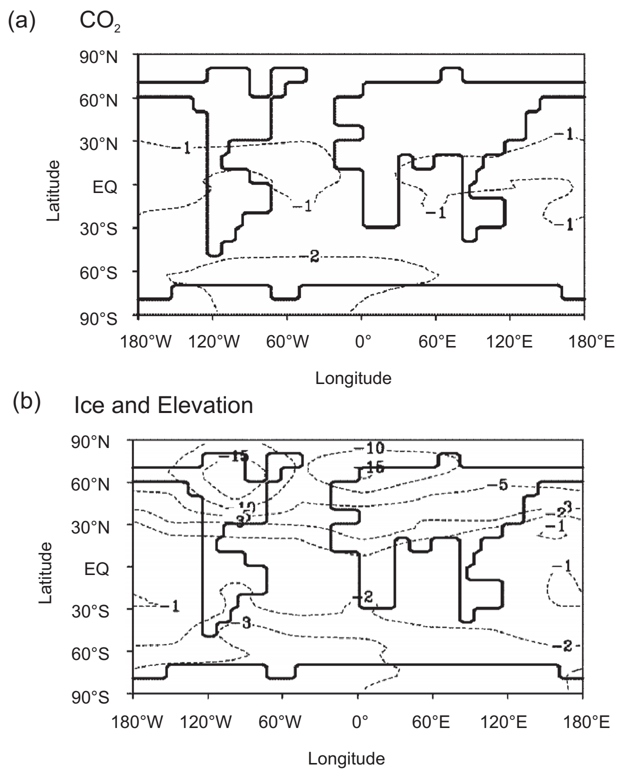

Figure 7.3 Factors contributing to changes between interglacial and full glacial equilibrium climate. Shown are changes in annual mean near-surface air temperature due to (a) lowering atmospheric CO_2 concentration from 280 ppm to 200 ppm, (b) topographic changes (i.e., changes in surface elevation, in surface albedo, and in land–ocean distribution) induced by prescribing ice sheets of the Last Glacial Maximum.

Another important lesson learned from EMICs is that changes in insolation are necessary to drive the climate system into a glacial mode, whereas changes in CO_2 operate as an internal amplifier. Keeping the geographic distribution of insolation, or more precisely the orbital parameters, constant at values typical for the Eemian interglacial, but prescribing CO_2 as some external forcing according to paleoclimatic reconstruction would yield no glacial inception (see Berger and Loutre 1997 and literature cited therein). In turn, keeping CO_2 constant at Eemian values does not prevent the last glacial inception. Moreover, experimentation with CLIMBER-2 reveals a rapid spread of ice sheets and a subsequent slower growth in ice volume once an insolation threshold is crossed. This suggests that the small ice cap instability seems to work in a geographically explicit model and that the glacial inception is presumably a bifurcation of the physical climate system (Calov et al. 2004).

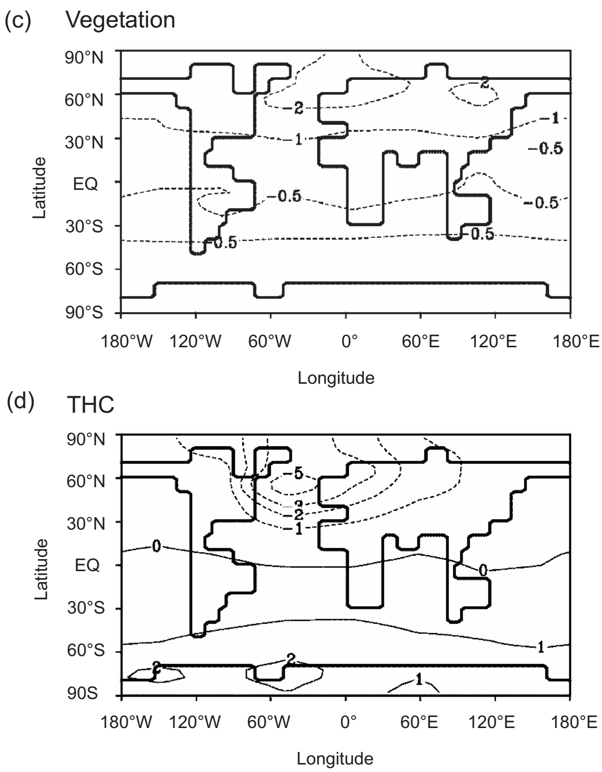

Figure 7.3 (continued) Shown are changes in annual mean near-surface air temperature due to (c) vegetation dynamics (i.e., shift of tree and grassland area), and (d) transition from the interstadial, warm to the stadial, cold mode of thermohaline circulation (THC). Figure from Ganopolski (2003) and used with permission of the Royal Society.

The sensitivity of late Quaternary dynamics to atmospheric CO_2 as internal amplifier has been demonstrated by a number of numerical experiments (see Berger and Loutre 1997). Their studies suggest that the Earth system is more sensitive to CO_2 changes when insolation variations are small (e.g., during MIS 11 and in present-day climate as well as for the next 50 ka) than when they are large (e.g., during MIS 5e, the Eemian). It appears that there could be a natural threshold of CO_2 concentration of presumably 250 ppmv above which the Earth system is not able to sustain a 100-ka glacial cycle, but oscillated at higher frequencies with a much smaller amplitude of ice volume.

CONCLUSIONS

Our focus in this chapter has been on Earth system stability from a global perspective. We have not addressed the problem of "hot spots," that is, regions on Earth that appear to be highly sensitive to external forcing due to strong internal amplifiers and refer the reader to Rahmstorf et al. and Payne (both this volume). We have considered which potential modes of operation were implicit in the natural Earth system, or climate system, in the Quaternary. We conclude that even after some 160 years of geological research into the ice ages, this has not yet been solved. However, we have some clues on what elements a theory of Quaternary Earth system dynamics should consist of in terms of concepts and model structure.

Saltzman (2002) has proposed a unified theory of Quaternary Earth system dynamics. The term "unified" is used because it combines theories based on orbital forcing and on greenhouse gas forcing, respectively. Saltzman supposes that the center manifold of the climate system involves the ice sheets and their bedrock and basal properties, coupled with tectonically forced and free variations of CO_2, a high-inertia deep thermohaline ocean. Whereas it is very likely that slow variables exist, it is still not obvious that those can be identified with particular physical entities just mentioned. Quite the contrary, in highly resolved spatiotemporal dynamics, such slow variables may emerge as complex patterns across physical entities, which strongly supports the approach of spatially resolved climate models. Interestingly, validation of inductive models appears to be an almost futile task: assessment of a number of inductive models cannot favor any model over its competitor on the grounds of tuning each model to the time series of global ice volume.

In the range of more comprehensive, quasi deductive models, only EMICs have been used for long-term studies. These numerical experiments support the idea of orbital forcing acting as a pacemaker of glacial–interglacial cycles (Hays et al. 1976). However, the situation is rather complex. Obviously, the response of the Earth system to a given forcing is a function of the actual state of the Earth system as well as meridional and seasonal changes of the forcing. Presumably, changes in insolation associated with changes in orbital parameters trigger fast internal feedbacks such as the water vapor–temperature feedback and the snow–albedo feedback, which then are further amplified by slower feedbacks, such as biogeochemical and biogeophysical feedback and the isostatic response of the lithosphere to ice-sheet loading. Some of these feedbacks even change sign during the course of an glacial–interglacial cycle.

The biggest mystery of all appears to be wrapped up with ice, whether the continental ice sheet at one pole or the extent of sea ice at the other. Evidence emerges that the ice sheets in the Pleistocene as well as biogeochemical cycles are critical components of both the free and forced conceptions of Pleistocene glacial cycles. Their response to a future of higher atmospheric CO_2 may well determine the gross dynamics of the climate system in the future.

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