GLACIAL CYCLES: TOWARD A NEW PARADIGM

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Abstract. The largest environmental changes in the recent geological history of the Earth are undoubtedly the successions of glacial and interglacial times. It has been clearly demonstrated that changes in the orbital parameters of our planet have a crucial role in these cycles. Nevertheless, several problems in classical astronomical theory of paleoclimate have indeed been identified: (1) The main cyclicity in the paleoclimatic record is close to 100,000 years, but there is no significant orbitally induced changes in the radiative forcing of the Earth in this frequency range (the "100-kyr problem"); (2) the most prominent glacial-interglacial transition occurs at a time of minimal orbital variations (the "stage 11 problem); and (3) at ~0.8 Ma a change from a 41-kyr dominant periodicity to a 100-kyr periodicity occurred without major changes in orbital forcing or in the Earth's configuration (the "late Pleistocene transition problem"). Additionally, the traditional view states that the climate system changes slowly and continuously together with the slow evolution of the large continental ice sheets, whereas recent high-resolution data from ice and marine sediment cores do not support such a gradual scenario. Most of the temperature rise at the last termination occurred over a few decades in the Northern Hemisphere, indicating a major and abrupt reorganization of the ocean-atmosphere system. Similarly, huge iceberg discharges during glacial times, known as Heinrich events, clearly demonstrate that ice sheet changes may also be sometimes quite abrupt. In light of these recent paleoclimatic data the Earth climate system appears much more unstable and seems to jump abruptly between different quasi steady states. Using the concept of thresholds, this new paradigm can be easily integrated into classical astronomical theory and compared with recent observational evidence. If the ice sheet changes are, by definition, the central phenomenon of glacial-interglacial cycles, other components of the climate system (atmospheric CO_2 concentration, Southern Ocean productivity, or global deep-ocean circulation) may play an even more fundamental role in these climatic cycles.

1. INTRODUCTION

The first astronomical theory of paleoclimates is already more than 150 years old (a detailed account of the history of this scientific adventure is given by *Imbrie and Imbrie* [1979]). The astronomical forcing is now well known, at least for the late Pleistocene. Recent advances in geochemistry helped to quantify the geological record, and it is now evident that climatic cycles have frequencies nearly identical to the Earth's orbital frequencies. However, the story is not finished, since we still do not understand how the climate system works and how small changes in the insolation at the top of the atmosphere can be amplified by the Earth system to create the large climatic changes associated with glacial-interglacial cycles. Traditionally, ice age models have concentrated on the behavior of the large Northern Hemisphere ice sheets, the Laurentide and the Fennoscandian. In light of recent paleoclimatic data this approach now appears insufficient. Indeed, ice age cycles involve a reorganization not only of the ice sheets but also of the ocean-atmosphere system, the deep ocean and its sedimentary interface, ocean chemistry, the carbon cycle, the terrestrial and marine ecosystems, and so forth. The whole Earth participates in the dynamics of ice ages in a complex fashion, and its components are tied together through a dense network of feedbacks. In particular, the atmospheric concentration of CO_2 and the existence of climatic thresholds appear to have a fundamental role in the glacial-interglacial cycles. In the current context of anthropogenic global warming, the understanding of the dynamics of ice ages, the largest recent changes in the climate system, is becoming a key scientific issue.

In section 2 I will briefly mention some important historic milestones in the discovery of ice ages and then present, in more detail, the astronomical theory and some simple conceptual models. In section 2.4 I will discuss how new observational and conceptual advances may help define a new paradigm for glacial cycles that could solve the traditional difficulties associated with classical astronomical theory.

2. ASTRONOMICAL THEORY OF PALEOCLIMATES

2.1. From Geology, to Astronomy, to Geochemistry

The idea that the Earth experienced severe glaciations in the past originates at the beginning of the

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nineteenth century. *Agassiz* [1838] was among the first to recognize that glaciation was the most natural explanation for the erratic boulders, moraines, and deeply scratched bedrocks that could be found in many places in the Alps, Scotland, and North America. Though several others had suggested major glacial advances before, Agassiz widely promoted the idea of an ice age and started a scientific debate that lasted more than 30 years.

A few years after Agassiz, *Adhémar* [1842] suggested that the orbital variations of the Earth could be responsible for climatic changes. Adhémar's theory was based on the known precession of the equinox and suggested that glaciations were caused by the change in the lengths of the seasons. Glaciations, caused by longer winters, would thus occur every 23 kyr in the Northern Hemisphere, with ice ages occurring in the Southern Hemisphere in opposite phase, as shown by the current presence of the Antarctic Ice Sheet. This theory was rapidly proved to be incorrect since the annual mean solar heating at the top of the atmosphere does not change with precession. Nevertheless, the idea of cyclic glaciations forced by the Earth's orbital changes was taken further by *Croll* [1875], who elaborated the first astronomical theory of paleoclimate. Croll hypothesized that precessional forcing, though only seasonal, might be crucial and that winter insolation might be critical. Colder winters would produce larger areas covered with snow, which could lead to glacial age because of the snow albedo feedback. He also showed the importance of the modulation by the 100-kyr eccentricity changes for this precessional forcing. He further hypothesized that the changing tilt of the Earth should play a role, and being aware that the astronomical forcing is small, he tried to find some internal amplifying mechanisms in the ocean circulation.

Interest in an astronomical theory of glacial cycles was renewed with the work of M. Milankovitch between 1920 and 1941 [*Milankovitch*, 1941], in which he computed the solar radiation at the top of the atmosphere for different latitudes, taking into account the changes in eccentricity, precession, and tilt of the Earth. In contrast to Croll's theory, Milankovitch argued that the summer season was critical. Colder summers enable the persistence throughout the year of snowfields in some high-latitude regions, leading to a net accumulation of ice and to the building of ice sheets (Figure 1). The Milankovitch theory predicted that the climatic cyclicity should be mainly at 23 kyr, because of precession, and at 41 kyr because of obliquity (or tilt) changes.

The first continuous records of the ice ages from marine sediment cores came in the 1950s [*Arrhénius*, 1952; *Ericson et al.*, 1956], and *Emiliani* [1955] provided the first record of the isotopic composition of fossil shells of foraminifers in these cores. For the first time, cyclicity was demonstrated, and Emiliani assigned each individual cycle a "marine isotopic stage number." *Shackleton* [1967] and *Duplessy et al.* [1970] suggested that most of Emiliani's signal was caused by ice volume changes, not by temperature changes. With the study of foraminiferal assemblages in marine sediment cores, *Imbrie and Kipp* [1971] could confirm these results and provide quantitative estimates of the glacial-interglacial temperature changes. Dating methods based on the radioisotopes of uranium, thorium, and potassium were also developed at this time. When applied to fossil coral reefs [*Broecker*, 1966; *Broecker et al.*, 1968], as well as to magnetic reversals [*Cox et al.*, 1963, 1964], a cyclicity of 100 kyr was clearly demonstrated [*Broecker and van Donk*, 1970; *Hays et al.*, 1969; *Kukla*, 1975]. However, the Milankovitch theory stated that the main cycles should be at 23 and 41 kyr. Careful spectral analysis of marine sediment cores led to the clear confirmation of the astronomical theory. Indeed, besides the 100-kyr cycle, three other cycles could be identified: 41, 23, and 19 kyr [*Hays et al.*, 1976]. The computations of the astronomical time series were now made easier with the help of computers, and *Vernekar* [1972] and *Berger* [1977, 1978] showed that the precession frequency is split into a 23-kyr and a 19-kyr cycle. Ice age cycles are therefore undoubtedly linked in some fashion to Earth's orbital variations.

2.2. Orbital Forcing

According to Kepler's laws, the Earth's orbit around the Sun is an ellipse, and one of its two foci is roughly the Sun. This orbit is also influenced by the motion of the other planets of the solar system. Among the geometrical characteristics of the Earth's orbit, only two have an influence on the solar heating received by the Earth: the ellipse semimajor axis a, which measures the size of the ellipse, and its eccentricity e (defined as $e = c/a$, where c is the distance from focus to center), which measures its elongation (Figure 2). There is no theoretical or experimental reason to think that a has changed in the past. In contrast, the eccentricity e changes significantly with 100-kyr, 400-kyr, and 2-Myr periodicities. When the eccentricity is large, the ellipse is more elongated, the annual mean Earth-Sun distance is slightly smaller, and the energy captured by the Earth is increased. The global mean annual solar radiation received by Earth is

$$W_A = \frac{S}{4\sqrt{1 - e^2}} = \frac{S_0}{4},$$

where S is the solar radiation received at a distance a from the Sun (S depends only on solar activity) and S_0, improperly defined as the "solar constant," also changes with the eccentricity. The variations in W_A are very small, as illustrated in Figure 3, and they cannot be directly responsible for the 100-kyr cycles observed in the paleoclimatic records.

However, the Earth is not a point. It is also not exactly a sphere, and the Sun and the Moon exert a torque on its equatorial bulge. This leads to a precession of the Earth's axis and to quasi-periodic changes in its tilt, or obliquity, ε (Figure 2). This obliquity defines the location

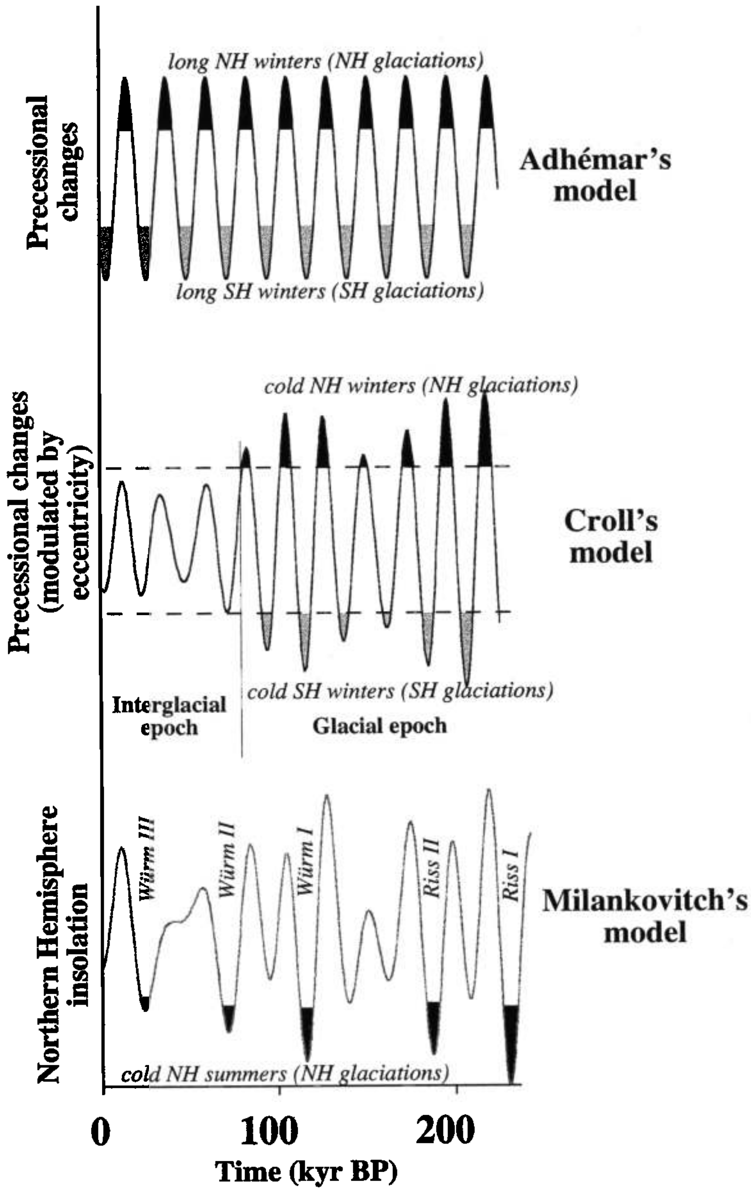

Figure 1. The ice ages according to *Adhémar* [1842], *Croll* [1875], and *Milankovitch* [1941]. Adhémar was aware only of the precession of equinoxes, and he related the glacial ages to the lengths of the seasons. Croll benefited from the advances in astronomy and was aware of changes in the other astronomical parameters, though he could not compute the obliquity changes. In his view, the interglacial epoch is associated with small eccentricity and therefore with small precessional changes. Milankovitch was the first to integrate the effect of all astronomical parameters and to compute explicitly the insolation at the top of the atmosphere. He understood that summer, not winter, was the critical season. His insolation minima were associated with the major alpine glacier advances recorded by geological evidence.

of the tropics and the polar circles, and changes in it will clearly have some climatic effect. When the obliquity increases, the poles receive more solar energy in summer but stay in the polar night during winter. The annual mean insolation therefore increases symmetrically at the poles and decreases at the equator, since the global Earth annual mean W_A does not depend on ε (see above). In contrast to eccentricity changes, obliquity variations have a substantial effect on the local annual mean insolation of several W m^{-2} (Figure 4).

The precession of the Earth's axis moves the vernal point γ (see Figure 2) with a quasi-period of 25,700 years. This is the well-known precession of the equinoxes. However, for climatic purposes, only the motion of γ relative to the perihelion is of interest. This is the climatic precession, measured by the $\tilde{\omega}$ angle. More precisely, it is usual to define the precessional parameter $e \sin \tilde{\omega}$, which combines the climatic precession and the eccentricity. In particular, when $e = 0$, the perihelion is undefined and the precessional parameter $e \sin \tilde{\omega}$ van-

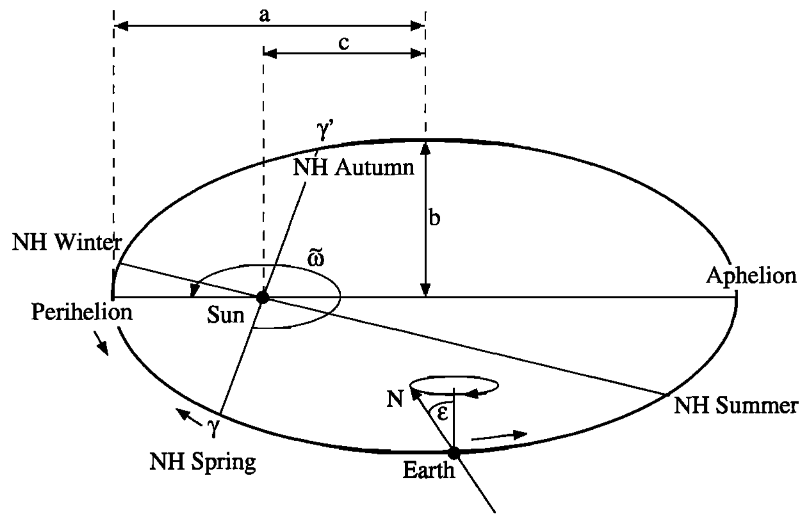

Figure 2. The orbital parameters of the Earth. Eccentricity e is defined as $e = c/a$, where a is the semimajor axis and c is the distance between the focus and the center of the ellipse. The semiminor axis b is then given by Pythagoras's theorem ($a^2 = b^2 + c^2$, which gives $b = a\sqrt{1 - e^2}$). The current eccentricity value is $e = 0.0167$, which means that the Earth's orbit is very close to a circle. The tilt of the Earth's axis with respect to the orbital plane is the obliquity ε (current value is $\varepsilon = 23.44°$). This tilt implies that the Earth equatorial plane intersects with its orbital plane, the intersection defining the $\gamma\gamma'$ line and the position of equinoxes and solstices. In the current configuration the Earth is closest to the Sun (perihelion) around January 3, just a few weeks after the Northern Hemisphere winter. This position, relative to the vernal equinox γ, is measured by the $\tilde{\omega}$ angle.

ishes. In other words, when the Earth orbit is circular, there is no climatic effect associated with precessional changes. As can be seen in Figure 5, seasonal insolation changes are of the order of 10–20%. They are antisymmetric with respect to seasons and hemispheres. The insolation excess (deficit) received in summer is compensated by the deficit (excess) in winter, and the insolation excess (deficit) received in the Northern Hemisphere is compensated by the deficit (excess) in the Southern Hemisphere. Definition of the precessional parameter is not universal, and $e \sin(\pi + \tilde{\omega})$, which only changes the sign of the precessional parameter, is widely used [cf. *Berger*, 1978].

A subtle detail in the astronomical forcing follows from Kepler's second law. The amount of energy received at a given latitude and between two given orbital positions measured from γ (for example, between the summer solstice and the autumnal equinox) does not depend on the climatic precession $\tilde{\omega}$. However, the time necessary for the Earth to move between these two orbital positions (for example, the length of the summer season) does change with climatic precession. The insolation, defined as the amount of energy received per unit time, therefore changes with climatic precession, but only through the lengths of the seasons. In some sense, Adhémar was right: It is indeed the changing speed of the Earth, and therefore the lengths of the seasons, that provides the main orbital forcing for glacial-interglacial cycles. In the present-day configuration, summer occurs near the aphelion, where the Earth moves slower and, for the same total amount of incoming solar energy, summer is longer and therefore cooler. According to Milankovitch's ideas, this situation favors the start of a glaciation.

The computation of the insolation time series is now easier with the help of computers, but a major intrinsic difficulty is the strongly nonlinear character of the celestial mechanical equations for the solar system. The solar system is, in fact, chaotic [*Laskar*, 1989], and a precise computation of the eccentricity e is impossible beyond a few tens of millions of years. The situation for the obliquity ε and precession $\tilde{\omega}$ is even worse, since their evolution depends on the exact shape of the Earth and its possible changes induced by glaciations or inner mantle convection [*Laskar et al.*, 1993; *Forte and Mitrovica*, 1997]. The precise computation of the insolation series beyond a few million years is therefore uncertain [*Laskar*, 1999]. Still, the main frequencies in orbital forcing were present in the remote geological past, and it is possible to build timescales up to several tens of millions of years [*Shackleton*, 1999].

2.3. Successes and Pitfalls of Astronomical Theory

Numerous records of past environmental changes obtained in the last 20 years largely confirm the link between insolation forcing and climate. A proxy for global ice volume, or sea level, is the isotopic composition of the oxygen in the carbonate from fossil foraminifera shells obtained from marine sediment cores. The spectral mapping and prediction (SPECMAP) record [*Imbrie et al.*, 1984] (Figure 6) is often used as a stratigraphic reference for the global changes in marine $\delta^{18}O$. When using marine cores in regions close to the freezing point (so that glacial temperatures cannot be much colder than at present time), the global change in marine $\delta^{18}O$ can be estimated to be ~1.0–1.1‰ [*Labeyrie et al.*, 1987]. This is confirmed by other methods [*Schrag et al.*, 1996]. Since the oceanic mean depth is ~4 km and the mean isotopic composition of the large ice sheets present at the glacial maximum was about −30 to −35‰ [*Jouzel et al.*, 1994], the calculated sea level drop was of the order 115–135 m (4 km × 1.0‰/30‰). A more direct estimate of 120 m is obtained by fossil coral terraces [*Chappell and Shackleton*, 1986]. This implies an ice sheet volume ~45 × 10^6 km^3 larger than the volume of today. This ice was located mainly in the Northern Hemisphere, over Canada (the Laurentide ice sheet) and Scandinavia (the Fennoscandian ice sheet). Postglacial rebound in these regions, measured by historical sea level records and fossil shorelines or coral reefs terraces records [*Fairbanks*, 1989], is used to estimate more precisely the evolution of the height and shape of these ice sheets [*Peltier*, 1994].

Spectral analysis of marine isotopic records (Figure 6) clearly reveals the characteristic astronomical frequencies. (The timescale for these records has usually been tuned to the astronomical forcing. Nevertheless, the same frequencies appear, though with smaller amplitude, using only the Brunhes/Matuyama magnetic reversal, dated with K/Ar methods, as a stratigraphic point.) In Figure 7a, the SPECMAP record is filtered in the 23-kyr precessional band and compared with the precessional forcing. It is remarkable that both time series have a quite similar modulation of their amplitude. This is probably one of the strongest arguments in favor of a simple causal relationship between the precessional forcing and the climatic response in this frequency band. Indeed, in contrast to other techniques, amplitude modulation is not affected by tuning [*Shackleton et al.*, 1995]. It is also remarkable that the relative amplitude of the 23-kyr and 19-kyr periodicities evolved during the last million years in a very similar fashion both in the forcing and in the paleoclimatic record. The climatic response in the 41-kyr frequency band is also almost linear, as illustrated in Figure 7b for the Ocean Drilling Program (ODP) 659 record [*Tiedemann et al.*, 1994]. All these observations strongly argue for a simple connection between climate and the insolation forcing in the precession and obliquity bands [*Imbrie et al.*, 1992].

The main glacial-interglacial periodicity is the 100-kyr cycle for which there is no direct connection with the eccentricity forcing [*Imbrie et al.*, 1993] (Figure 6). In particular, this 100-kyr cyclicity is considerably smaller before ~0.8 Ma, where climatic variability is dominated by the 41-kyr periodicity [*Pisias and Moore*, 1981; *Start and Prell*, 1984]. Furthermore, the 100-kyr cyclicity is not so well defined, as is illustrated in Table 1, since the time between two terminations varies between 85 and ~120 kyr. In contrast to the precessional and obliquity bands, it is therefore impossible to find a simple linear relationship with the forcing for the 100-kyr periodicity. Furthermore, the major periodicity of eccentricity changes is 400 kyr (see Figure 3), but such cyclicity is absent, or very weak, in most paleoclimatic records. Some more complex nonlinear relationships have been suggested between climate and this 400-kyr periodicity (frequency modulation [*Rial*, 1999]), and some deep-sea dissolution records also exhibit cyclicity that could be related to the 400-kyr periodicity [*Bassinot et al.*, 1994a]. Clearly, the presence in climatic records of a strong 100-kyr periodicity, without any obvious 400-kyr periodicity, is one of the major difficulties for classical Milankovitch theory.

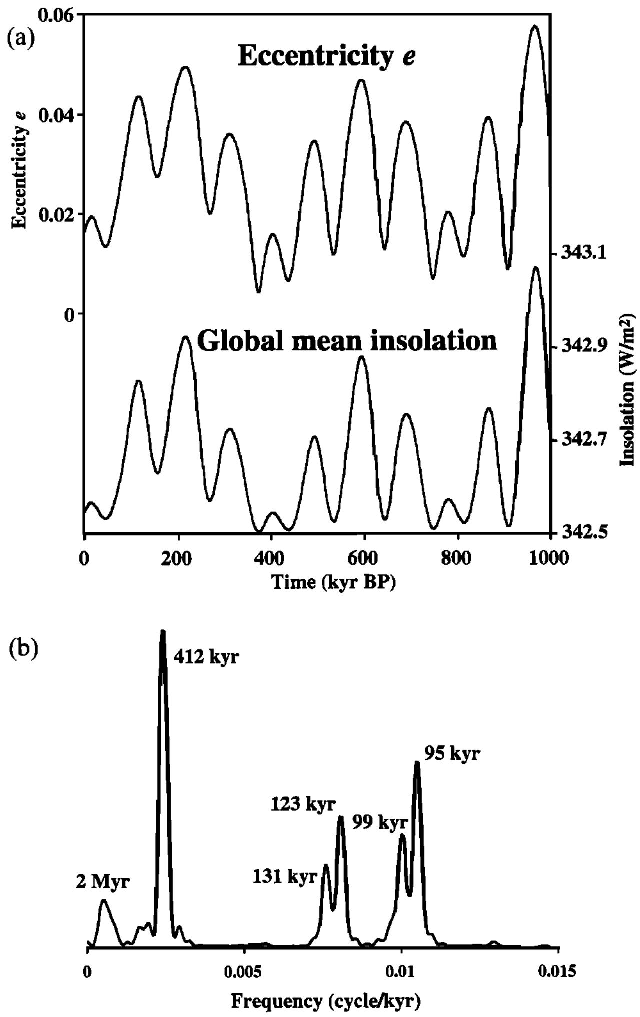

Figure 3. (a) Changes in eccentricity *e* for the last million years and its small effect on the global annual mean insolation received by the Earth (assuming a constant solar activity). (b) Spectral analysis of the eccentricity changes, revealing major periodicities at ~400 kyr and in the 100-kyr band (arbitrary vertical linear scale).

A closely related question is the "stage 11 problem." When the Earth's orbit is almost circular, the seasonal insolation changes due to precession are very small, and such a situation occurs at ~400 ka B.P. (Figure 5). In contrast to Milankovitch theory, the recorded climatic changes at 400 ka B.P. are not weak. On the contrary,

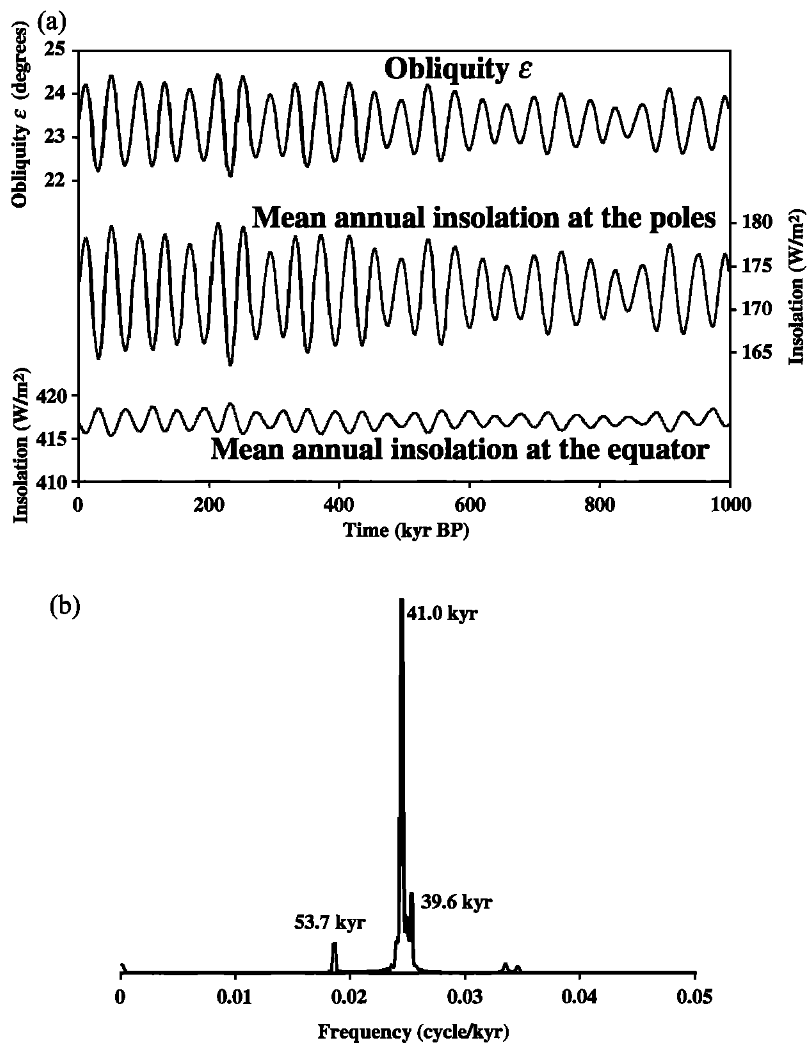

Figure 4. (a) Changes in obliquity ε for the last million years and the annual mean insolation received at the poles and at the equator. (b) Spectral analysis of the obliquity changes, revealing one major periodicity at 41 kyr (arbitrary vertical linear scale).

the glacial-interglacial transition between isotopic stages 12 and 11 is documented as probably the largest transition, both in isotopic records (see Figure 6) and in other sea level proxies. A recent estimate of sea level for stage 12 is −140 m below the present-day level [*Rohling et al.*, 1998] and +20 m for stage 11 [*Kindler and Hearty*, 2000]. This obviously raises the question of which ice sheets grew and melted at that time [*Chappell*, 1998; *Cuffey and Marshall*, 2000; *Scherer et al.*, 1998]. Stage 11 appears to be longer than the other interglacials, as illustrated by the Southern Ocean sea surface temperatures given in Figure 8. It is also a time of massive coral reef buildup [*Droxler*, 2000] and maximum deep-ocean carbonate dissolution [*Farrell and Prell*, 1989; *Bassinot et al.*, 1994a]. Knowing that the present and future eccentricity is also very small (see Figure 3), we see that all these peculiarities make stage 11 particularly interesting for the future of the Earth's climate [*Howard*, 1997; *Droxler*, 2000].

A symmetrical problem occurs for stage 7. Indeed, it is a period of maximum eccentricity and therefore a time of maximum seasonal forcing. However, instead of a well-marked interglacial, stage 7 looks more like a mild glacial episode. A particularly intriguing question concerns the apparent decoupling of the maximum precessional forcing (which occurs at stage 7.3), the maximum temperature (which happens in many locations at stage 7.5), and the minimum ice volume (which seems to occur at stage 7.1 (see Figure 8) or stage 7.3 [*Martinson et al.*, 1987], depending on isotopic curves. All these observations clearly point to a serious deficiency in classic Milankovitch theory.

Some have suggested that the "apparent" 100-kyr cyclicity looks similar to a red noise process [*Kominz and Pisias*, 1979] or could be explained by stochastic resonance (random processes, together with the weak eccentricity changes, could switch climate from glacial to interglacial [see, e.g., *Benzi et al.* [1982]). However, one feature of the Vostok record is the similarity of stages 5 and 9. A natural explanation can be found in the astronomical forcing. Indeed, both the eccentricity and the

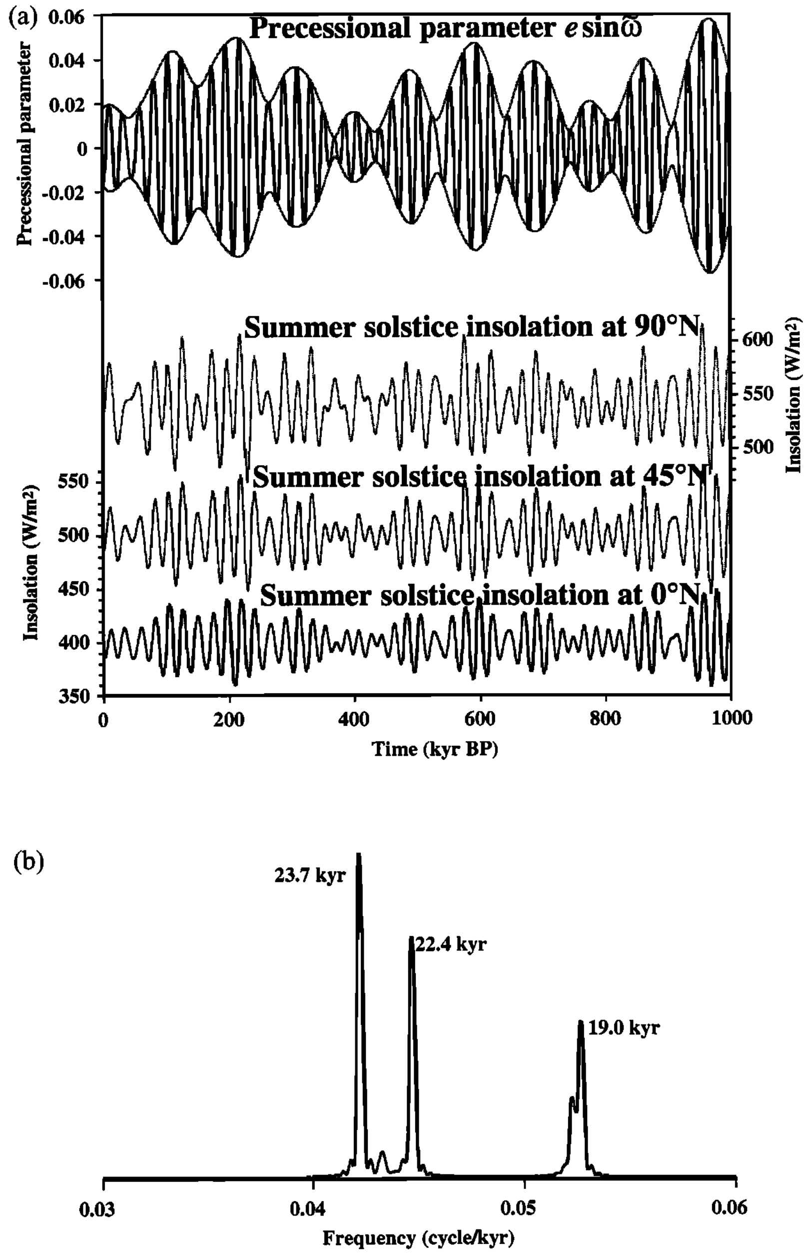

Figure 5. (a) Changes in the precessional parameter e sin $\tilde{\omega}$ for the last million years and the seasonal insolation received at different northern latitudes. (b) Spectral analysis of the precessional parameter changes, revealing two groups of periodicities, around 23 and 19 kyr (arbitrary vertical linear scale).

phasing between obliquity changes and precessional changes are almost identical at these two periods of time. This looks like a clear demonstration that the Earth's system is, in fact, strongly deterministic.

2.4. Conceptual Models of Glacial Cycles

In the nineteenth century and at the beginning of the twentieth century, computation of the variations of the Earth's orbital elements was a critical problem [see, e.g., *Berger*, 1988]. Similarly, until advances in geochemistry in the 1960s, reliable quantitative and well-dated proxies of past climatic changes were almost nonexistent. If these two problems have been in large part addressed, we are now confronted with another tremendous challenge: the modeling of the Earth's system. A successful model of glacial-interglacial cycles (the largest recent and well-documented global changes) will be a crucial milestone in the understanding of the complex interactions of the many components of our planet. We are, unfortunately, quite far from achieving this objective. Up to the present, models of glacial-interglacial cycles have been limited, most of the time, to the modeling of the evolution of ice sheets. It is beyond the scope of this paper to make an exhaustive review of all the efforts that have been performed in this domain, and I will only mention a few simple examples.

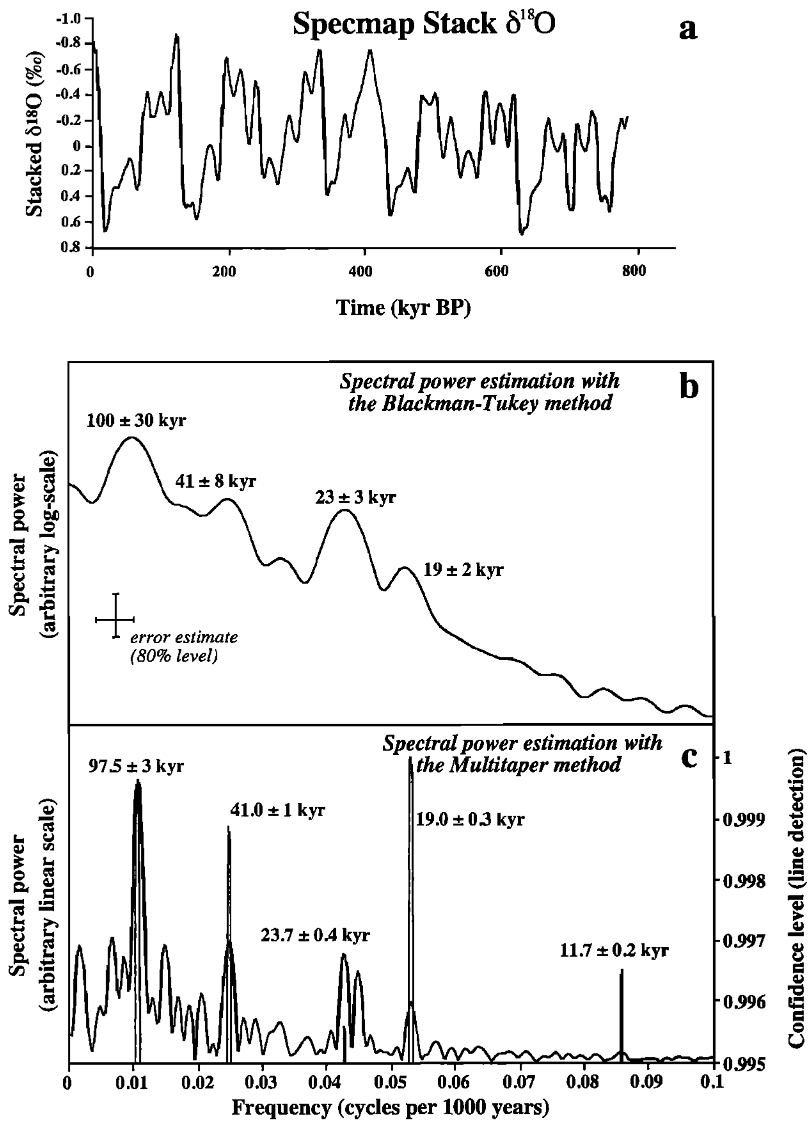

Figure 6. (a) The spectral mapping and prediction (SPECMAP) record [*Imbrie et al.*, 1984]. (b) Spectral analysis of SPECMAP using the standard Blackman-Tukey method. (c) The same analysis with the multitaper method. In Figures 6b and 6c the astronomical frequencies are clearly visible. The first harmonic of the precessional frequency is also detected by the multitaper method.

Following Milankovitch (summer insolation at high northern latitudes is responsible for the glacial-interglacial cycles), many conceptual models have tried to deduce ice volume changes from the summer insolation at 65°N. *Calder* [1974] simply states that below a given level of insolation, the ice sheets are growing, while above this level they are shrinking. The equation is

$$\frac{dV}{dt} = -k(i - i_0),$$

with t being time, $k = k_M$ if the insolation i is larger than i_0 (melting), and $k = k_A$ otherwise (accumulation of ice). In addition, the ice volume V is constrained to remain positive. The result is plotted in Figure 9, and the comparison with the data is quite poor. The precessional response is much too strong and the model comes back to an interglacial stage almost every 23 kyr. Nevertheless, this crude model predicts correctly all the major terminations, for the last 0.8 Myr. Note that in 1974 the timing of these transitions was still poorly known, since the SPECMAP work and the calibration of timescales onto the precessional forcing started only around 1980. A posteriori, Calder's model succeeds where many other models are still failing. The main drawback of Calder's model is its lack of structural stability: Any small changes in the input parameters i_0, k_M, or k_A will lead to very different, unrealistic results. This can be easily understood from the equation above. Indeed, the ice volume V is just the integral of relative insolation changes, and any small changes in parameters will induce an unrealistic growth in V.

A more robust model has been given by *Imbrie and*

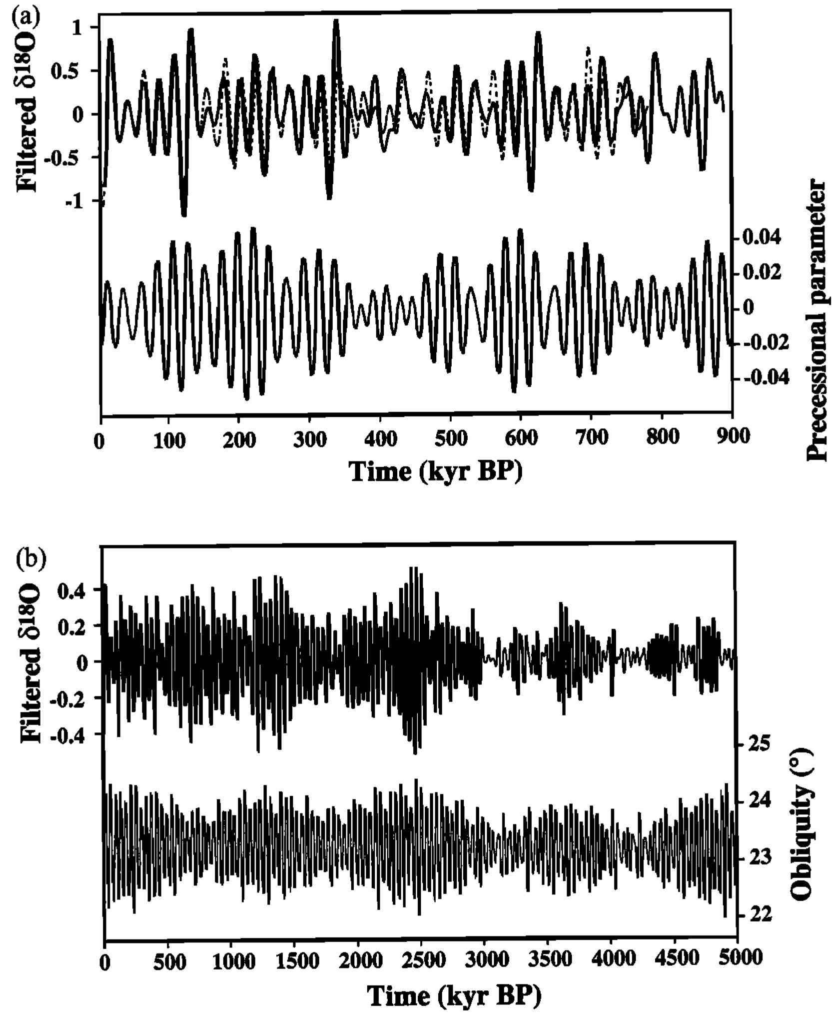

Figure 7. (a) The SPECMAP record [*Imbrie et al.*, 1984] (dashed curve) and the *Bassinot et al.* [1994b] record (bold curve) are filtered in the 23-kyr band and compared with the precessional parameter. (b) The 5-Myr long Ocean Drilling Program (ODP) 659 $\delta^{18}O$ record [*Tiedemann et al.*, 1994] is filtered in the 41-kyr band and compared with obliquity. The amplitude modulation of both the 23-kyr and the 41-kyr cyclicity appears very similar in the astronomical forcing and in the paleoclimatic record. This is probably the strongest argument in favor of a simple quasi-linear relationship between the climatic system and insolation forcing in these two frequency bands.

Imbrie [1980]. The equation is written, in dimensionless form, as

$$\frac{dV}{dt} = \frac{(i - V)}{\tau},$$

where $\tau = \tau_M$ if $V > i$ (melting) and $\tau = \tau_A$ otherwise (accumulation of ice). In other words, the ice volume is simply relaxed to the forcing, with a different time constant, depending on the sign of ice volume changes. In order to work properly the accumulation time constant τ_A needs to be smaller than the melting time constant τ_M, which is contradictory to the often noted idea that glacial cycles are characterized by slow accumulation and rapid melting of the ice sheets. The results (Figure 10) show a fairly good agreement with the data for the last cycle but a poor agreement for other cycles. In particular, there is a strong 400-kyr cyclicity, without a clear 100-kyr cyclicity. This leads to very small ice volume changes during termination V. This is another illustration of the "stage 11 problem." Though quite imperfect, the *Imbrie and Imbrie* [1980] model has sometimes been used to establish the age scale of paleoclimatic records [e.g., *Bassinot et al.*, 1994b], but the exact fashion by which the record is "tuned" to the astronomical forcing does not significantly change the results, within a "precessional phasing uncertainty" of a few thousands of years [*Martinson et al.*, 1987].

In order to address the 100-kyr problem, several models with long internal time constants have been built. For example, the isostatic response of the bedrock under the weight of the ice sheets was used to explain the apparent asymmetry of the 100-kyr cycles, with a slow buildup of ice and a rapid deglaciation [*Oerlermans*, 1982]. Indeed, the summit of a large ice sheet will easily

TABLE 1. Lengths of the Last Six Glacial Cycles, Measured From Termination to Termination (Glacial-Interglacial Transitions)[a]

Cycle	*DSDP 607*	*ODP 659*	*ODP 663*	*ODP 664*	*ODP 677*	*ODP 806*	*ODP 846*	*ODP 849*	*ODP 925*	*V28-239*	*MD90 0963*	*Mean*	*SD*
I–II	125.8	109.5	120.1	114.0	137.6	112.0	133.1	124.9	127.8	117.2	162.0	125.8	14.9
II–III	81.5	107.6	111.4	114.6	114.2	122.2	113.3	139.0	119.2	114.0	121.7	114.4	13.7
III–IV	104.6	97.7	89.8	92.0	86.3	86.7	92.6	93.6	99.3	93.3	87.6	93.0	5.7
IV–V	95.1	99.3	93.7	90.4	74.4	82.3	84.3	79.8	?	61.9	79.0	84.0	11.1
V–VI	77.1	128.6	114.4	111.9	106.9	97.9	117.3	108.7	?	109.6	82.5	105.5	15.7
VI–VII	94.6	86.6	74.9	68.6	74.9	108.1	68.7	79.5	74.7	96.6	111.7	85.4	15.3
Mean	96.5	104.9	100.7	98.6	99.0	101.5	101.5	104.3	105.3	98.8	107.4	101.7	3.4
SD	17.5	14.2	17.4	18.3	25.0	15.4	23.8	24.4	23.6	20.4	31.7	16.8	

[a]The timescale of each record was established assuming a constant sedimentation rate between termination I (fixed at 13.5 ka) and the Brunhes-Matuyama magnetic reversal (fixed at 772.2 ka). It is interesting to note that the standard deviation of the cycle lengths is larger for a given record than for a given cycle. In other words, for each record the mean duration is indeed ~100 kyr, but with quite a large dispersion, whereas for a given cycle the mean duration is variable, but with a significantly smaller dispersion. A natural conclusion is that the cycle length indeed varies from ~85 to ~120 kyr. Abbreviations are DSDP, Deep Sea Drilling Project; ODP, Ocean Drilling Project. From *Raymo* [1997].

culminate at ~3 km, with the bedrock below the ice lowered by ~1 km. Since Earth's mantle viscosity is quite large, there is a several thousand year delay between loading of the ice and reorganization of topography [*Peltier*, 1994]. The buildup of the ice sheet will thus be hampered by the still high altitudes of the growing ice sheet, while the melting will become easier because of the depressed altitude of a shrinking ice sheet. Still, a time constant of 50–100 kyr is difficult, or almost impossible, to explain with such mechanisms. Another approach was to look at the rapid, millennial-scale, internal variability of the climate system as a potential source for longer timescale variability, by the nonlinear combination of frequencies [*Ghil and Le Treut*, 1981; *Le Treut and Ghil*, 1983]. This is certainly a promising approach, and millennial-scale variability, as outlined in section 3.1, probably has a crucial role in the problem of glacial-interglacial cycles.

The conceptual models described above illustrate some key mechanisms. More complex models have been used, with more realistic representations of the physics at work in the system, but also with larger sets of tunable parameters. Some energy balance models, coupled to simplified ice sheet models, have had some successes in reproducing the glacial-interglacial cycles [e.g., *Pollard*, 1983; *Tarasov and Peltier*, 1997]. The Louvain-la-Neuve two-dimensional climate model (LLN-2D) [*Gallée et al.*, 1991], which couples a zonally averaged atmosphere with an ice sheet model, has been used extensively to investigate this problem in detail [see, e.g., *Berger et al.*, 1999]. In contrast to these Earth models of intermediate complexity (EMICs), general circulation models (GCMs) are much too expensive in computer time to simulate climate over such long timescales. They have nevertheless been used for specific time periods, like the Last Glacial Maximum, in order to assess their ability to simulate very different climates, in particular within the Paleoclimate Modeling Intercomparison Project (PMIP) exercise [e.g., *Pinot et al.*, 1999; *Kageyama et al.*, 2001].

3. ABRUPTNESS OF CLIMATIC CHANGES

3.1. From Catastrophism, to Gradualism, to Abrupt Events

In the early nineteenth century the Earth's history was understood as a succession of cataclysmic events, with the Great Flood from the Old Testament being but the last one. Agassiz's statement that the ice age "must have led to the destruction of all organic life at the Earth's surface" was certainly in full agreement with this dominant catastrophism. It is interesting to note how geological philosophy has since been changed to gradualism: Geological changes must be very slow and gradual. The above dramatic statement from Agassiz would now be taken as a serious drawback of the theory, as illustrated in the context of the current controversy on the "snowball Earth theory," which suggests the occurrence of a fully glaciated Earth just before the Cambrian life explosion [*Hoffman et al.*, 1998]. The idea that glacial-interglacial cycles are a slow response of the climate system to slow insolation changes is therefore still widespread. Indeed, the original theory states that small insolation changes will induce slight changes in permanent snow and ice cover areas, which will induce further temperature changes because of the high albedo of ice. This ice albedo feedback was assumed to be the main amplifying mechanism. Since ice sheet changes are occurring only on the several thousand year timescale, climate variations should be very slow. However, new paleoclimatic data do not fit into the classical gradualism scheme.

The last 10 years are marked by the discovery of widespread sub-Milankovitch variability in climate. The first clear indicators of such millennial-scale changes came from ice records in Greenland [*Dansgaard et al.*, 1982, 1993]. These climatic warm excursions in glacial times have a typical duration of ~1000–3000 years (Dansgaard-Oeschger events). In marine sediments from the North Atlantic, abrupt events corresponding to

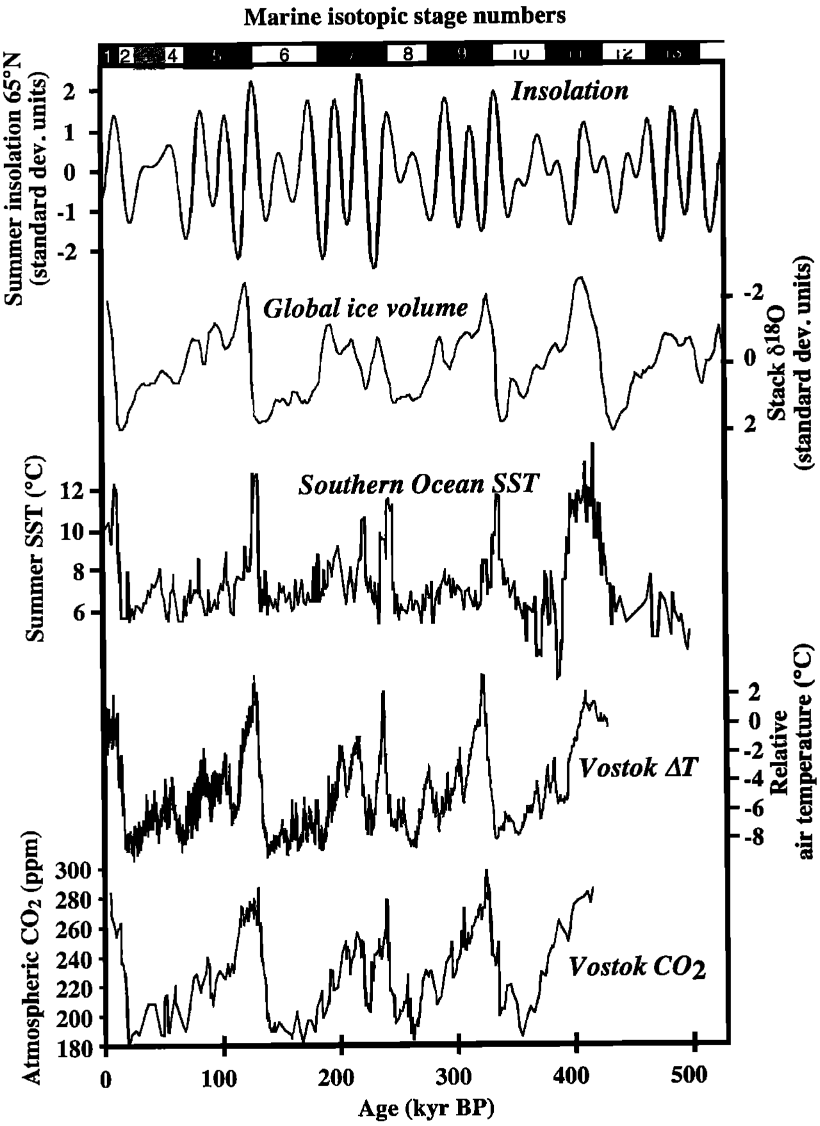

Figure 8. An illustration of the pitfalls of the Milankovitch theory. Topmost curve is the summer solstice insolation at 65°N, normalized to zero mean and unit variance [*Laskar et al.*, 1993]. According to classical Milankovitch theory this represents the main external forcing. Next curve is the global ice volume estimated by the isotopic composition of foraminifera shells [*Bassinot et al.*, 1994b]. Next curve is a Southern Ocean temperature record from the record RC11–120 [*Hays et al.*, 1976]. Next curve is air temperature difference from the present over Antarctica, estimated by the isotopic composition of the ice [*Petit et al.*, 1999]. Bottom curve is atmospheric concentration of CO_2 from the Vostok record [*Petit et al.*, 1999]. It must be emphasized that each record has its own independent timescale and that the precise relative chronology of events, within "precessional phasing uncertainty," is certainly unrealistic. The last climate cycle (the last 120 kyr) is quite simple and correlates well with the forcing. During stage 11, forcing is small and the climatic response is large. During stage 7 the maxima of forcing, temperature, and minima of ice volume are not simultaneous. At the first precessional cycle (stage 7.5) the temperatures are maximum in the Southern Hemisphere, as well as in many other places. The second precessional cycle (stage 7.3) corresponds to the strongest seasonal forcing. In this isotopic record the minimum ice volume appears to happen at the last precessional cycle (stage 7.1).

massive iceberg discharges were also discovered [*Heinrich*, 1988; *Bond et al.*, 1992]. These Heinrich events are observed between 40°N and 55°N, from the Labrador Sea to the margins of Portugal. A correlation with Dansgaard-Oeschger events was established [*Bond et al.*, 1993], with each Heinrich event associated with the coldest phase of a group of several Dansgaard-Oeschger events (Figure 11). This millennial-scale variability has now been found in many different locations and is clearly a global-scale phenomenon. The most impressive feature of these changes is the abruptness of the associated climate changes above Greenland. Indeed, the transition from cold to warm occurs within only a few decades [*Dansgaard et al.*, 1989], while the associated

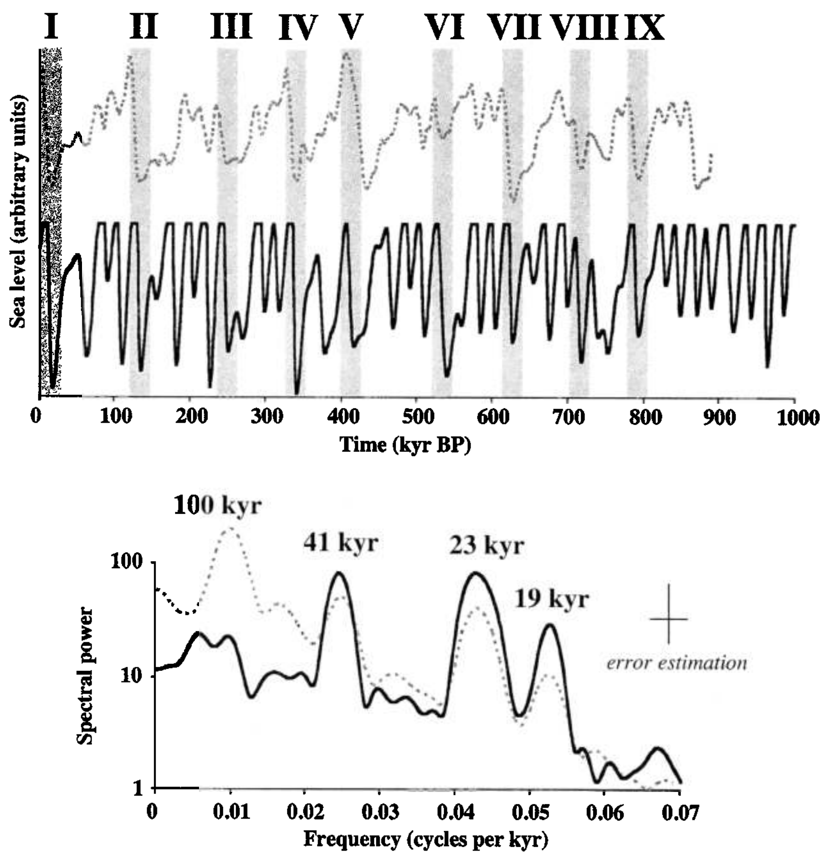

Figure 9. Results from the *Calder* [1974] model. The threshold i_0 is equal to 502 W m^{-2}, and the ratio k_A/k_M is chosen equal to 0.22. The forcing i is the summer solstice insolation at 65°N [*Laskar*, 1990]. The result is very sensitive to these choices. The agreement with the record is quite poor, but this crude model still predicts the major transitions at the right time, a feature that many, more sophisticated models do not reproduce well. An isotopic record is given here for comparison [*Bassinot et al.*, 1994b].

amplitude is about half a full glacial-interglacial change [*Severinghaus et al.*, 1998; *Jouzel*, 1999]. Similar records clearly demonstrate this abruptness in Europe [*von Grafenstein et al.*, 1999] and in the tropical Atlantic [*Hughen et al.*, 1996].

Most of the temperature change associated with the last deglaciation in Greenland is just but one among these Dansgaard-Oeschger abrupt warming events. Such rapid changes are observed at each glacial-interglacial transition in the methane record from Vostok [*Petit et al.*, 1999]. This highlights the close connection between sub-Milankovitch variability and glacial-interglacial cycles. Similarly, deep-ocean chemistry in the North Atlantic also appears to change abruptly, in association with both the last glacial inception [*Adkins et al.*, 1997] and the last deglaciation [*Adkins et al.*, 1998]. All these observations reveal one of the weak points in classical Milankovitch theory. Temperature, and more generally the whole ocean-atmosphere system, can change, and did change, much faster than did the global ice volume. Actually, the slow changes in the insolation forcing and the huge inertia of the ice sheets at glacial times do not imply slow climatic change, even in the context of astronomical theory.

Heinrich events are catastrophic releases of icebergs in the North Atlantic from the Laurentide and Fennoscandian ice sheets. How large their effect is on global ice volume and sea level is still a matter of debate, but the possibility that it may be significant does exist. Similarly, the abruptness of the Dansgaard-Oeschger events may affect considerably the mass balance of the large Northern Hemisphere ice sheets. In both cases, these are clues that the ice sheets themselves may be quite reactive in the climate system. The Antarctic Ice Sheet seems also much more unstable in glacial time than previously suspected [*Kanfoush et al.*, 2000]. A clear possibility is that the traditional SPECMAP curve in Figure 6 is only a smoothed version of what happened in reality to sea level. The fact that high sea level stands recorded by coral reefs are systematically above the estimations from isotopic records during glacial times [*Chappell and Shackleton*, 1986; *Balbon*, 2000] may also be an indication of a greater frequency of sea level changes. We still have no estimation of the rapidity and amplitude of such eventual rapid sea level variations. Still, to some extent, the possibility for rather abrupt changes exists not only for the ocean-atmosphere system, but also for the ice sheets themselves.

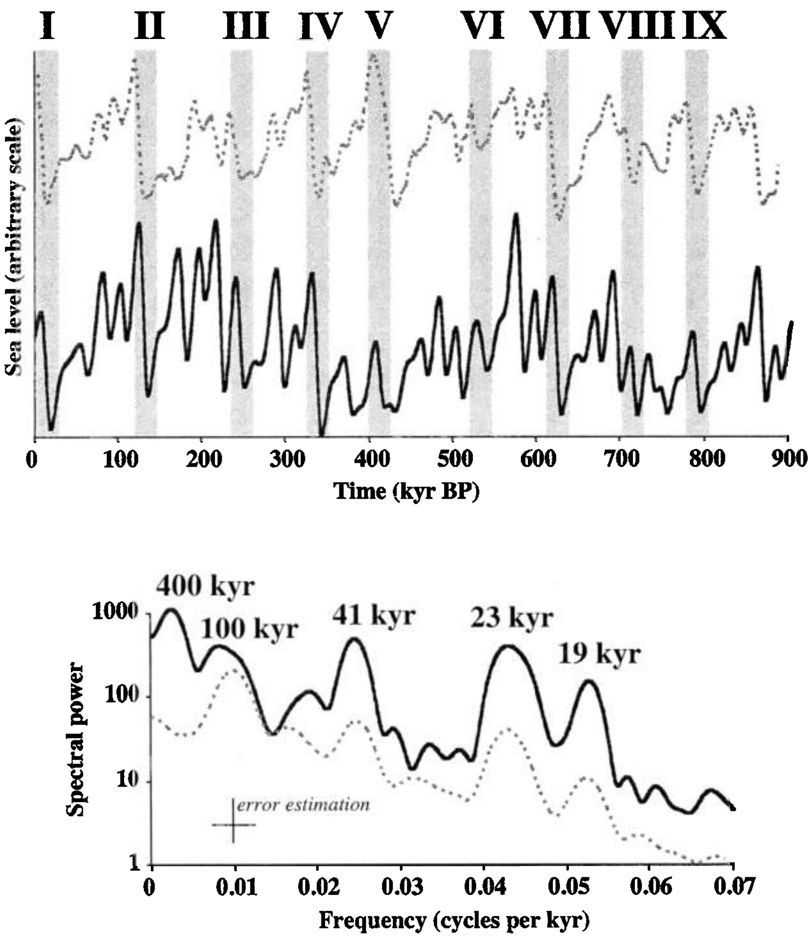

Figure 10. Same as Figure 9, but for the Imbrie model [*Imbrie and Imbrie*, 1980]. The forcing *i* is the summer solstice insolation at 65°N. The time constants are τ_M = 42 kyr and τ_A = 10 kyr.

3.2. "Decoupling" Ice Sheet and Temperature Changes

Beyond the abruptness of the recorded past environmental changes, the diversity among the different paleoenvironmental records can also provide important clues. As illustrated in Figure 8, the most obvious feature of such a multiproxy comparison is the similarity between the different records. A much more interesting issue is the differences between them. As was already mentioned in section 2.3, stage 11 and stage 7 are two examples where insolation and ice volume do not behave in parallel, and during stage 7, ice volume and temperature also seem to have different extrema. These differences emphasize the importance of looking at climate as a multidimensional dynamical system. In particular, temperature is not linked simply to ice volume. Temperature may change independently and abruptly, with leads or lags and with amplitudes that do not necessarily parallel ice volume changes. In particular, there is a need to clearly define "glacial maxima" or "interglacial" as extrema either in the global ice volume, or in temperature, but not both at the same time, which is, unfortunately, common practice. For example, the Last Glacial Maximum (LGM), defined as the maximum volume of continental ice (maximum in benthic foraminifera $\delta^{18}O$), occurs at ~21 ka B.P. between two much colder events, Heinrich event 1 (17 ka B.P.) and Heinrich event 2 (23 ka B.P.). The LGM therefore does not correspond to the coldest conditions in the North Atlantic, and the minimal sea surface temperatures estimated by *Climate: Long-Range Investigation, Mapping, and Prediction* (*CLIMAP*) *Project Members* [1981] are often too cold to represent LGM conditions [*Sarnthein et al.*, 1995]. Similarly, it is misleading to call "deglaciation" the slow or abrupt warmings observed in the records in association with glacial-interglacial cycles. They may indeed not be exactly synchronous with the melting of continental ice.

In Figure 8 it is clear that the terminations are systematically associated with increases in temperature, at least in the Southern Hemisphere, and also with increases in the atmospheric CO_2. On the contrary, as illustrated by stage 7, temperature maxima are not always associated with minimal ice volume, or with maximal Northern Hemisphere insolation. In other words, if the highest temperatures are inducing deglaciations, the ultimate cause for these temperature maxima probably cannot be found easily in the seasonal insolation forcing. A careful inspection of these curves in Figure 8 gives a

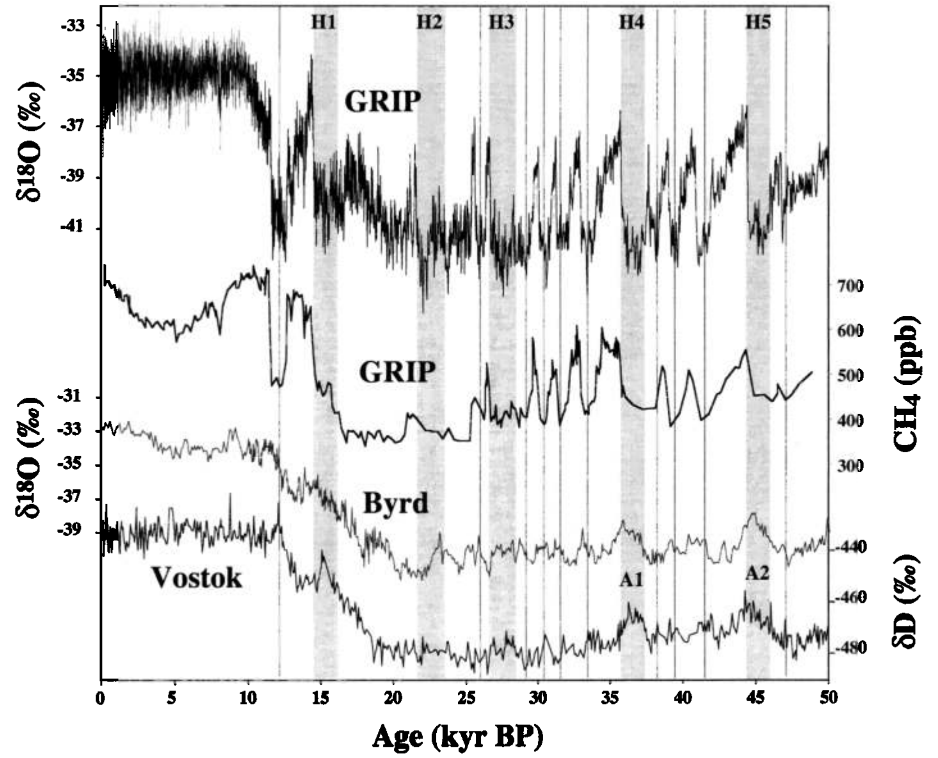

Figure 11. Climatic variability during glacial times from the Greenland and Antarctic ice cores. The precise correlation between these cores was possible through methane measurements [*Blunier et al.*, 1998]. The full thermal amplitude between glacial and interglacial time is ~20°C in Greenland (Greenland Ice Core Project (GRIP)) and ~10°C in Antarctica (Byrd and Vostok). In Greenland, about half of this amplitude occurs abruptly at ~14 ka B.P. The methane record is strongly correlated to the isotopic record, which reflects temperature changes. The Heinrich events (shaded bars labeled H1 to H5) correspond to the coldest episodes at GRIP and the warmest episodes in Antarctica.

crucial clue: The terminations are not associated with the largest maxima in summer insolation but always follow the smallest maxima in summer insolation [*Raymo*, 1997; *Paillard*, 1998]. In other words, the smallest insolation maxima are favoring a major glaciation, which will then induce a rapid deglaciation, or termination, at the next insolation maximum, independent of the insolation magnitude. This is precisely the idea that I followed when building a conceptual threshold model for the glacial-interglacial cycles [*Paillard*, 1998].

3.3. Thresholds as an Integrating Concept

On the basis of the evidence of abrupt climatic changes and on the apparent "decoupling," at least for some episodes, of ice sheet and temperature variations, it is natural to elaborate a conceptual model able to switch abruptly between different climatic states, in relation to both astronomical forcing and ice sheet evolution. The *Paillard* [1998] model assumes that climate has three different modes, or regimes, called *i* (interglacial), *g* (mild glacial), and *G* (full glacial). These climatic regimes have a (discrete) dynamics coupled to, but not strictly tied to, the slower evolution of the continental ice volume. In other words, climate is controlling ice sheet evolution, more than the opposite. The rules used to switch from one mode to the other are illustrated in Figure 12. The $i \rightarrow g$ transition occurs when a threshold i_0 is crossed on the insolation forcing. The $g \rightarrow G$ transition occurs when a threshold v_{MAX} is crossed on

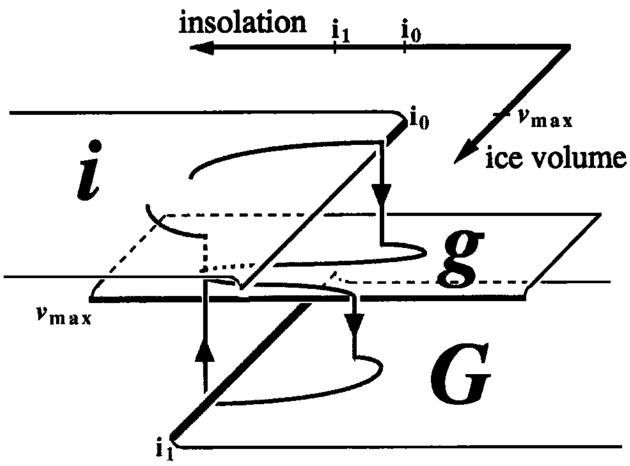

Figure 12. The threshold model. Climate is assumed to have three different regimes: *i* (interglacial), *g* (mild glacial), and *G* (full glacial). Transition between the regimes occurs when the insolation forcing crosses a given threshold i_0 or i_1, or when the ice volume exceeds the value v_{MAX}.

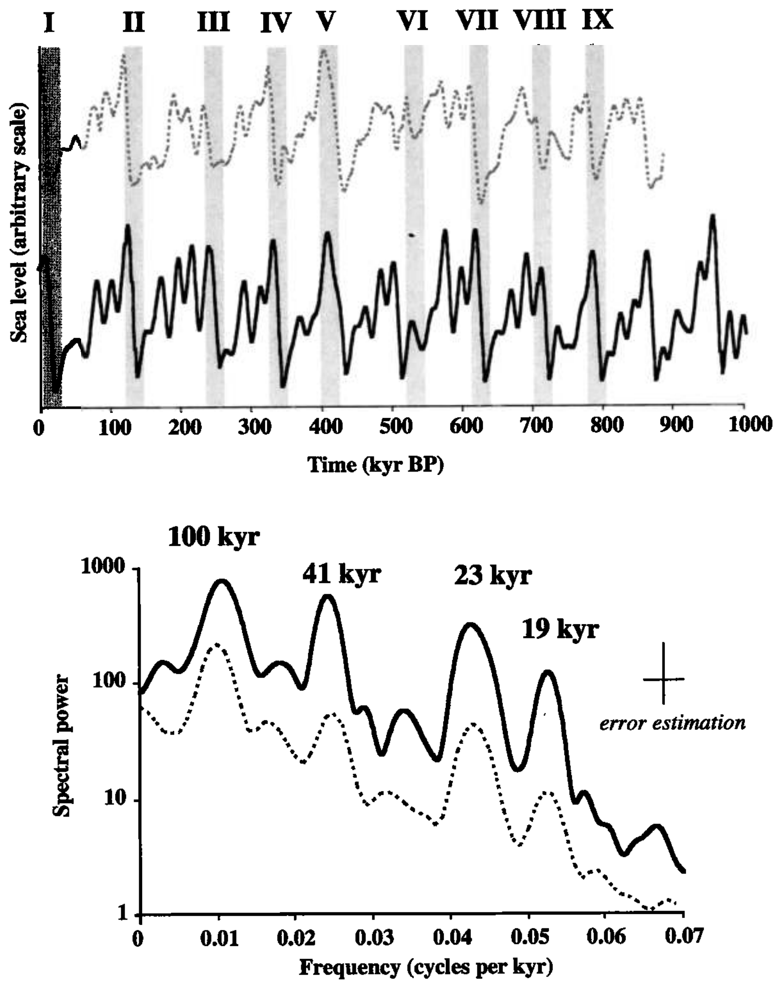

Figure 13. Same as Figure 9, but for *Paillard*'s [1998] model. Threshold values are $i_0 = -0.75$ and $i_1 = 0$. Time constants are $\tau_i = 10$ kyr, $\tau_G = \tau_g = 50$ kyr, and $\tau_F = 25$ kyr.

the ice volume. The $G \rightarrow i$ transition occurs when a threshold i_1 is crossed on the insolation forcing. For each mode the ice volume equation is linear:

$$\frac{dV}{dt} = -\frac{(V_R - V)}{\tau_R} - \frac{F}{\tau_F},$$

where R is the current regime, volume V is relaxed to V_R (equal to 0 if $R = i$, or equal to 1 if $R = g$ or G), F is a slight truncation of the normalized summer insolation forcing, and τ_R and τ_F are the relaxation time constants. This model is robust with respect to changes in parameter values. The results (Figure 13) compare well with the paleoclimatic record. In contrast to other simple models, ice volume is decoupled from temperature, idealized here as only three climatic states. In particular, the warmest episodes (i regimes) correspond to abrupt terminations and should be compared with the warm and high CO_2 episodes recorded in the Antarctic Vostok record (Figure 8). In particular, all terminations are predicted at about the right time, up to precessional phasing uncertainty. At this point we understand why Calder's model (Figure 9) had such success in its timing of terminations. Calder's model was good at predicting the glacial extremes associated with small insolation maxima. Just like Paillard's model, Calder's model was also based on an insolation threshold mechanism that requires that beyond a given value of the external forcing, the climate system behaves differently. This idea, though very crude in these conceptual models, appears to be crucial in the dynamics of glacial-interglacial cycles.

In addition to thresholds the Paillard model is also based on multiple equilibria and hysteresis phenomena. In other words, once the threshold has been crossed, the forcing needs to change substantially, and therefore the Earth's system needs a substantial amount of time in order to come back to the original state. This irreversibility can be found in many components of the climate system, like the ocean thermohaline circulation [*Rahmstorf*, 1995], or more simply, in the ice sheet albedo feedbacks [*Crowley and North*, 1991].

To illustrate how this threshold concept affects the timing and shape of the next glacial cycle, the three simple models presented here [*Calder*, 1974; *Imbrie and Imbrie*, 1980; *Paillard*, 1998] are integrated for the next

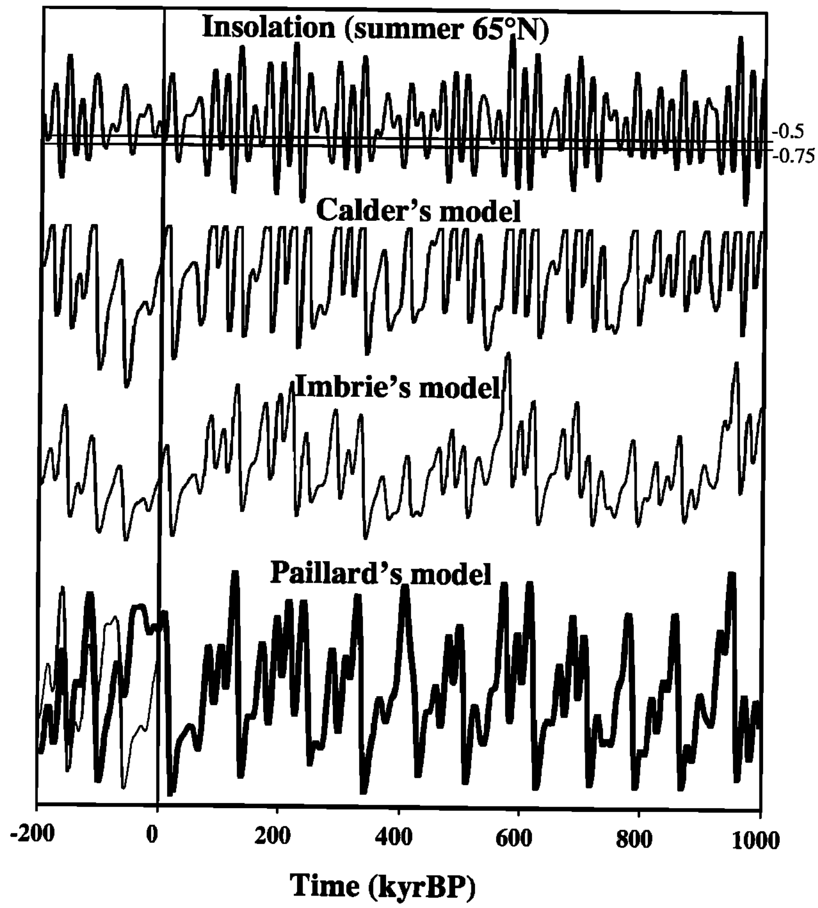

Figure 14. Model extrapolations for the future. The top curve is the forcing, the summer insolation at 65°N [*Berger*, 1978]. The three lower curves compare the Calder, Imbrie, and Paillard models over the last million years and the next 200 kyr. The bold curve in the Paillard model corresponds to the original threshold $i_0 = -0.75$, while the thin curve corresponds to $i_0 = -0.5$. These thresholds are also indicated on the insolation curve. Both i_0 values give undistinguishable results for the last million years, but very different results for the next cycle.

200 kyr (Figure 14). Similar to stage 11, the seasonal insolation forcing will be very weak for the next cycle, since the eccentricity will be even lower than it was 400 kyr ago and will remain low for a much longer period of time. Both the Calder and Imbrie models have difficulties reproducing stage 11, and their predictions for the next cycle are probably suspect. Paillard's model, when extrapolated, produces an exceptionally long interglacial lasting 50 kyr in the future. This conclusion has also been reached recently with the LLN-2D model [*Loutre and Berger*, 2000] and corresponds also to the observed longer duration for stage 11. This clearly contradicts the usual claim that astronomical forcing will shortly bring our planet into a glacial stage and that anthropogenic greenhouse gases will only counterbalance, or soften, this unpleasant fate. If Paillard's model is correct, the long interglacial of the next 50 kyr will be heightened significantly by greenhouse gases, and no glacial softening of global warming is likely because the next glacial stage will probably not be a "standard" one.

However, if we choose a value for the model i_0 threshold between -0.09 and -0.63 standard deviation units (instead of a value between -0.64 and -0.97), we obtain a completely different result. Since the present-day insolation minimum is ~ -0.633 standard deviation units, the current interglacial is switched off and consequently becomes much shorter, just like in the other two models. With $i_0 = -0.5$ we have already been in the glacial g regime for more than 1 kyr, with colder temperatures and ice sheets growing significantly, which probably does not correspond to reality (for still higher i_0 values, above -0.09, stage 11 also becomes shorter, one precession cycle instead of two, but then terminations III and IV are misplaced, which invalidates this parameter setting). However, the most impressive feature of these two results is that they are almost indistinguishable over the last million years but are entirely different for the next two climatic cycles. This clearly highlights the eventual difficulty of prediction in a threshold-based system. The thresholds in this conceptual model are representing, in the crudest way, the strong nonlinearities of the global Earth system, including the ocean-atmosphere, the cryosphere, the biosphere, and the lithosphere. We urgently need a better physical understanding of this fully coupled system in order to assess the reality of such thresholds. Some clues toward this understanding may be in the Southern Hemisphere.

3.4. A Critical Role for the Southern Hemisphere

Since most of the additional continental ice during glacial times is located in the Northern Hemisphere over Canada and Fennoscandinavia, little attention has been paid to what may eventually happen in the Southern Hemisphere. This certainly needs to be corrected in a revision of astronomical theory. In accordance with Milankovitch's ideas, ice volume changes are lagging the Northern Hemisphere summer insolation variations by several thousands of years. However, the Southern Ocean temperature records [*CLIMAP Project Members*, 1984; *Howard and Prell*, 1984; *Pichon et al.*, 1992; *Imbrie et al.*, 1992] as well as the Vostok isotopic record for the penultimate deglaciation (termination II) [*Sowers et al.*, 1993] clearly indicate that warming occurred there several thousands of years before the ice volume started to shrink, approximately in phase with Northern Hemisphere summer insolation changes [*Broecker and Henderson*, 1998]. Why should the deglaciation start in the Southern Hemisphere, in phase with Northern Hemisphere seasonal insolation changes? This is probably the wrong question to ask, though. As was illustrated previously in the threshold model, there is no conceptual difficulty to a general warm i regime before and during the melting of the ice sheets, a regime which might more properly be called "deglacial" instead of "interglacial." A central issue is to understand how global this warm period was. It is indeed extremely difficult to establish the leads and lags, i.e., the relative chronology of events, in remote parts of the Earth. However, we might speculate that the high albedo of the large Northern Hemisphere ice sheets will certainly keep high northern latitudes cold for an extended period of time. At the beginning, a global warming will be more evident far from these ice sheets. Then, when they start to melt substantially, the lower albedo will permit even higher temperatures.

The ice core results provide some important information in this respect. The Greenland and Antarctic records can be precisely correlated using the methane concentration measured in air bubbles preserved in the ice [*Blunier et al.*, 1998]. The atmospheric methane concentration is a global parameter, and its variations are very rapid. In fact, these variations are strongly correlated with the temperature changes observed in Greenland (Figure 11), with abrupt CH_4 increases lagging those of temperature by only 20–30 years [*Severinghaus et al.*, 1998]. As a crude approximation, we may therefore use the methane concentration in the Antarctic ice cores as a proxy for the high northern latitude temperatures. We thus obtain, in the same core, the possibility of a direct interhemispheric comparison over four climatic cycles. The results for the last four terminations are plotted in Figure 15. The Last Glacial Maximum in Greenland was about $-20°C$ below present-day values [*Cuffey et al.*, 1995], while in Antarctica it was only about $-10°C$ below present day. Accordingly, in Figure 15, in order to compare the amplitude and phase of temperature changes at both poles, the methane record at Vostok has been scaled so that its amplitude is about twice that of the local temperature changes. We can easily notice that for each transition, both records have very similar warming trends, in both amplitude and phase, just before the abrupt methane transition. This clearly suggests that a general warming occurs simultaneously at both poles, up to a given threshold value, beyond which the Northern Hemisphere is abruptly additionally warmed and ice sheets rapidly melt.

Simultaneous warming does not easily fit into traditional Milankovitch theory. In fact, seasonal insolation changes usually invoked to explain glacial-interglacial cycles are antisymmetric with respect to hemispheres. This is clearly not seen in Figure 15. We need to look at another forcing mechanism. A natural candidate is the mean annual insolation forcing. As is shown in Figure 4, the mean annual insolation depends only on obliquity and varies with a 41-kyr periodicity. The ocean heat capacity is large, and ocean currents will transport heat on timescales of a few decades. Therefore the ocean can integrate the radiative forcing over several years. The summer insolation forcing may be crucial for the ice sheet mass balance, but if we want to understand only the mean temperature changes, it is much more natural to look first at the annual mean insolation forcing. What the temperature changes would be in the absence of ice sheet changes is not a purely academic problem. Indeed, during interglacials, it is possible to define periods of minimal and nearly constant ice volume and then to look at the temperature trends at different latitudes. Such a study was performed for the last interglacial (stage 5.5) in the North Atlantic sector [*Cortijo et al.*, 1999]. Marine cores located north of ~50°N show decreasing temperature trends, while cores located south of 40°N show increasing temperature trends. These results are fully consistent with an annual insolation forcing mechanism (see Figure 4). Usually, paleoclimatic time series have both a 23-kyr and a 41-kyr cyclicity, but the deuterium excess at Vostok is almost exclusively dominated by a 41-kyr periodicity [*Vimeux et al.*, 1999]. These data strongly argue that the role of the annual mean insolation forcing may have been overlooked in the traditional formulation of the Milankovitch theory. Another strong argument in favor of such an obliquity mechanism is the spectrum of the paleoclimatic records before the late Pleistocene transition. Indeed, before ~0.9 Ma the climatic variations occurred mainly with a 41-kyr cyclicity, not the 23-kyr cyclicity suggested by the classical theory [*Ruddiman et al.*, 1986]. This is clearly a further indica-

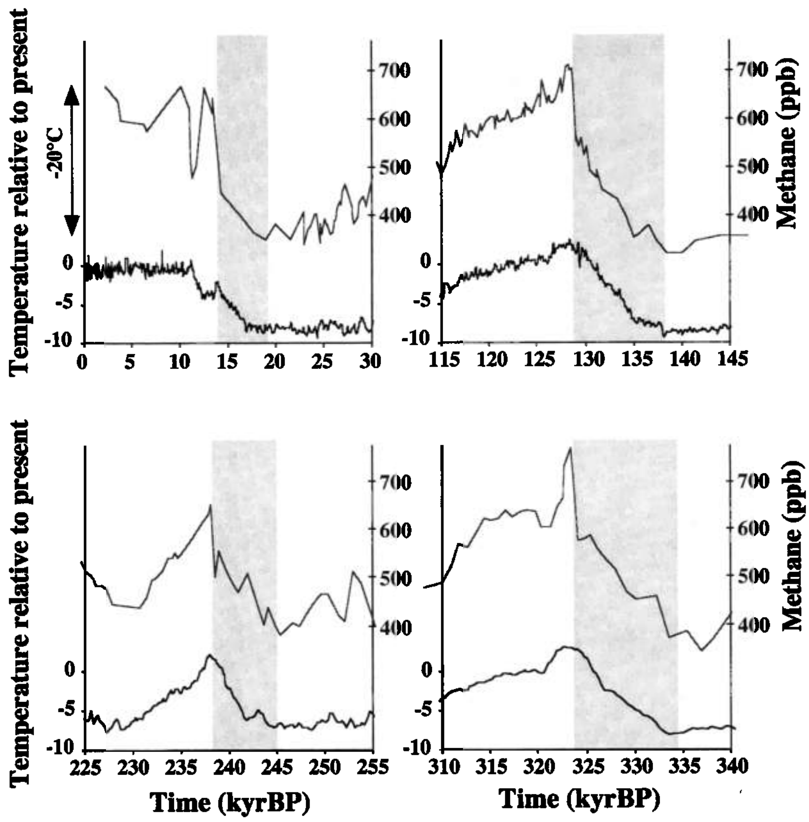

Figure 15. Comparison of CH_4 and δD records at Vostok for the last four terminations. Methane is interpreted here as a Northern Hemisphere temperature proxy and is scaled with a total glacial-interglacial amplitude of ~20°C (see Figure 11). Warming trends before the abrupt methane increases are very similar in both hemispheres, in both amplitude and phase.

tion that the mean annual insolation may have a critical role.

This symmetric warming at both poles may induce a substantial global climatic effect. Indeed, the strong similarity between the Vostok temperature and CO_2 records suggests that the Earth's atmospheric CO_2 may be controlled in large part by the climate of the Southern Ocean [*Petit et al.*, 1999]. This idea has been used recently with some success in simplified geochemical box models of the carbon cycle [*Toggweiler*, 1999; *Stephens and Keeling*, 2000], though it is not clear yet if the link between Southern Ocean climate and CO_2 is physical (through sea ice extent [*Stephens and Keeling*, 2000] or ocean circulation and mixing [*Toggweiler*, 1999]) or if this link is biological (through atmospheric dust flux and ocean productivity [*Martin*, 1990; *Broecker and Henderson*, 1998]). If this link between Southern Ocean climate and CO_2 is real, it is then possible to transform a Southern Ocean temperature increase into a global temperature increase, simply by the outgassing of oceanic CO_2 into the atmosphere. This would certainly be a very efficient way to bring the Earth climate into a rapid deglaciation.

The deglaciations happened with about a 41-kyr periodicity up to the late Pleistocene, and the above scenario, based on symmetric polar insolation forcing, may account rather well for this observation. However, for the last ~0.9 Myr the main periodicity comes close to 100 kyr. As was illustrated by *Paillard* [1998], this can be easily accounted for if we assume that climate system dynamics is based on thresholds and that these thresholds depend, for example, on the slow million-year-scale trend in CO_2 induced by tectonic changes. As was already mentioned above, a crucial observation for understanding the timing of the ice age cycles is that a major termination always follows a full glacial stage. The recent work on sub-Milankovitch variability has demonstrated that during glacial times, the huge iceberg discharges known as Heinrich events in the North Atlantic had a significant effect on the ocean thermohaline circulation. The North Atlantic Deep Water formation is very sensitive to freshwater fluxes and can rather easily be switched off. Using temperature and salinity reconstructions for a particular Heinrich event, it was possible to show that the surface hydrology of the North Atlantic implies a nearly complete stop of this meridional ocean overturning [*Paillard and Cortijo*, 1999]. The Atlantic Ocean contributes significantly to the interhemispheric energy transport, which is currently in favor of the Northern Hemisphere. Such a switch in the Atlantic can eventually reverse this situation and induce a warming in the Southern Ocean, which corresponds quite well with the recent observations, as can be seen in Figure 11 [*Blunier et al.*, 1998]. This mechanism has often been described as a bipolar seesaw [*Broecker*, 1998]. It is then conceivable that during full glacial times, Heinrich events, as well as the associated Southern Ocean warmings, will be more pronounced. There is thus the possibility that a severe glaciation in the Northern Hemisphere will help induce an extra Southern Ocean warming. If this warming occurs in phase with the astronomical obliquity forcing, it may lead to sufficient outgassing of CO_2 and induce a significant global planetary warming. Such a global warming would lead to a rapid deglaciation.

3.5. Discussion and Perspectives

In order to evaluate the scenario outlined above, much work remains to be done, both on paleoclimatic data and on models. Some critical information on the relative timing of events could further be obtained from the gas analysis of ice core records, but we also need a more geographically complete picture of the dynamics of the world climate during glacial cycles, and therefore a precise relative chronology of events for marine and continental records. The classical stratigraphic tool used in marine sediments is the $\delta^{18}O$ isotopic record from foraminifera. Planktic records are largely influenced by local temperature and salinity changes. It is therefore quite dangerous to use such surface records as proxies for global ice volume. Unfortunately, "reference"-stacked records are often based on planktic foraminifera [*Imbrie et al.*, 1984; *Bassinot et al.*, 1994b], and it is still quite common practice to directly associate transitions in these surface water records with the terminations [e.g., *Henderson and Slowey*, 2000], an association that is only valid within a few thousand years. In order to understand the dynamics of climate, we need a much better temporal framework. Though often technically more difficult, it would be more appropriate, for stratigraphic purposes, to use only benthic records, since they reflect more closely the changes in global ice volume. Unfortunately, there is no consensus on a reference-stacked isotopic record, based only on benthic foraminifera, for the entire late Pleistocene.

These benthic isotopic signals also record (though to a smaller extent than planktic ones) significant local temperature and salinity effects and may have different amplitudes and phasing in different parts of the world. Understanding how these differences relate to deep-ocean temperature and salinity basin-scale changes would be of critical interest, both for stratigraphic purposes and for ocean dynamical purposes. A multiproxy approach, using $\delta^{18}O$ pore water measurements [*Schrag et al.*, 1996], fossil coral reef data [*Chappell and Shackleton*, 1986] and other techniques [*Rohling et al.*, 1998], is highly desirable for obtaining a detailed understanding of the local and global deep-ocean oxygen isotopic composition and its relationship to sea level and global ice volume. For example, a precise assessment of the size of continental ice during stage 7.5 would be quite interesting. Indeed, during the last cycle the interglacial episodes (stages 1 and 5.5) are characterized by warmer deep-ocean waters [*Labeyrie et al.*, 1987]. This temperature signal adds up to the global isotopic seawater signal to produce very light values for the isotopic composition of benthic foraminifera. If stage 7.5 were similarly globally warm, the isotopic composition of benthic foraminifera would give an underestimation of global ice volume, which could then be larger than is suggested in Figure 6. Some data from the Norwegian Sea suggest that ice volume during stage 7.5 was indeed unusually large for an interglacial [*Vogelsang*, 1990]. If confirmed, this would clearly validate the idea that general warmings are causing deglaciations, not the opposite. In other words, the answers to the classical problems of Milankovitch theory are probably not linked to the evolution of ice sheets but, as outlined here, are linked to the rest of the Earth's system: the ocean-atmosphere and probably the carbon cycle.

Model studies of the coupled ocean-atmosphere-ice-sheet and carbon cycle system will soon be feasible with Earth models of intermediate complexity (EMICs). The ocean-atmosphere is the "fast component" of the Earth's system, and building a reasonable ocean-atmosphere model to be used on 10^4- to 10^5-year timescales is still a challenge, but recent progress in this field has been achieved [*Ganopolski et al.*, 1998]. The coupling with ice sheet models has already been performed with such EMICs [e.g., *Berger et al.*, 1999], and some promising new subgrid-scale parameterizations have been developed [*Marshall and Clarke*, 1999]. However, we still have no satisfying, widely accepted explanation for the lower atmospheric CO_2 during glacial times. A better physical understanding and modeling of glacial-interglacial cycles is probably not possible before this problem is successfully addressed. Once this crucial step is achieved, it will be possible, hopefully in the near future, to apply standard data assimilation techniques to these Earth models and thus to find some optimal quantitative interpretation of the many different data available. A coherent picture of the dynamics at work during glacial-interglacial cycles will then emerge.

4. CONCLUSION

The classical Milankovitch theory needs to be revised to account both for the traditional peculiarities of the records, like the 100-kyr cyclicity and the stage 11 problem, and for the recent observational evidence of abrupt climatic changes, in association with the main terminations. Since the relevant dynamical timescales vary from 10 to 10^5 years, the traditional concepts based on linear, or weakly nonlinear, systems (like resonance, spectral analysis, frequency modulation, and so forth) appear probably insufficient to fully capture the dynamics of the 100-kyr cycles. As the simplest strongly nonlinear system, the concept of climatic thresholds appears to be quite natural and fruitful in this context. Among the important clues to solve this mystery, the Vostok record, which now covers four climatic cycles, provides important information on such global parameters as the atmospheric concentration of carbon dioxide and methane. We now start to have some idea of the phase relationships between the Northern and Southern Hemispheres, as well as some idea of the sequence of events surrounding the terminations [e.g., *Broecker and Henderson*, 1998]. Atmospheric CO_2 had no role whatsoever in the original, classical, astronomical theory, but it now appears as a central issue for the understanding of glacial-interglacial cycles [*Shackleton*, 2000]. These cycles represent the largest recent global changes in our environment, with a thermal amplitude of several degrees in global mean, which is about the magnitude of the climatic projections for the next century, according to an Intergovernmental Panel on Climate Change (IPCC) report [*Houghton et al.*, 1995]. The recent paleoclimatic data tell us that such major climatic changes have been abrupt in the past and that hysteresis phenomena are probably necessary to account for the observations. In other words, if classical astronomical theory described glacial-interglacial cycles as a slow continuous, "reversible" or "diabatic" process, then current evidence strongly argues that it is a rapid, discontinuous, "irreversible" or "adiabatic" process. This paradigm shift has obvious implications for the assessment of the Earth's evolution in the context of current anthropogenic global warming.

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