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MILANKOVITCH THEORY – HITS AND MISSES

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Abstract

Milankovitch Theory has become an important tool in geologic practice and thought, and is sufficiently conspicuous to provide a rewarding target for criticism. The chief problem arising has to do with the prominence of a cycle near 100,000 years, whose origin is not clear. Most practitioners, presumably, would accept a close relationship of that cycle to precession of the equinoxes (that is, cyclic changes in seasonality), along with dynamical properties of the system that enhance the amplitude of the 100-kyr cycle at the expense of others. In any case, Milankovitch Theory has proved useful, both for age assignments and for stimulating thought about relationships between climate change and sedimentation, as is readily evident from the relevant literature. It would be difficult to replace. Neither does it seem desirable to do so: the chief problem noted in regard of the theory (the 100-kyr problem) is not necessarily a part of the theory, which is concerned with change rather than with condition. The 100-kyr cycle is linked to condition. The problem raised by critics seems to be the time scale of integration of change, a problem not addressed in Milankovitch Theory. A necessity for additional processes and mechanisms not considered in Milankovitch Theory cannot be excluded.

Introduction

"Milankovitch Theory" has become part of the toolbox of ocean historians in the last several decades (Shackleton, 2006; A. Berger, 2009; Hays, 2009). In fact, the theory has achieved textbook status after many decades of discussion, and is now a tool without peer when applied to problems of dating ice-age sediments from the deep-sea floor, or when determining sedimentation rates of such sediments even well before the northern ice ages. Beyond such application, however, Milankovitch Theory has profound implications for all of climatology and the Earth sciences in general. As a revolutionary force in natural philosophy, it emphasizes external factors in the determination of geologic processes on the surface of the planet. Thus, it is certainly worthy of the intense discussion and examination it has received. In a recent book entitled "Ice Ages and Astronomical Causes," Muller and MacDonald (experts in astrophysics and geophysics, respectively) have raised serious objections to the Theory, based mainly on arguments using time-series analyses (Muller and MacDonald, 2000). Here I attempt to explain why Milankovitch Theory is useful and here to stay, albeit with room for additions and improvement.

In consequence of the fundamental importance of the Theory for the practice of climate and ocean history, and for the history of science in general, Milutin Milankovitch (1879-1958), Serbian engineer and mathematician, is now recognized by many scientists as one of the great pioneers of the 20th century whose insights deeply changed geologic thinking, along with those of the German meteorologist Alfred Lothar Wegener (1880-1930) and those of the American physicist Luis Alvarez (1911-1988).

As will be recalled, Wegener (1929) proposed Continental Drift (now a corollary of Plate Tectonics, the basis of modern geology) and Alvarez and co-workers (1980) proposed the impact of a bolide from space to explain the extinction of the dinosaurs at the end of the Cretaceous, which changed all discussion about evolution in Earth history. As is true for Milankovitch's proposition (1930, 1941), these theories identified external forcing (from Earth's mantle and outer space, respectively) as major factors in the history of the Earth's surface and the living organisms thereon. As a result of these developments in the geosciences, Earth's tectonic and fluid systems dominating observable processes on Earth's surface are increasingly seen in terms of response to outside forcing.

Milankovitch recognized that external forcing controls much of the multi-millennial climate fluctuations of the late Quaternary; that is, he saw the ice ages as manifestations of responses of the Earth's climate system to astronomical factors governing the characteristics of Earth's orbit and the tilt of its axis. According to Milankovitch, translation into climate change of these perfectly cyclic phenomena is through variations in solar irradiation of high latitudes on the northern hemisphere, in summer. This insight regarding the mechanism of translation was of major significance and still reverberates through paleoclimatology and paleoceanography (that is, through climate and ocean history).

As in the case of Wegener's hypothesis, it took many decades for Milankovitch's ideas to prevail. The delay, in large part, was a consequence of the fact that the materials and tools that allowed a testing of his hypothesis were not available at the time he published his work. The crucial observations that support Milankovitch Theory are linked to cyclic deposition of different types of sediments and fossils on the deep-sea floor, as documented in long cores of the type first raised by the Swedish Albatross Expedition (Pettersson, 1953; Olausson, 1996). Milankovitch's concepts were ready for testing when such cores became available, after WW II, beginning with the studies of Arrhenius (1952) and of Emiliani (1955), and continued at Lamont Geological Observatory and other partners in the CLIMAP project (see articles in Cline and Hays, 1976). Again, the parallels to the development of Wegener's notions are striking: Wegener's ideas also became textbook matter through the rise of post-war oceanography, with paleomagnetism occupying a central position. Paleomagnetism proved crucial in the success of Milankovitch Theory, as it is strictly linked to the sequence of cycles and thus implies precise dating both in the Quaternary (e.g., Johnson, 1982; Shackleton et al., 1990; Tauxe et al., 1992; Bassinot et al., 1994) and in

older sediments (e.g., Hilgen, 1991, 1994; Shackleton et al., 1995, 2000), even back into Triassic time (Kent and Olsen, 1999; Olsen and Kent, 1999).

Concepts linking the ice ages to astronomy have deep roots: they go back well into the 19th century, having been expounded, in principle, by the British geologists James Croll and James Geikie, for example. Croll's treatment of astronomic forcing, especially, became widely known and cited thanks to an excellent exposition combined with ingenious arguments concerning meteorology (Croll, 1875). However, as was the fate of earlier attempts at invoking astronomical forcing for ice-age climate changes, Croll's views did not take hold, being dismissed by important contemporary geologists on the basis that they purported to explain things that were yet to be documented (e.g., Penck and Brűckner, 1909). The documentation required is that ice ages indeed occur in cycles. The fact was unknown as late as the start of the 20th century. Penck and Brűckner, for example, recognized four major glaciations, which they named after rivers issuing from the Alps: Gűnz, Mindel, Riss and Wűrm. Their scheme was still in use in the 1960s, in major works on climate history (e.g., Schwarzbach, 1961; see also Flint, 1957, and Ericson and Wollin, 1964).

In addition, such cycles, once discovered, must fit the precise chronology of astronomic forcing (e.g., Broecker, 1966). This second condition, which presupposes a correct time scale, emerged only toward the end of the 20th century, with considerable involvement of information from paleomagnetic work, notably the date for the Brunhes-Matuyama boundary (Shackleton and Opdyke, 1973; Hays et al., 1976; Imbrie and Imbrie, 1979). As a consequence of improvements in paleomagnetic dating, the deep-sea chronology for the Quaternary (Shackleton et al., 1990) is now quite
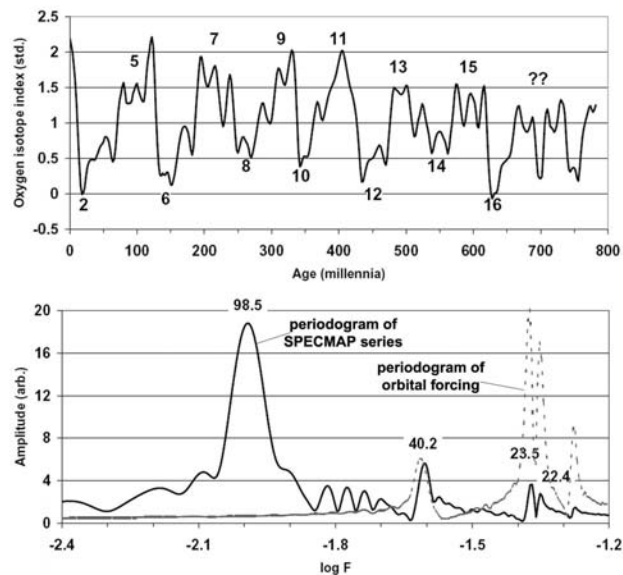

Figure 1. A modern application of Milankovitch Theory (data in Imbrie et al., 1984). Upper: plot of the SPECMAP template, with oxygen isotope values here converted to standard units (mean=1; stdev.=0.5), and labeled with Emiliani stages. Lower: Periodograms (Fourier scan of autocorrelation) of SPECMAP series (solid line) and of purported orbital forcing (insolation data, A. Berger and Loutre, 1991). The SPECMAP cycles are labeled with their periods in thousands of years (kyr); orbital values are 41.0, 23.7, 22.4, and 18.9 kyr, strikingly similar to a number of periods seen in the SPECMAP template.

reliable, and the task has become to tie regional Pleistocene Alpine stratigraphy to the deep-sea record, rather than the other way around (see, e.g., Ehlers, 1994). (The "Pleistocene" is the pre-"Holocene" part of the "Quaternary;" that is, the geologic epoch with the ice ages.)

The iconic representation of Milankovitch Theory for geologic applications is the "SPECMAP" time scale, named after a project involving a large number of scientists, and led by the American geologist and ocean historian John Imbrie. The project focused on the spectral analysis of deep-sea records in piston cores (which was soon realized as a crucial tool in Quaternary research; e.g., Pisias and Moore, 1981) and on the mapping of glacial conditions in the ocean (reviews in Bassinot, 2009, and in Hays, 2009) (see Figure 1). The time scale represented by the SPECMAP series (which is based on tuning to Milankovitch input but also owes much to the paleomagnetic fixpoint in Shackleton and Opdyke, 1973) is reliable back to 650,000 years ago (that is, Marine Isotope Stage 16 or MIS 16). It has been widely used since its publication by Imbrie et al. (1984). The fact that deep-sea cores were involved in producing the scale (the template is a stack of five isotope series) shines through in the circumstance that much of the Holocene is missing from the SPECMAP template. Presumably, surface sediments were blown away during the coring process.

As the time scale evolved, it supported Milankovitch's emphasis on summer insolation in high northern latitudes (that is, melting) in preference to ideas that focus on building ice caps. When first proposing his hypothesis, in the 1920s, Milankovitch gained the moral support of the leading climatologist of his time, Wladimir Köppen (1846-1940), who thought that making the decay of northern ice sheets central to producing ice-age climate fluctuations was a good idea. He, along with his son-in-law Alfred Wegener (the latter presumably inured to criticism by colleagues clinging to tradition), first published Milankovitch's hypothesis as Milankovitch's insolation curve along with age
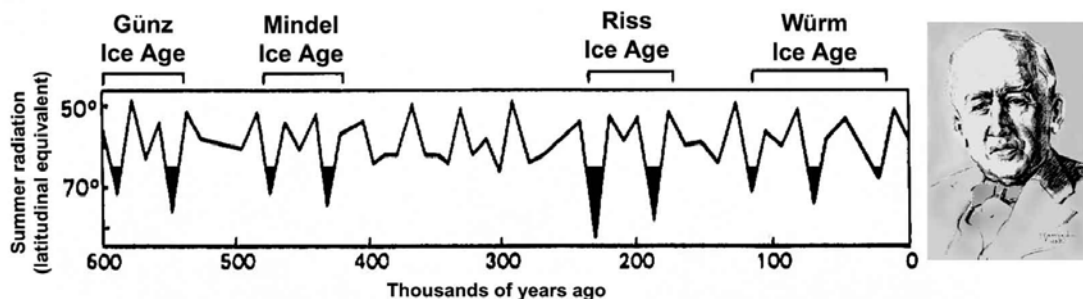

Figure 2. Milankovitch's hypothesis in Köppen and Wegener (1924), here simplified. Milankovitch (portrait to the right) used orbital calculations of the astronomer Stockwell to reconstruct the summer radiation at 65ºN, which he presented in terms of latitudinal shifts. In Köppen and Wegener's published version the graph is offered as a template for age dating of the Alpine glaciation sequence proposed by Penck and Brückner (1909). (Source of portrait: Milankovitch Symposium Belgrade 2004; shading added.)

assignments to the then current scheme of glaciations (Figure 2), of course with full credit to the author (Köppen and Wegener, 1924).

Other important early support came from the German geologists W. Soergel, B. Eberl, and F.E. Zeuner. The latter, who worked at the British Museum in London, published an important textbook on the ice ages in English (Zeuner, 1945). Nevertheless, Milankovitch's ideas remained controversial for a very long time. The time span between the first publication of Milankovitch's graph and that of the SPECMAP template is 60 years. As late as 1961, the German geologist and textbook author M. Schwarzbach, when discussing the dating of Quaternary deposits, put Milankovitch Theory in the realm of speculation and concluded (p. 230) "The [Milankovitch] insolation series are apparently *not* suitable for explaining the multiple glaciations in the Quaternary." (Transl. W.H.B.)

History, however, decided otherwise. Köppen's early positive assessment of Milankovitch's hypothesis (Köppen, 1931, p. 41ff.) proved durable. It turned out that, when explaining the ice-age fluctuations, the problem is *not* how to make ice in a warm world; instead, it is how to *get rid of the ice in an unusually cold world*. Contrary ideas on this point still surface on occasion, for example in the hypothesis of Muller and MacDonald (1997, 2000), which purports to explain the 100-kyr cycle of the ice ages by rhythmically obscuring the sun, and in the context of the onset of the ice ages, when geologists call for ice buildup from an increased supply of moisture, mindful of the fact that Siberia, with cold but dry air, does not have glaciers (discussion in W. Berger and Wefer, 1996). The effect of the shift in emphasis about what it is that needs explaining is profound. We now follow Milankovitch in paying attention to whether northern summers are warm enough to melt the snow and ice that the winters readily provide.

The one big problem that soon emerged (and which is evident in the spectrum of the SPECMAP series, Figure 1) is that the late Quaternary is dominated by a cycle approximately 100,000 years long. Milankovitch Theory has no explanation for this phenomenon (the "100-kyr problem"). The long cycle is conspicuous especially in the period studied by Milankovitch; that is, in the last 600,000 years (a fact first hinted at in the data of van Donk, 1976; and later elaborated using an improved time scale by Berger and Wefer, 1992, and by Mudelsee and Schulz, 1997). Thus (somewhat ironically) the presence of a 100-kyr cycle helps define a "Milankovitch Chron" (Figure 3), which may be taken as the last third of the Quaternary; that is, the time since the very large glaciation called "MIS 16" by ocean historians. Invoking the changing eccentricity of Earth's orbit for producing the 100-kyr cycle (Imbrie et al., 1984) seems eminently reasonable, since eccentricity governs the precession effect, which is clearly represented in many of the deep-sea records, notably in the link to deglaciation events (Broecker, 1984; W. Berger, 1997; Raymo, 1997). Doubts remain, however (Muller and MacDonald, 1997, 2000; Maslin and Ridgwell, 2005).
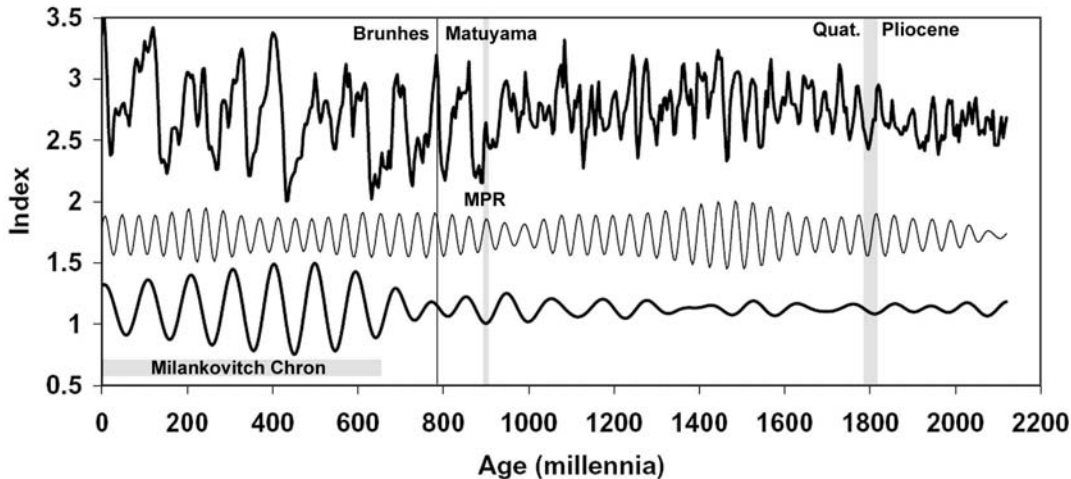
Figure 3. The isotopic record of sediments on Ontong Java Plateau (ODP Leg 130), in linear transformations of the $\delta^{18}O$ index, and the content of major cycles (near 40 kyr and near 100 kyr) as seen in the Fourier expansion. Note the position of the "Milankovitch Chron" as the last third of the ice age span ("Quat.") since Stage 16, and with the 100-kyr cycle dominant. In contrast, the 40-kyr cycle (middle of graph) spans the length of the record. Brunhes-Matuyama boundary near 790 kyr. MPR, Mid-Pleistocene (climate-) Revolution, near 920 kyr. After W. Berger and Wefer (1992), from W. Berger et al. (1994).

Milankovitch Theory and Corollaries

Milankovitch Theory has been amply and critically reviewed in recent years (e.g., Imbrie and Imbrie, 1979; A. Berger, 1988, 2009; articles in A. Berger et al., 1984; A. Berger et al., 1992; Imbrie et al., 1992, 1993; Muller and MacDonald, 2000); thus, there is no need to elaborate on the many technical aspects of the theory here. However, it is well to remember that the science of climate history itself is intimately linked to the discovery of the ice ages in the middle of the 19th century. This makes the Milankovitch revolution a crucial founding feat of climatology, one that emphasizes the central role of northern polar regions in climate change. Furthermore, it offers the additional insight that astronomical conditions in the solar system govern external geological processes linked to climate change. Likewise, such conditions govern changes in the circulation patterns and in the productivity of the sea, which makes them key elements in the reconstruction of ocean history, and in the assessment of the sensitivity of ocean dynamics to large-scale climate change.

Milankovitch, with a good deal of insight (and quite possibly influenced by contemporaries such as R. Spitaler and J.J. Murphy; see Brooks, 1949, for review of the ideas of these pioneers), focused on the changing availability of summer heat in high northern latitudes, where the conversion of insolation to

heat strongly depends on positive feedback from the response of ground albedo. Snow and ice are highly reflective of incoming sunlight, whereas dark ground and vegetation are not (for climate-relevant feedbacks see, e.g., Hansen et al., 1984). Thus, relatively small changes in ground cover are readily converted to major changes in ambient temperature and hence in the stability of ice.

Milankovitch's choice of season and latitude (summer, 65ºN), then, is readily appreciated. Likewise for the orbital forcing itself: unsurprisingly, when the disk of the sun is large more sunlight is received than when it appears small. Owing to the changing distance of Earth from the sun (the orbit being a slowly changing ellipse, with the sun in one of the focal points), and to the migration of the seasons along the orbit ("precession") the sun's disk changes in size through the seasons, on time scales of millennia. According to Milankovitch, if the disk is large in summer in high northern latitudes (that is, perihelion in northern summer), melting can occur, but if small (that is, perihelion in northern winter), ice buildup proceeds. Since the seasons migrate along the orbit, completing a cycle roughly every 21,000 years, the melting opportunity has this cyclicity (actually, several cycles are involved, all of which are near this value). In addition, the tilt of the Earth's axis changes through a range of somewhat less than three degrees on a cycle near 41,000 years (present intermediate tilt, 23º27'). The tilt ("obliquity") determines how high the sun can rise during noon, in northern summer. A higher position translates into higher insolation in high latitudes, in summer.

When verifying Milankovitch's proposition, then, we should look for a pervasive influence of precession and obliquity in the climate narrative of the ice ages. Two things are necessary to achieve the test: (1) a continuous record of climate history, and (2) one that is dated precisely, so that the lengths of the cycles (their period or frequency) can be determined with confidence. For the purpose of testing, dates have to be external to orbital arguments. Naturally, if a belief in the correctness of Milankovitch played a role in assigning ages to the record (or choosing cores worthy of analysis), the series thus derived becomes much less attractive for testing whether Milankovitch Theory holds. Likewise, if the external dates are incorrect, doubts will arise about the logical validity of such a test, whether the test has positive or negative results. In this context it is relevant that the dating of the Brunhes-Matuyama boundary (the last major reversal of the Earth's magnetic field), which proved important in assigning ages to ice-age sediments in deep-sea cores in the last third of the 20th century, only provided a reliable age point after 1990 (Izett et al., 1991; Baksi et al., 1992; Baksi, 1994). This makes age assignments before that time subject to especially critical scrutiny, whenever paleomagnetics are involved.

Because dating problems run through the history of research on sediment cycles (and remain glaringly relevant for all geological research that deal with more ancient gap-ridden sequences on land), and because relevant doubts are forcefully expressed on occasion by knowledgeable scientists whose views are

not easily dismissed, there is always room for exploring the relationships between Milankovitch Forcing (MF) and sediments in question. As far as the deep-sea record, the foremost proxy that serves for stratigraphic sequences consists of the varying content of oxygen isotopes in foraminifer shells (the proxy introduced by Emiliani, 1955). However, a great number of other proxies can serve, including grain-size, carbonate content, and physical properties in general. All can yield most interesting results with respect to the sensitivity of the sediment system to Milankovitch forcing (e.g., Mayer et al., 1993).

What might a valid test look like? One needs a continuous proxy record in an ice-age sediment sequence along with correct age assignments. An excellent continuous isotope record in a deep-sea core is provided by Bassinot et al. (1994) for the second half of the Quaternary. For Milankovitch-independent dating,
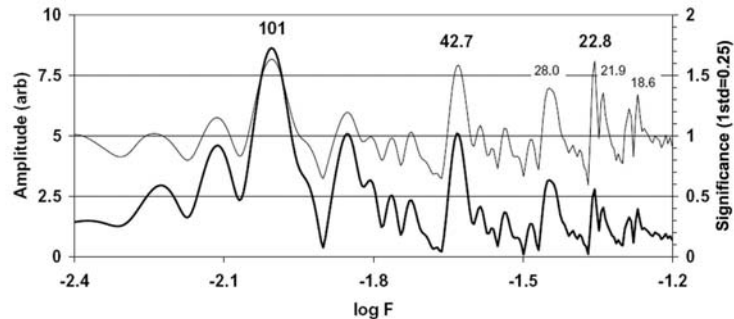

Figure 4. Periodogram of the oxygen isotope series of Bassinot et al. (1994), re-dated (see text), and confined to the last 800,000 years (heavy line). Bold labels of peaks: values (in thousands of years) rise above two standard deviations (=0.5) in a window comprising a factor of three, within the spectrum (scale on right, applied to thin line).

the use of the position of the B-M boundary is convenient. The boundary occurs after Isotope Stage 20 and before the peak of Stage 19 (Shackleton and Opdyke, 1973); it is here taken as 790 kyr in agreement with W. Berger et al. (1995). Furthermore, an assignment of 130 kyr for the termination following Stage 6 seems reasonable, based on published coral data (e.g., Bloom et al., 1974; Chen et al., 1991; Muhs, 2002, and refs. therein). For the surface sediment, I assign an age of 8 kyr, based on the observation (from inspection of the Bassinot et al. list along with personal expectations based on various box cores) that the Holocene is largely missing in the isotope series of the core under consideration (MD900963). For the purpose of down-core assignments, in consequence, I have simply added 2 kyr to the ages given by Bassinot et al. (1994) down to the depth of 1.2 m. The next control point (130 kyr) was set at 7.8 m, based on the isotopic sequence. Finally, the Brunhes-Matuyama boundary was set at 35.55 m, again based on the isotopic sequence. The average difference in age assignments to the published samples in this study as compared with those of Bassinot et al. (1994) is 14.25 kyr, and the standard deviation is 12.14 kyr.

I next interpolated the isotope data for 1-kyr steps after applying a three-point sliding boxcar to the published series, and performed the spectral analysis, using a Fourier scan (similar to traditional Fourier analysis, but with steps of 1% in the

"expansion" – now no longer reversible) of the autocorrelation (which provides for an automatic taper when weighted by overlap of the correlated series). For significance, I employ the standard deviations of peak values above the mean of a sliding window of width factor-of-three (width of 0.477 on the x-axis). A sliding window tends to remove the overall reddening within a spectrum, thus bringing out local anomalies. The method has the advantage of avoiding the need for a modeling of arbitrary series for comparison with the analyzed one, but has the disadvantage of assigning a low significance to peaks occurring next to a high and broad peak.

The spectral peaks in the oxygen isotope record (based on analysis of the planktic foraminifer species *G. ruber*) of Bassinot et al. (1994) that are discovered in this fashion are at 101 kyr, 42.7 kyr, and 22.8 kyr (bold numbers in Figure 4 are values beyond two standard deviations; that is, >1.5 on the y-scale to the right). Periods of lesser significance are marked in regular font. A period near 71 kyr is not marked. This period is discussed in some detail by Muller and McDonald (2000, p.258ff.) It is not necessarily of much interest as an independent clue to forcing, being rather close to an interference cycle (difference tone) of the 100-kyr cycle and obliquity.

The values marked with bold font are quite close to those found by Hays et al. (1976), which are listed as 100, 43, 24, and 19 (in thousands). Regarding these findings, Hays (2009) states (p. 163): "These analyses provided convincing evidence that orbital variations are responsible for the timing of major glacial-interglacial fluctuations …" While opinions on this precise point may differ, there is no question that the paper cited (and co-authored) by Hays established that Milankovitch Forcing is present in deep-sea proxy series and is consequently useful in the determination of sedimentation rates. Hays (2009) also emphasized the role of reliable dating in establishing the Milankovitch connection. Likewise, Hays stressed the match to the orbit- and rotation-related cycles found by the Belgian astronomer André Berger (values at 41.0, 23.7, 22.4, and 18.9 kyr).

Two problems arise in the context: (1) the dominant cycle within these isotopic records (the one near 100 kyr) is not present in the orbital data, except perhaps as eccentricity (whose influence depends on precession cycles and their link to terminations), (2) the obliquity cycle in the proxy records is slightly longer than is expected from astronomy (43 versus 41). The first problem presumably calls for forcing other than purely orbital (for example, for Earth-bound oscillation captured by precession, or else for alternative methods of astronomical forcing as proposed by Muller and MacDonald, 1997). The second problem would seem to yield to slight differences in the time scale adopted, for example by moving the Brunhes-Matuyama boundary to 780 kyr from 790 kyr, and the Stage 6/5 transition to 135 from 130. The first adjustment would adopt an age in agreement with Baksi et al. (1992); the second adjustment would move in a direction suggested by the dating of certain cave deposits in Nevada (Winograd et al., 1992). The 135 kyr age is also the one preferred by Muller and McDonald (2000,

p. 213), although the reason for their preference (other than a looked-for discrepancy with Milankovitch Theory) is not entirely clear. Other possible reasons for discrepancies in spectral lines between expectation and observation include disturbances from the coring process at sea, with differential compression of soft layers.

Whatever the solution to the conundrums encountered in deep-sea sediments, the oxygen isotope record of deep-sea benthic foraminifers has been celebrated as a guide to the changing volume of ice masses during the ice ages (Shackleton, 2006). Shackleton assumes that temperature fluctuations at great depth are minor, since the range is limited downward by freezing. In fact, extensive stacking of such benthic records has produced a rich treasure chest of isotope data for both the Quaternary and the earlier portions of the Cenozoic (Miller et al., 1978; Zachos et al., 2001; Lisiecki and Raymo, 2005). It seems reasonable to compare the record thus provided to what is expected from Milankovitch Theory, at least within the Milankovitch Chron.

Here I use the compilation of Zachos et al. (2001) for the purpose of investigating the effects of Milankovitch-type forcing, interpolating their data for 1-kyr steps. Comparison with the June forcing of the last 700,000 years (with data computed by A. Berger, 1977, 1978; A. Berger and M.F. Loutre, 1991) does not reveal any striking parallels between the purported forcing and the proxy-defined response (Figure 5, upper panel). However, when using the rates of change in the proxy record (obtained from numeric differences), and comparing this difference series with the same forcing (Figure 5, middle panel) interesting matches and other patterns emerge.

The differentiation, of course, suppresses the long-term fluctuations in favor of the short-term ones, which is where the forcing is located in the Milankovitch spectrum (W. Berger, 2011). Also, not surprisingly, when response is defined in terms of change, the link between forcing and response is materially strengthened over the link between forcing and the actual (integrated) record, which presumably contains many features not related to forcing. An argument could be made, in fact, that Milankovitch Theory ties *change* in the system to forcing and not the *condition* of the system (although this is not evident in Köppen's presentation of Milankovitch's theory: Köppen and Wegener, 1924, Köppen, 1931; which presumably also reflects Milankovitch's views; V. Milanković,1995, p.107; see Figure 2).

The goodness of the match between the first derivative of the proxy data and the northern high-latitude summer insolation (Figure 5, middle panel) suggests, primarily, that the core records stacked by Zachos et al. (2001) have been carefully tuned to MF, thus deriving their age assignments from orbital variations (that is, from "astrochronology"). The unusually high proxy peaks are identical with the deglaciation events labeled "terminations." Following their identification by Broecker and van Donk (1970), they have been dated in subsequent studies in accordance with Milankovitch pacing, and they are now widely recognized as vital ingredients in defining the response of the climate system to orbital forcing. Needless to say, the actual mechanisms responsible for rapid deglaciation remain somewhat obscure and hypothetical (e.g., Andrews and Barry, 1978; Pollard, 1984; and many others since, see reviews in Gornitz, 2009).
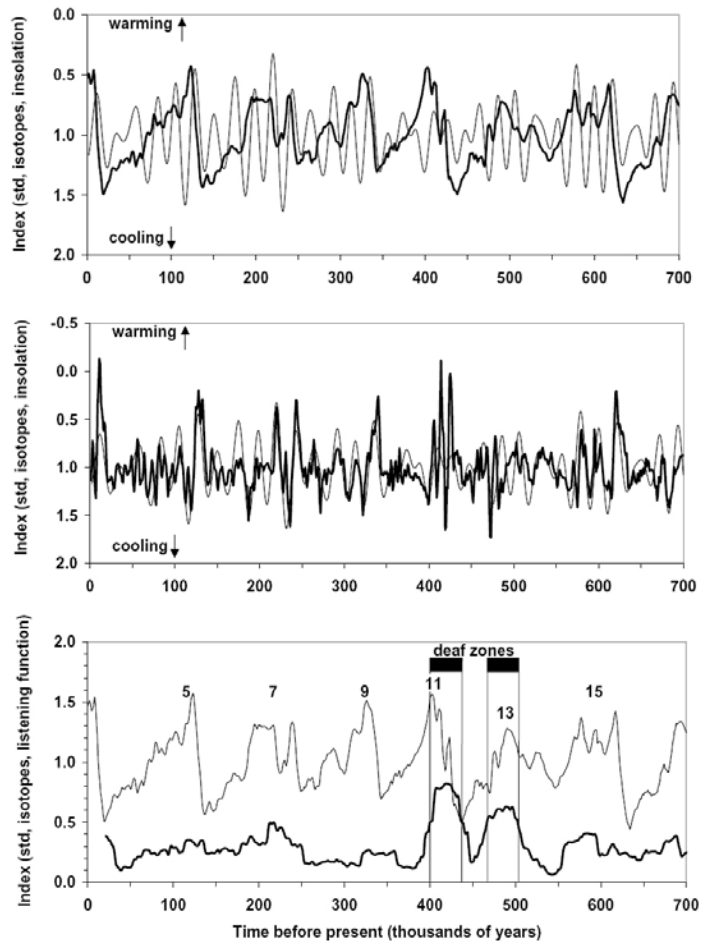

Figure 5. Oxygen isotopes of benthic deep-sea foraminifers (heavy line, data from Zachos et al., 2001) and relationships to Milankovitch Forcing (data from A. Berger, 1978, and A. Berger and M.F. Loutre, 1991). Uppermost panel: forcing (June, 65°N) compared with interpolated proxy data (all in standardized units). Middle panel: forcing (thin line) compared with derivative of proxy data. Lowermost panel: squared difference of forcing and proxy in a 40-kyr window (1 stdev. =0.5), compared with original proxy series (thin line).

When comparing the amplitudes of the forcing with that of the response, in the middle panel of Figure 5, one notices that relatively low (but increasing) response follows the major peaks in response (the terminations), with one exception (near 240 millennia ago). The pattern of increasing response between terminations suggests the action of positive feedback factors that increase with ice mass,

hence reflect growing instability of ice. It is a reminder that internal feedback processes involving the stability of ice should not be neglected when contemplating the climatic fluctuations of the ice ages (e.g., Emiliani and Geiss, 1959; Weertman, 1976; Oerlemans and van der Veen, 1984; Pollard, 1984; Saltzman et al., 1984; Birchfield and Grumbine, 1985; Ghil, 1989; Bond et al., 1992; W. Berger and Jansen, 1995; Alley, 1998; Paul and Berger, 1999; Calov et al., 2002). These are not new ideas. In principle, the same kind of caution about multiple (and historically modified) factors in the ice age story is already discussed by Alfred Russel Wallace (1823-1913), the man who caused Darwin to publish on the origin of species, in his classic volume on biogeography (Wallace, 1895).

A similar message (that there are internal feedbacks at work and that they vary through time) emerges from the data at hand when plotting the averaged squares of differences between MF and system response (input and output standardized for the length of the series) as obtained in a 40-kyr window (Figure 5, lowermost panel). In fact, there are time intervals ("deaf zones") when the system response differs materially from the forcing; that is, the system is barely listening to the varying Milankovitch-type insolation. Within the Milankovitch Chron, such deafness is concentrated between 400 and 500 kyr, with the squared difference in forcing and response exceeding one standard deviation. The apparent discrepancy in expected response in this region has been referred to as the "Stage-11 problem" on occasion. It is seen to be both less and more than that. (For reviews of Stage 11 see Droxler et al., 2003.)

The reason, presumably, that the proxy record within the deaf zones does not look fundamentally different from that before and after is that MF is not necessarily the dominant guide for climate change, but rather an external modifier of inherent oscillations (Saltzman et al., 1984; Ghil, 1989; W. Berger, 1999). The situation confirms the choice of the word "pacemaker" in the title in the article by Hays, Imbrie, and Shackleton (1976), the much-cited pioneer paper that greatly strengthened trust in the concept of Milankovitch Forcing. It must be admitted, however, that the pacemaker is not working as usual between 400 and 500 thousand years ago. Apparently, the efficiency of "pacing" varies greatly in intensity. Nevertheless, the chief ice-age cycle continues in the familiar fashion during that interval of poor pacing, following its own internal rules.

Applications and Success Stories

The chief benefit of the triumph of Milankovitch Theory has been the availability of a serviceable time scale. The main product of applying the theory to the deep-sea record is a template to which the various findings regarding ice-age history can be referred, in sequences on land and on the sea floor, without undue distortion of apparent rates of sedimentation (Figures 1 and 6). The construction

of the template has captured much attention and enthusiasm, perhaps not so much for its intrinsic logical beauty but because it is useful.

For example, guidance in dating from Milankovitch tuning readily allows a comparison of templates based on planktonic foraminifers with templates based on benthic species (Figure 6), with the proxy from benthic foraminifers thought to hew much closer to ice mass than that from planktonic ones (which strongly varies with temperature, presumably). After dating by Milankovitch tuning and normalization, the series are in fact surprisingly similar in the case here illustrated (Ontong Java data, *G. sacculifer*, W. Berger et al., 1996, *versus* the compilation of Zachos et al., 2001; *Cibicidoides*), suggesting that any variations in temperature in the planktonic species are closely correlated with the ice effect, for much of the Pleistocene.

In the planktonic record a trend since the last warm time (MIS 5e) toward anomalously lighter oxygen isotope values is seen, presumably indicating unusual warming in the western equatorial Pacific in that time interval (5e marks the time of maximum sea-level stand, said to be at least 6 m higher than now; Shinn, 2001). Increased clogging of Indonesian passages (the exits for the warm pool's trade-wind driven waters), from critical
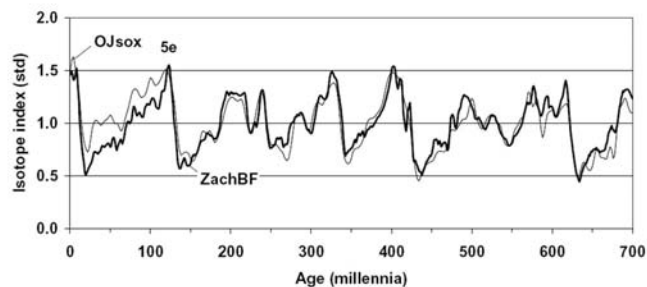

Figure 6. Comparison of oxygen isotope records based on planktonic and benthic foraminifers, after Milankovitch dating of the Ontong-Java series (Ojsox) and standardization. Heavy line: benthic foraminifers, Zachos et al. (2001), interpolated. Thin line: Ontong Java compilation, Berger et al. (1996).

buildup of coral rubble in Indonesian shelf seas as a consequence of large sea-level fluctuations may be responsible for the extra warming seen for MIS 5 in the western equatorial Pacific. The buildup of the warm pool presumably affected the intensity of ENSO events (and may have favored the buildup of coral in the Great Barrier Reef; W. Berger and Wefer, 2003). In any case, the increased difference between the planktonic and the benthic records within MIS 5 and after indicates that there are long-term planetary processes at work that affect the response of the climate system to Milankovitch Forcing during the Quaternary, and do so differently for deep and shallow waters.

The complexities of a changing response are also evident in proxy sequences that are not based on isotopes (listed, e.g., in Wefer et al., 1999), such as physical properties of carbonate sediments from Ontong Java Plateau (Mayer et al., 1993) or wind-blown components (Rea et al., 1986) or variations in magnetic susceptibility or in color. The latter are prominent in a core taken off the mouth of

the Congo River, during ODP Leg 175 (Wefer et al., 1998). They appear closely linked to precession and are discussed next.

The color variations in the record from off the Congo (ODP 1075) are believed to reflect changes in the productivity of overlying waters. Delivery of organic matter to the sea floor affects chemical processes within surface sediments, which in turn bear on sediment properties including color. The color (that is, the spectrum of reflected standardized white light) is readily recorded. Changes can be expressed in terms of changes in the ratio of lines in the spectrum, for example, the ratio between red and blue. A first look at the raw data emerging from such processing conveys the impression that the color variations are cyclic and that they strongly reflect information from precessional forcing (Figure 7). In addition, it is clear from inspection that the nature of the color variations changes along with the nature of the ice ages, as the Milankovitch Chron is being entered. Somehow, the response of the climate system to the orbital forcing becomes much stronger at that time; in fact, within the "deaf zone" (as defined above) it becomes so strong relative to the forcing it must be termed highly irregular.

The message is that the level of response to MF, in terms of the productivity of the sea off tropical Africa, depends on the presence and behavior of large amounts of ice on land (which is one defining characteristic of the Milankovitch Chron). The reason, it may be surmised, is a strong link of the wind field to the ice-dependent planetary temperature gradients. The winds, in turn, govern both the intensity of upwelling and that of the monsoon. The wind field's variability apparently is enhanced when large ice masses go through large changes. The Milankovitch Chron, in consequence, has both the lowest and the highest values in the red/blue ratio within the record off the Congo River (Figure 7, lower panel).
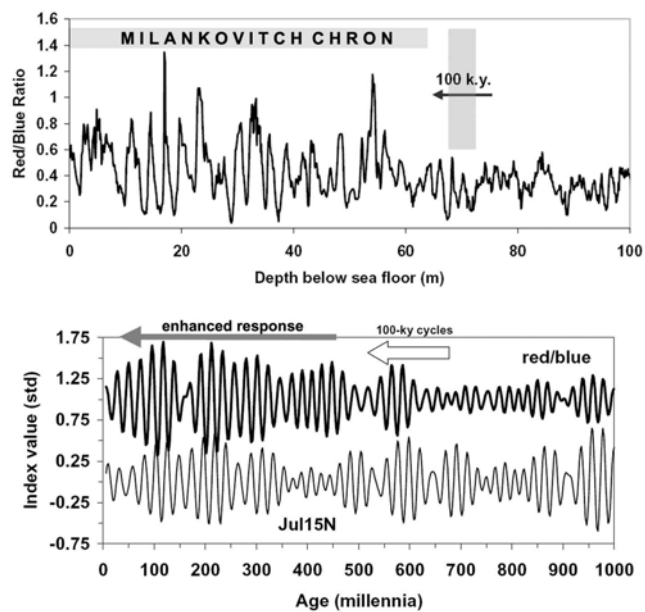

Figure 7. Color variations in Core 1075 of ODP Leg 175, drilled off the Congo River (Wefer et al., 1998). Top panel, raw data showing distinct break in amplitude of red/blue ratio after MIS 16 (near 65 m below sea floor). Bottom panel: standardized values of the precessional cycles in the color ratio compared with standardized insolation values for July at 15ºN, as calculated by André Berger (Louvain, Belgium).

The question arises how this information might bear on Quaternary productivity variations in general and on the outlook on a warming planet in particular.

Regarding the Quaternary, one would expect large productivity fluctuations in parallel with glacial periods and interglacials. The link to wind strength favors increased productivity during glacial periods over large parts of the ocean, as has been observed in numerous studies (Arrhenius, 1952; Műller and Suess, 1979; Thiede and Suess, 1983; Mix, 1989; W. Berger and Herguera, 1992; Paytan et al., 1996; Sarnthein et al., 1988). In terms of the modern world of warming, one might expect decreased productivity with winds losing vigor as high latitudes warm faster than the rest, thus decreasing the temperature gradient. Such an expectation would agree with observations concerning the behavior of upwelling off California over the last several decades (Roemmich and McGowan, 1995; McGowan et al., 1996; W. Berger, 2009).

Regarding the results of spectral analysis, the color record off the Congo emerges as a compromise between the long-term oscillations of the ice-age system (100-kyr and 41-kyr cycles) and a strong response to precession (17 to 25 kyr) from orbital forcing. It is the difference in response, in the precessional band, which is a consequence of the amplitude of the long-term cycles.

A possible link between the controls on ocean productivity as seen in Quaternary sediments and expectations for the future brings out an important aspect of Quaternary deep-sea research. Much of the work on Milankovitch Theory as reflected in deep-sea sediments appears to have been carried out in the hope and with the promise to gain insights relevant to the great challenges facing humankind as the planet's greenhouse gases increase at a rapid rate (Shackleton, 2006). Few would doubt that a rise in sea level associated with warming constitutes one of the primary concerns on the list of expected troubles on a warming planet. In fact, the maximum rate at which sea level can rise would seem to be of central interest when contemplating the ongoing changes in planetary climate, since a large portion of humankind congregates in lowlands near the sea.

The ice-age record has relevant information on this point. As is seen in Figure 5, middle panel, the rates of change of the oxygen isotope record obtained from tuning to Milankovitch forcing implies considerable amplitudes for the rates of melting (and hence rise of sea level) for the terminations. For the last deglaciation (where dates and thus rates are bolstered by numerous radiocarbon determinations) a change of around 100 m in sea level was achieved within about 10,000 years, for an overall rate of 1 meter per century (Emiliani, 1992). The value may be taken as a realistic baseline for fast melting. The question then is by what factor this rate is temporarily exceeded during major meltwater pulses.

Much has been learned from the study of corals (Fairbanks et al., 1989; Bard et al., 1990, 1996; Shinn, 2001; Peltier and Fairbanks, 2006), with rates of 2.5 m per century and more noted for some millennia. Earlier deglaciation events, less readily available for detailed study, are accessible through the conversion of

isotope ratios to change in sea level. By assuming that changes in temperature and changes in ice volume run parallel (Figure 6), a precise (and correspondingly uncertain) determination of the relationship between oxygen isotopes and sea level can be made irrelevant. When this is done, rates of up to 3m per century emerge from the isotopic record of the Late Quaternary when combined with knowledge about the total range of change in sea level (W. Berger, 2008), in good agreement with the coral data. These values are valid for intervals of millennia. Naturally, much more interest is concentrated on the time scale of centuries, the shorter scale being relevant for the fate of extant individuals and their known offspring. The question then is how do we derive estimates for the century scale from results derived for the millennium scale.

The problem is not entirely intractable, but certain assumptions are necessary when tackling it. Assuming similarities of behavior on the century scale with behavior on the millennium scale (that is, assuming a fractal distribution of pulsing within the melting process), the possibility arises of rates of sea-level rise in excess of five meters per century. Such values support the serious warnings by the NASA climatologist James Hansen in this regard (Hansen, 2009).

How likely are the high values of maximum sea-level rise obtained from the foregoing analysis? We do not know. However, an estimate can be made regarding the decrease in abundance of high values above the base level of 1 m per century. An analysis (unpublished) of the available data, including those from the deep-sea record as given in Zachos et al. (2001) and Lisiecki and Raymo (2005), suggests that a doubling of millennial averages of sea-level rise beyond the baseline of 1 m per century involves a decrease in abundance of a factor of three. Again, to assume that the same ratio holds on the century scale is to presuppose that such ratios are not very sensitive to time scale. This may be so. Strictly speaking, however, the sensitivity of the probabilities of sea-level rise for melting at different rates in different time scales is not known. (I hasten to add, mindful that ignorance is not a satisfactory basis for complacency, that there is no compelling reason to apply a high probability to the extrapolation of present values for sealevel rise to the future, as seen in the latest assessment of the Intergovernmental Panel on Climate Change (IPCC, 2007.)

There remains yet another major unknown factor, this one in regard to the trigger or the threshold for the onset of major melting of polar ice masses. Just when can we expect to see a rapid rise of sea level, ten times higher than the present values of a few millimeters per year? We do not know. All we can say, from experience with the many millennia of the ice-age records in the deep sea, is that once melting starts, it stimulates further melting for centuries. Deglaciation keeps going once begun in earnest: a great example of the dilemma of the sorcerer's apprentice.

Forcing becomes a trigger whenever the time is ripe for the collapse of large ice masses, and once the process has started, deglaciation appears to follow a

course all of its own. Thus the assessment for the future: once the rise of sea level approaches or exceeds the 1 m per century typical for historical deglaciation events, the options with respect to influencing the course of events would seem extremely limited. At that point, moving out of the way, building houses on stilts, preparing for travel by boat (rather than bicycle, car or train), or expending major efforts on the erection of dams would seem the only remaining choices of action. For a large portion of humankind such strategies of mitigation may not be feasible. In any case, they should be contemplated before the event.

Difficulties and Open Questions, and a Remedy

The main difficulty in the acceptance of Milankovitch Theory, even after its general adaptation by the community studying the ice ages, has been the afore-mentioned appearance of long-term cycles in the middle of the Quaternary (as discussed, for example, by Pisias and Moore, 1981, by Ruddiman et al., 1986, 1989, and by Maslin and Ridgwell, 2005) and the conspicuous dominance of the 100-kyr cycle within the time span studied by Milankovitch (the last third of the Quaternary), which prompted considerable discussion (e.g., Imbrie et al., 1992, 1993; Muller and MacDonald, 1997, 2000).

It is possible to rationalize the rise of long-period climate change by invoking certain internal factors (Saltzman and Sutera, 1987). The dominant of these, presumably, would be a greatly increased ice mass (e.g., W. Berger and Jansen, 1994), along with catastrophic calving after sufficient buildup of instability (Pollard, 1984; W. Berger, 1997, 1999; Paul and Berger, 1999). However, such efforts fall short of fully explaining, in terms of well-defined physical processes, either the appearance of long-term periods, or the origin of their precise length. Similarly, the reason for a range of fluctuation of the ice mass, as seen in the range of variations of sea level near 120 m, is not understood. In other words, it is not entirely clear why we do not see a range near 160 m or one near 80 m during the Milankovitch Chron. Thus, while discovery has proceeded and brought a great amount of useful facts and insights into ice-age lore, especially from the study of deep-sea sediments (as summarized in Imbrie and Imbrie, 1979; and more recently on a textbook level in Crowley and North, 1991, and in various articles in Gornitz, 2009), understanding in terms of geophysics has not kept pace. A similar discrepancy between discovery and comprehension is seen regarding the widely admired ice-core investigations and the (rightly celebrated) discovery of cycles in carbon dioxide through time (Petit et al., 1999).

Returning to Milankovitch Theory, we can now see that the determination of the position of glacial periods, within the insolation series (Figure 2), essentially ignored all applicable geophysics, and especially the physics of making and destroying ice. We should not be too harsh in judging the omission, however, realizing that progress in this regard has been but moderate within the many

decades since. Along with existing uncertainties in dating of the various types of ice-age records beyond the latest Quaternary, for example, comes an uncertainty in phase of response with respect to Milankovitch Forcing. In turn, this situation precludes reliable statements of what is being forced and how, when considering long stretches of time even within the Quaternary and certainly beyond, in pre-Quaternary times.

Neither can we fault the contemporary critics of Milankovitch for failing to accept his hypothesis. The main strength of Milankovitch's hypothesis derived from the prestige of Wladimir Köppen, who said Milankovitch's ideas were good and serviceable. While Köppen turned out to be correct in principle, this could not have been foreseen. For example, at present perihelion occurs early in January (that is, in northern winter). According to Milankovitch this is a good situation, in general, to make glaciers. If this is so, why are ice sheets not fat and growing? Or was the Little Ice Age a belated step in the right direction, only interrupted by the impact of the release of carbon dioxide?

It is likely that we shall never know. Presumably, the reason for a warm and long-lasting Holocene is that the sun-distance effect that informs much of Milankovitch Theory is just one of the factors that are important in changing climate. The long-term state of the climate system plays a role as well in modulating response to short-term forcing on the precessional scale. At present, the land surfaces that obtain the winter snow have not sufficiently rebounded from the depressed position they acquired when once deeply covered by ice. They need to rise some more to be able to keep the snow now falling in winter through the following summer, for thousands of years. Canada and Scandinavia are still rising. When elevations are high enough, snow can stay and the positive albedo feedback can then begin to work its magic in cooling the planet in high latitudes (and throughout the ocean) – if the forcing still cooperates.

As mentioned, we can eliminate from consideration much of the "slow physics" such as isostatic movements and the changes in elevation resulting from changes in ice mass, by differentiation of the proxy record. In this fashion, we can document the presence of Milankovitch Forcing in the record using spectral analysis, without getting side-tracked by long-term internal oscillations and similar complications. To demonstrate the procedure, I again use the data of
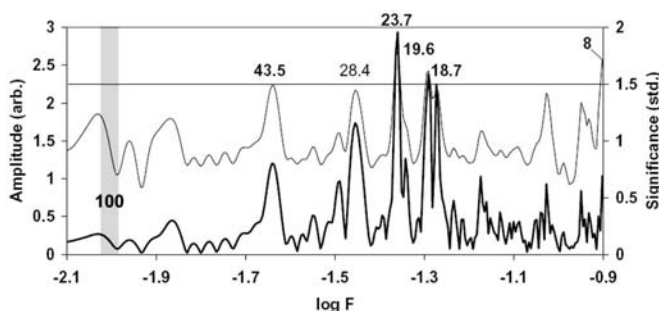

Figure 8. Periodogram of the differentiated data series of Bassinot et al. (1994), re-dated as in Figure 4. Values refer to thousands of years. Bold numbers close to and above the 1.5-line (scale to the right): significant peaks. Note the absence of power at 100 kyr.

Bassinot et al. (1994), with the same dating as previously, but now analyzing the difference series (Figure 8).

The results strongly suggest significant variation near obliquity and in various lines related to precession, with no significant variation near the period of 100 kyr (log F of –2; marked as a gray vertical band in Figure 8). This is as expected if Milankovitch Forcing (and especially precession) drives the change in ice mass (rather than fixing the position of the ice mass, as implied in Köppen's representation of Milankovitch Theory). Arguments about the correctness of Milankovitch Theory, then, seem to revolve mainly about the difference between integration and differentiation of the climate record.

Milankovitch beyond the Ice Ages

Once accepted, Milankovitch Forcing was readily applied to Quaternary sediments older than those of the Milankovitch Chron (that is, the last third of the Pleistocene), eventually yielding a time scale for climate history of the Neogene and beyond (Hilgen, 1991; Shackleton et al. 1995), using methods honed for sequences of the late Quaternary (e.g., Martinson, 1987) combined with paleomagnetics. To be sure, the definition of the lower boundary of the Quaternary (traditionally set near 1.8 Ma) is based on preferences grounded in history; that is, the definition is arbitrary with respect to the climate fluctuations within the period. What is of interest to the climate historian, instead, is the onset of the buildup of ice masses on the northern hemisphere, and the type of ensuing fluctuations (e.g., Shackleton et al., 1984; Hay, 1992; Whitman and Berger, 1992; Raymo, 1994). The onset is readily seen (and dated to just after 3 Ma by tuning to MF) within various continuous $\delta^{18}O$ records (e.g., Jansen et al., 1993; Mix et al., 1995) including the compilations of Zachos et al. (2001), and of Lisiecki and Raymo (2005). However, the physical cause or causes for the placement in time are linked to the problem of northern hemisphere glaciation in general, and are not at all yet obvious, even after considerable discussion (e.g., Hay, 1992; Maslin et al., 1998).

A date of 3 Ma (slightly older than the modern value obtained from astrochronology) was proposed, incidentally, some time ago by Berggren (1972). Berggren studied the timing of appearance of ice-rafted debris in sediments recovered during Leg 12 of the Deep Sea Drilling Project. Needless to say, ice-rafted debris is a more powerfully convincing piece of evidence than oxygen-isotope excursions, for documenting the transition into ice ages (e.g., Jansen et al., 2000), which in fact spanned millions of years within the late Neogene (Jansen and Sjøholm, 1991; Larsen et al., 1994). Incidentally, the transition period near 3 Ma (the last big cooling step) is of special interest to anthropologists, as the evolving hominid *Australopithecus* line in Africa appears to split at about that time into the big-jawed *Paranthropus* and the brain-oriented *Homo* lines (DeMenocal and Bloemendal, 1995). Presumably, the need for an

enlarged brain had to do with increasingly complex interactions between the relevant primates involved, in a social setting. A role for climatic change in guiding social activities is not obvious.

Present-day astronomical configurations apparently being stable well into the Miocene, late Neogene deep-sea sediments are readily dated using Milankovitch Forcing as a basis (Hilgen, 1991; Tiedemann et al., 1994; Shackleton et al., 1995), with profound implications for the adjustment of the paleomagnetic time scale. In any case, Milankovitch cycles have been routinely reported from Neogene sediments for quite some time (e.g., Dean and Gardner, 1985; Pisias et al., 1995; Shackleton et al., 1995). At some point, when calculating astronomical factors for the more distant past, stability of the solar system becomes an unsolved problem (Laskar, 1988; A. Berger et al., 1992; Laskar et al., 1992), with a growing possibility of substantial deviations from familiar behavior. It is in this respect that the discovery of Milankovitch-type cycles in ancient sediments can contribute to the knowledge of stability and chaos in the solar system (Palike et al., 2004), contrary to the assumption by Schwarzbach (1961, p.223), that geologists have nothing to contribute regarding the astronomical foundations of the insolation series of interest in climate history.

Stability of the solar system is not the only problem faced when applying Milankovitch Theory to the distant past, of course. Just finding the appropriate cycles within chronically incomplete sequences is an enormous challenge, as discussed by one of the foremost pioneers of appropriate searches (Schwarzacher, 1991). In cases, certain adjustments of time series analysis that account for the transformation of time scales to thickness scales can yield useful results (Herbert, 1994). However, even when cycles are found and reasonably well documented, the physics of the forcing is by no means likely to emerge.

On long geological time scales, the basic geography of the planet cannot be taken as constant. Tectonic uplift has to be considered (Ruddiman and Kutzbach, 1991; Raymo and Ruddiman, 1992), along with the associated hypothetical effects on the sensitivity of the climate system to external forcing. In addition, changes in the configuration of ocean gateways are important (Berggren and Hollister, 1974; Kennett, 1982; Haq, 1984; Toggweiler and Bjornsson, 2000), and changes in the carbon dioxide content of the atmosphere, and in the availability of methane ice on the sea floor (which introduces considerable instability to the climate system). Finally, one has to consider the drifting of continents (Kutzbach, 1994), which changes their albedo properties, among other things. Already for the onset of the ice ages and for the trends within the Quaternary itself complexities arise from tectonics, ocean circulation and erosion, of course. But general geologic considerations become ever more urgent for the more distant past, when the planet was quite different from what it is today, and its response to any outside forcing would have been different therefore (Ruddiman, 2001).

Cyclic sedimentation has been observed all through the Phanerozoic (that is, the last half billion years or so). In fact, observations in the late Paleozoic produced some of the most striking early examples of such sedimentation (Moore, 1931). Of course, sediment sequences closer in time are more amenable to study regarding the meaning of cycles, both abundance and diversity being greater (and thus allowing a choice of suitable sequences). It is thus that the Cretaceous has received much attention in this respect (e.g., Barron et al., 1985; Fischer et al., 1985; Herbert and Fischer, 1986; Boyd et al., 1994; Gale et al., 2002; for review of older studies see articles in Einsele and Seilacher, 1984, as well as Fischer, 1986, 1991; and Crowley, 1999). Besides, among Mesozoic sequences, the Cretaceous contains the sediments that are still accessible on the deep-sea floor by drilling, and where there is a reasonable chance to find continuous records to which Milankovitch arguments are readily applied (Herbert and D'Hondt, 1990).

Of special interest, then, in terms of changing climate sensitivity to external cyclic forcing, is the evidence for cyclic deposition of marine sediments within the Cretaceous. It is not evident that the fluctuations seen in deep-sea cores are linked to changes in ice mass on land, although an argument for global eustacey can be made for Cenomanian time, if ammonite biostratigraphy is assumed to have the necessary resolution for demonstrating global synchroneity of sea-level change (Gale et al., 2002). However, the climate was warm, especially in the middle Cretaceous (Herman and Spicer, 1997; Huber et al., 2002; Norris et al., 2002), as was the deep water (Douglas and Savin, 1975). For many (or most) of the cycles observed one must assume rhythmic variations of oxygen content in the deep sea; that is, cyclic changes in the production of type and amounts of bottom water. To these aspects of cyclic sedimentation we turn next.

Warm Oceans: A Pervasive Shortage of Oxygen

Warm waters hold a lot less oxygen than cold. The renewal of deep waters in the Cretaceous most likely owed much to sporadic outflow of saline waters from a multitude of shelf seas in arid regions (with relatively cool winters) (e.g., Brass et al., 1982). The process is at work right now, within the Mediterranean, and can be studied there (e.g., Anati and Stommel, 1970). The shelf-derived waters destined to join the deep ocean (presumably transferred from the depths of a Tethys open to the world ocean) had a modest content of oxygen, in contrast to today's deepwater sources in high latitudes, where very cold and oxygen-rich water sink to depth at a high rate. With respect to productivity (and hence to the supply of organic matter to the sea floor, where sediment properties are shaped), it is important to consider that one of the corollaries of low oxygen is the reduction of nitrate, a vital component of the nutrient mixture that stimulates production. Warm oceans with oxygen-deficient deep waters, presumably, were low in nitrate, greatly increasing the sensitivity of the production system to the availability of nitrogen compounds.

We must assume that the overall productivity of Cretaceous oceans pivoted on the supply and re-use of phosphorus released from the sea floor (and finding its way into surface waters where they could stimulate the synthesis of nitrogen compounds by cyanobacteria). Without stirring of recently arrived sediments on the sea floor, re-mobilization of nutrients, including phosphate, was greatly slowed. Thus, widespread anaerobic conditions, which kept benthic organisms from stirring of sediments and thus hindered the recycling of phosphorus, worked against high production. The same is true, presumably, of the removal of iron from the sea as iron sulfide: photosynthesizing and nitrogen-fixing organisms need iron as well as phosphate (Falkowski et al., 1998).

In today's ocean, oxygen-depleted waters are prime agents of fish kills under certain conditions, a point first made by the Dutch geologist Margaret Brongersma-Sanders, in the context of the origin of petroleum (Brongersma-Sanders, 1948). Thus, the supply of oxygen, always a problem in the warm Cretaceous ocean, may have provoked a long string of regional and even global biological crises in the deep sea, especially in the middle part of the epoch. The evidence for oxygen deficiency is quite clear, both in sequences on land and in the deep sea. Mid-Cretaceous black shales in deep-sea sediments were reported from the Atlantic Ocean in the early stages of the Deep-Sea Drilling Project (Lancelot et al., 1972). They were found to be very rich in organic matter. It is reasonable, based on these findings, to expect fluctuations centered on changing amounts of organic matter in sediments that are not in the central condition of black shale formation but near the margin of that setting; that is, we should see sequences resembling the familiar marl-shale intercalations in shelf sediments. The question why boundaries are less sharp in the deep sea arises, and invites the contemplation of different time spans and conditions for benthic mixing (see, e.g., Savdra and Bottjer, 1994).

The prevalence of overall low oxygen conditions in the middle of the Cretaceous is quite recognizable from the chemistry of the sediments of the time. Such geochemical evidence for low oxygen conditions is especially abundant within certain well-defined periods, which gave rise to the concept of "oceanic anoxic events", a term coined by the geologists Seymour Schlanger and Hugh Jenkyns, in 1976. Typically, evidence for such "events" (lasting millions of years) was found in the Atlantic, but some evidence came from the Pacific and from the Indian Ocean as well. Anoxia in the deep Tethys is represented within cyclic sequences exposed in Italy (Herbert and Fischer, 1986; Herbert et al., 1986).

Evidence for a worldwide shortage of oxygen at depth came from isotopic analysis of pelagic carbonates (Scholle and Arthur, 1980; Arthur et al., 1985). Isotopic stratigraphy showed that the periods of black shale accumulation are reflected in a marked change in the ratio of the two isotopes carbon-13 and carbon-12, within the dissolved carbon dioxide of the ocean. During the black-shale periods, carbon-13 was increased within seawater relative to the

background ratio of carbon-13 to carbon-12 (as seen in calcareous fossils). The simplest explanation is that increased deposition of organic matter (which is enriched in carbon-12), in a greatly expanded oxygen minimum zone, changed the ratio in the remaining carbon pool in the sea toward enrichment of carbon-13, as observed.

An oxygen-stressed ocean should respond readily to small disturbances in overall climatic conditions. A little cooling here, a little less rainfall or more evaporation there, within shelf basins supplying deep water, this could readily make a difference in the supply of oxygen to the deep ocean. In turn, relatively small changes in the oxygen supply can be recorded on the sea floor, whenever the supply is very small to begin with. Thus, at very low levels, bacterial mats form on the sea floor. At levels not much higher, oxygen-consuming organisms graze these mats. In contrast, when oxygen levels are comparatively high, halving or doubling them makes but little difference to the organisms living on the sea floor.

It is with this enhanced sensitivity from low oxygen values in mind that we should view the discovery of Milankovitch-type cycles in many Cretaceous deep-sea deposits (Figure 9). Whenever perihelion occurred in northern summer, the warming of shelf seas in the dry belt north of the tropics was increased (more evaporation). Also, northern winters cooled more than normal during such times, hence provided for colder salt-rich waters. As a result, it seems, shelf-derived deepwater production may have been increased during intervals of high seasonality, and thus oxygenation at depth (much as proposed by Erba and Premoli Silva for Albian sediments exposed in Italy). On the deep-sea floor,
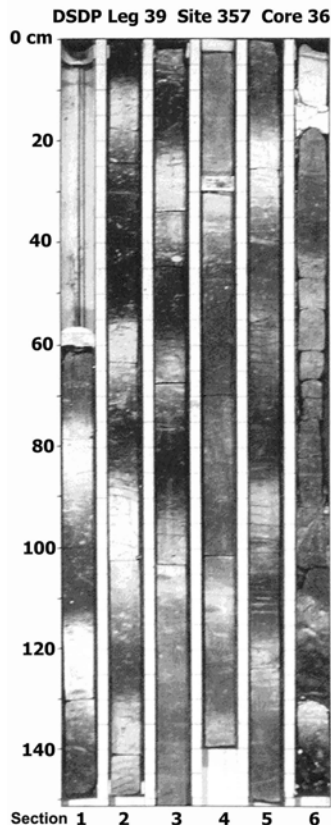

Figure 9. Evidence for regular cyclic deposition in the late Cretaceous deep-sea environment (Campanian, Rio Grande Rise), presumably reflecting varying oxygen content in deep waters in response to climate change. From T. Herbert (in a pamphlet of the Joint Oceanographic Institutions, 1997).

reaction of additional oxygen with ambient organic carbon would have produced carbon dioxide and hence carbonic acid, and led to the dissolution of carbonate. The effect, presumably, would be a darkening of the recording sediments.

Of course, the sense of the precession-related modification of climate was opposite north and south of the equator. However, most of the relevant land surfaces and shelf seas presumably were in the northern hemisphere, linked to the northern shores of the Tethys, thus retaining the chief feature of Milankovitch Theory – the dominant influence of the northern hemisphere. Alternative ways of producing light-dark cycles are readily envisaged (e.g., Herbert and D'Hondt, 1990; Einsele and Ricken, 1991; Boyd et al., 1994; Park and Ogelsby, 1994); thus, the generation of such cycles is an open problem to be considered in each particular case being studied. A role for ice mass cannot be excluded, in changing the depths of shelf seas supplying deep water. In a shelf setting (which is appropriate for most sequences seen on land), dilution by terrigenous sediments must play an especially important role, in addition to ocean chemistry and circulation (Ricken, 1994). But, presumably, oxygenation remains a central factor everywhere (Pratt, 1984; Arthur et al, 1986; Eicher and Diner, 1991).

There is an interesting corollary to the concept of pulsed supply of saline shelf-sea waters. If sporadically increased salinity was an important ingredient in bottom water formation during the Cretaceous (from precession-driven changes in evaporation in shelf seas delivering deep water), we should then expect the occasional creation (and perhaps long-lasting presence) of abyssal salt lakes that were difficult to remove by mixing (since the water was quite heavy from the salt). If such abyssal lakes existed, we should see unusual abundances of minerals precipitated in sediments covered by the brine. Zeolite and rhodochrosite come to mind (e.g., Berger and von Rad, 1972). Where hot vents issued into such brines, we should find plenty of pyrite and other metal sulfides, and even native copper. The implications for productivity would be quite remarkable: such abyssal dead lakes would act as a black hole for nutrients, everything falling into them being swallowed and nothing released for recycling.

Summary, Comments and Conclusions

Milankovitch Theory, having proven its usefulness in the dating of Quaternary sediments and beyond, and in the explanation (however tentative) of the observed fluctuations in oxygen isotopes and other proxies, is here to stay. This assessment is based not on a logical inevitability of the mathematical and physical arguments involved when applying the Theory (points belabored by critics) as on plausibility married to utility. Assuming that the Theory is correct allows the assignment of paleomagnetic reversal ages that are verifiable by radioactive dating (Johnson, 1982; Shackleton et al., 1990; Hilgen, 1994), as well as stimulating thinking in respect of climate control on cyclic sedimentation (Einsele et al., 1991; De Boer and Smith, 1994). If Milankovitch Theory were to be replaced by some other conjecture, the proposed replacement better have superior plausibility and convenience of use, and be better grounded in logic and physics. In that sense (of being exceedingly difficult to replace) Milankovitch now

indeed has the kind of "grandfather" status deplored by Muller and MacDonald (2000, pp. 273-274). The reason for this status is not just a background of history; rather, it is a lack of competent competition.

True, some of the relevant observations (such as the 100-kyr cycle) remain puzzling and unsolved, but this does not invalidate the basic theory in wholesale fashion, especially since the theory is about change, and not about the integration of climate processes represented by the 100-kyr cycle. In preference to rejection, discrepancies between expectation and observation call for additions to the theory; that is, for the exploration of long-term processes and dynamics not previously properly studied and applied to stratigraphy (e.g., Pollard, 1984; Ghil, 1989; Smith, 1994; Rial, 1999; and also Muller and MacDonald, 1997). At this time, there simply is no other theory defining the input. If only the output is available (in terms of the geologic record), guessing at the input leads directly into circular (and therefore useless) reasoning.

Incidentally, if only the long-term cyclic aspect of the ice ages is considered important (rather than the pattern resulting from Milankovitch Theory) a projection of the coming of the next ice age will differ from one done in the Milankovitch world. By such reasoning, the next ice age is relatively close, using MIS 5e (the "Eem" Interglacial) as an analogy (as exemplified in the beautifully illustrated book on ice age mammals by von Koenigswald, 2002, p.11; although Milankovitch Theory is explained on p. 33). However, in the Milankovitch world MIS 11, not MIS 5, is relevant for generating expectations for the immediate geological future, as pointed out repeatedly by André Berger (see Droxler et al., 2003). (In addition, of course, long-term disturbances from human impacts must now be considered.)

If Milankovitch Theory is ever to be abandoned by geologists studying cyclic sedimentation, it will be because it fails in providing plausible explanations of observed phenomena, thus leading investigators into a cul-de-sac. This has not happened. To the contrary, the possibilities in the study of geologic phenomena when using this tool seem as yet unbounded.

References

Alley, R.B., Palaeoclimatology – icing the North Atlantic. Nature 392, 335.
Alvarez, L.W., W. Alvarez, F. Asaro, H.V. Michel, 1980, *Extraterrestrial cause for the Cretaceous-Tertiary extinction.* Science 208,1095-1108.
Anati, D., and H. Stommel, 1970, *The initial phase of deep water formation in the northwest Mediterranean during MEDOC '69 on the basis of observations made by Atlantis II, January 25, 1969 to February 12, 1969.* Cahiers Océanographiques 22, 343-351.
Andrews, J.T., and R.G. Barry, 1978. Glacial inception and disintegration during the last glaciation. Ann. Rev. Earth Planet. Sci. 6, 205-228.
Arrhenius, G.O.S., 1952. Sediment cores from the east Pacific. Rept. Swed. Deep-Sea

Exped. 1947-1948, 5 (1) 1-227.

Arthur, M.A., W.E. Dean, and S.O. Schlanger, 1985. Variations in the global carbon cycle during the Cretaceous related to climate, volcanism, and changes in atmospheric CO_2 . Amer. Geophys. Union Geophys Monogr. 32, 504-529.

Arthur, M.A., D.J. Bottjer, W.E. Dean, A.G. Fischer, D.E. Hattin, E.G. Kauffman, et al., 1986. Rhythmic bedding in Upper Cretaceous pelagic carbonate sequences: varying sedimentary response to climatic forcing. Geology 14, 153-156.

Baksi, A.K., 1994, Concordant sea-floor spreading rates obtained from geochronology, astrochronology and space geodesy. Geophys. Research Letters, 21, 133-136.

Baksi, A.K., V. Hsu, M.O. McWilliams, and E. Farrar, 1992. $^{40}Ar/^{39}Ar$ dating of the Brunhes-Matuyama geomagnetic field reversal. Science 256, 356-357.

Bard, E., B. Hamelin, R.G. Fairbanks, A. Zindler, M. Arnold, G. Mathieu, 1990. Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. *Nature* 345, 405-410.

Bard, E., B. Hamelin, M. Arnold, L. Montaggioni, G. Cabioch, G. Faure and F. Rougerie, 1996. Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. Nature 382, 241-244.

Barron, E.J., M.A. Arthur, and E.G. Kauffman, 1985. Cretaceous rhythmic bedding sequences: a plausible link between orbital variations and climate. Earth Planet. Sci. Letts. 72, 327-340.

Bassinot, F.C., 2009. SPECMAP. In: V. Gornitz (ed.) Encyclopedia of Paleoclimatology and Ancient Environments. Springer, Dordrecht, pp. 911-915.

Bassinot, F.C., L.D. Labeyrie, E. Vincent, X. Quidelleur, N.J. Shackleton and Y. Lancelot, 1994. The astronomical theory of climate and the age of the Brunhes-Matuyama magnetic reversal. Earth Planet. Sci. Lett., 126, 91-108.

Berger, A.L., 1977. Support for the astronomical theory of climatic change, Nature 269, 44–45.

Berger, A., 1978: Long-term variations of caloric insolation resulting from the Earth's orbital elements. *Quaternary Research*, 9: 139-167.

Berger, A., 1989. The spectral characteristics of pre-Quaternary climatic records, an example of the relationship between the astronomical theory and geo-sciences. In: A. Berger, S. Schneider, and J.C. Duplessy (eds.) Climate and Geo-Sciences. Kluwer Academic, Dordrecht, pp. 47-76.

Berger, A. L., 1988. Milankovitch theory and climate. *Reviews of Geophysics* 26: 624-57.

Berger, A.L., 2009. Astronomical theory of climate change. In: V. Gornitz (ed.) Encyclopedia of Paleoclimatology and Ancient Environments. Springer, Dordrecht, pp. 51-57.

Berger, A., and M.F. Loutre, 1991. Insolation values for the climate of the last 10 million years. Quaternary Sciences Reviews, 10, 297-317.

A. Berger and M.F. Loutre, 1994. Astronomical forcing through geologic time. Spec. Publs. Int. Assoc. Sediment. 19, 15-24.

Berger, A., Imbrie, J., Hays, J., Kukla, G., and Saltzman, B. (Eds.), 1984. Milankovitch and Climate: Understanding the Response to Astronomical Forcing: Dordrecht (D. Reidel). 2 vols. 895pp.

Berger, A., Loutre, M.F., and Laskar, J., 1992. Stability of the astronomical frequencies over the Earth's history for paleoclimate studies. Science 255:560-566.

Berger, W.H., 1997. Experimenting with ice-age cycles in a spreadsheet. J. Geoscience Education, 45, 428-439.

Berger, W.H., 1999. The 100-kyr ice-age cycle: internal oscillation or inclinational forcing? Int. Journ. Earth Sciences, 88:305-316.

Berger, W.H., 2008. Sea level in the Late Quaternary: Patterns of variation and

implications. International Journal of Earth Sciences, 97, 1143-1150.

Berger, W.H., 2009. Ocean – Reflections on a Century of Exploration. UC Press, Berkeley 519pp.

Berger, W.H., 2011. Geologist at sea: Aspects of ocean history. Ann. Reviews Marine Science 3 (1)1-34.

Berger, W.H., and J.C. Herguera, 1992. Reading the sedimentary record of the ocean's productivity. In: P.G. Falkowski and A.D. Woodhead (eds.) Primary Productivity and Biogeochemical Cycles in the Sea. Plenum Press, New York, 455-486.

Berger, W.H., and E. Jansen, 1994. Mid-Pleistocene climate shift: The Nansen connection. In: O.M. Johanessen, R.D. Muench, and J.E. Overland (eds.) The Polar Oceans and Their Role in Shaping the Global Environment: The Nansen Centennial Volume. AGU Geophysical Monograph 84:295-311.

Berger, W.H., and E. Jansen, 1995. Younger Dryas episode: Ice collapse and super-fjord heat pump. In: S.R. Troelstra, J.E. van Hinte, G.M. Ganssen (eds.) The Younger Dryas, p.61-105, North-Holland, Amsterdam.

Berger, W.H., and U. von Rad, 1972. Cretaceous and Cenozoic sediments from the Atlantic Ocean. Initial Reports of the Deep Sea Drilling Project, Vol. 14, Washington, D. C.: 787-954.

Berger, W.H., and G. Wefer, 1992. Klimageschichte aus Tiefseesedimenten – Neues vom Ontong Java Plateau (Westpazifik). Naturwissenschaften 79, 541-550.

Berger, W.H., and G. Wefer, 1996. Expeditions into the past: Paleoceanographic studies in the South Atlantic. In: G. Wefer, W.H. Berger, G. Siedler, D.J. Webb (eds) The South Atlantic: Present and Past Circulation. Springer-Verlag Berlin Heidelberg, 363-410.

Berger, W.H., and G. Wefer, 2003. On the Dynamics of the Ice Ages: Stage-11 Paradox, Mid-Brunhes Climate Shift, and 100-ky Cycle. In: A.W. Droxler, R.Z. Poore and L.H. Burckle (eds.) Earth's Climate and Orbital Eccentricity: The Marine Isotope Stage 11 Question. AGU Geophysical Monograph 137, 41-59.

Berger, W.H., T. Bickert, E. Jansen, G. Wefer, and M. Yasuda, 1994. The central mystery of the Quaternary ice age: a view from the South Pacific. Oceanus 36 (4):53-56.

Berger, W.H., M. Yasuda, T. Bickert, and G. Wefer, 1995. Brunhes-Matuyama boundary: 790 k.y. date consistent with ODP Leg 130 oxygen isotope records based on fit to Milankovitch template. Geophysical Research Letters, 22 (12) 1525-1528.

Berger, W.H., T. Bickert, M.K. Yasuda, and G. Wefer, 1996. Reconstruction of atmospheric CO_2 from the deep-sea record of Ontong Java Plateau: The Milankovitch Chron. Geol. Rundschau, 85, 466-495.

Berggren, W.A., 1972, *Late Pliocene - Pleistocene glaciation.* Initial Reports Deep Sea Drilling Project 12, 953-963.

Berggren, W.A., and C.D. Hollister, 1974, *Paleogeography, paleobiogeography and the history of circulation in the Atlantic Ocean.* In W.W. Hay (ed.) *Studies in Paleo-Oceanography.* Soc. Econ. Paleont. Mineral., Spec. Publ. 20, p. 126-186.

Birchfield GE, Grumbine RW (1985) "Slow" physics of large continental ice sheets and underlying bedrock and its relation to the Pleistocene ice ages. J. Geophys. Res. 90:11,294-11,302

Bloom, A.L., W.S. Broecker, J.M.A. Chappell, R.K. Matthews, and K.J. Mesolella, 1974. Quaternary sea level fluctuations on a tectonic coast: New $^{230}Th/^{234}U$ dates from the Huon Peninsula, New Guinea. Quaternary Research 4, 185-205.

Bond, G., Heinrich, H., Huon, S., Broecker, W. S., Labeyrie, L., Andrews, J., McManus, J., Clasen, S., Tedesco, K., Jantschik, R., and Simet, C., 1992: Evidence for massive discharges of icebergs into the glacial Northern Atlantic. Nature 360, 245-249.

Boyd, R., Z. Huang, and S. O'Connell, 1994. Milankovitch cyclicity in Late Cretaceous sediments from Exmouth Plateau off northwest Australia. Spec. Pubs. Int. Assoc. Sediment. 19, 145-166.

Brass, G.W., J.R. Southam, and W.H. Peterson,1982. Warm saline bottom waters in the ancient ocean. Nature 296, 620-623.

Broecker, W.S., 1966. Absolute dating and the astronomical theory of glaciation. Science 151, 299-304.

Broecker, W.S., 1984. Terminations. In: A. Berger et al. (eds.) Milakovitch and Climate, Part 2. D. Reidel, Dordrecht, pp. 687-698.

Broecker, W.S., and J. van Donk, 1970. Insolation changes, ice volumes, and the O^{18} record in deep-sea cores. Review of Geophysics and Space Physics, 8, 169-198.

Brooks, C.E.P., 1949. Climate Through the Ages, 2nd ed.. Republished in 1970, by Dover, New York, 395pp.

Brongersma-Sanders, M., 1948. The importance of upwelling water to vertebrate paleontology and oil geology. Verhand. der Koninklijke Nederlandsche Akad. van Wetensch., Afd. Natuurkunde. Sect 2, Pt. 45 (4) 1-112.

Chen, J.H., H.A. Curran, B. White, G.J. Wasserburg, 1991. Precise chronology of the last interglacial period: 234U-230Th data from fossil coral reefs in the Bahamas. Geol. Soc. Am. Bull. 103:82-97.

Calov, R., A. Ganopolski, V. Petoukhov, and M. Claussen, 2002. Large-scale instabilities of the Laurentide ice sheet simulated in a fully coupled climate-system model. *Geophysical Research Letters,* 29, 2216.

Cline, R.M., and J.D. Hays, 1976 (eds.) Investigation of Late Quaternary paleoceanography and paleoclimatology. Geol. Soc. Amer. Memoir, v.145, 1-464.

Croll, J, 1875, *Climate and Time in their Geological Relations. A Theory of Secular Changes of the Earth's Climate.* Daldy, Isbister, & Co., London, 577pp.

Crowley, T.J., 1999. Pre-Mesozoic ice ages: Their bearing on understanding the climate system. Geol. Soc. America Memoir 192, 1-106.

Crowley, T.J., and G.R. North, 1991. Paleoclimatology. Oxford University Press, New York and Oxford, 339pp.

Dean, W.E., and J.V. Gardner, 1986. Milankovitch cycles in Neogene deep-sea sediments. Paleoceanography 1, 539-553.

De Boer, P.L., and D.G. Smith (eds.) 1994. Orbital Forcing and Cyclic Sequences. Spec. Publs. Int. Assoc. Sediment. 19, 1-559.

DeMenocal, P.B., and J. Bloemendal, 1995. Plio-Pleistocene climatic variability in subtropical Africa and the paleoenvironment of hominid evolution: A combined data-model approach. In: E.S. Vrba, G.H. Denton, T.C. Partridge, and L.H. Burckle (eds.) Paleoclimate and Evolution, with Emphasis on Human Origins. Yale Univ. Press, New Haven, pp. 262-288.

Douglas, R.G., and S. Savin, 1975. Oxygen and carbon isotope analyses of Tertiary and Cretaceous microfossils from Shatsky Rise and other sites in the North Pacific Ocean. Initial Rpts. Deep Sea Drilling Project 32, 509-520.

Droxler, A.W., R.Z. Poore, and L.H. Burckle (eds.) 2003. Earth's Climate and Orbital Eccentricity – The Marine Isotope Stage 11 Question. American Geophysical Union, Geophysical Monograph 137, 1-240.

Ehlers, J., 1994. Allgemeine und historische Quartärgeologie. Ferdinand Enke, Stuttgart, 358pp.

Eicher, D.L., and R. Diner, 1991. Environmental factors controlling Cretaceous limestone-marlstone rhythms. In: G. Einsele, W. Ricken, and A. Seilacher (eds.) Cycles and Events in Stratigraphy. Springer, Berlin Heidelberg, pp. 79-93.

Einsele, G., and A. Seilacher (eds.) 1982. Cyclic and Event Stratification. Springer,

Berlin Heidelberg, 536pp.

Einsele, G., and W. Ricken, 1991. Limestone-marl alternation – an overview. In: G. Einsele, W. Ricken, and A. Seilacher (eds.) Cycles and Events in Stratigraphy. Springer, Berlin Heidelberg, pp. 23-47.

Einsele, G., W. Ricken, and A. Seilacher (eds.) 1991. Cycles and Events in Stratigraphy. Springer, Berlin Heidelberg, 955pp.

Emiliani, C., 1955. *Pleistocene temperatures*. Journal of Geology, 63, 538-578.

Emiliani, C., 1992. Planet Earth – Cosmology, Geology, and the Evolution of Life and Environment. Cambridge University Press, Cambridge and New York, 718pp.

Emiliani, C., and J. Geiss, 1959. On glaciations and their causes. Geologische Rundschau, 46 (2) 576-601 (1957).

Erba, E., and I. Premoli Silva, 1994. Orbitally driven cycles in trace-fossil distribution from the Piobbico core (late Albian, central Italy). Spec. Publs. Int. Assoc. Sediment. 19, 211-225.

Ericson, D.B., and G. Wollin, 1964. *The Deep and the Past*. New York: Knopf. 303pp

Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature, 342(6250):637-642.

Falkowski, P.G., Barber, R.T., Smetacek, V., 1998. Biogeochemical controls and feedback on ocean primary production. Science 281, 200–206.

Fischer, A.G., 1986. Climatic rhythms recorded in strata. Ann. Rev. Earth Planet. Sci. 14, 351-376.

Fischer, A.G.,1991. Orbital cyclicity in Mesozoic strata. In: G. Einsele, W. Ricken and A. Seilacher (eds.) Cycles and Events in Stratigraphy. Springer, Berlin Heidelberg, pp. 48-62.

Fischer, A.G., 1986. Climatic rhythms recorded in strata. Ann. Rev. Earth Planet. Sci. 14, 351-376.

Fischer, A.G., T.D. Herbert, and I. Premoli-Silva, 1985. Carbonate bedding cycles in Cretaceous pelagic and hemipelagic sediments. In: L.M. Pratt, E.G. Kauffman, and F.B. Zelt (eds.) Fine-grained deposits and biofacies of the Cretaceous Western Interior Seaway: evidence of cyclic processes. Soc. Econ. Paleontol. Mineral. Xx, 1-10.

Flint, R.F., 1957. Glacial and Pleistocene Geology. John Wiley & Sons, New York, 553pp.

Gale, A.S., J. Hardenbol, B. Hathway, W.J. Kennedy, J.R. Young, and Y. Phansalkar, 2002. Global correlation of Cenomanian (Upper Cretaceous) sequences: Evidence for Milankovitch control on sea level. Geology 30, 291-294.

Ghil, M., 1989. Deceptively-simple models of climatic change. In: A. Berger, S. Schneider, J.C. Duplessy (eds.) Climate and Geosciences. Kluwer, Dordrecht, pp. 211-240.

Gornitz, V. (ed.) 2009.Encyclopedia of Paleoclimatology and Ancient Environments. Springer, Dordrecht, 1047pp.

Hansen, J., A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, R. Ruedy and J. Lerner, 1984. Climate sensitivity: analysis of feedback effects. AGU Geophysical Monogr. 29, 130-163.

Hansen, J., 2009. *Storms of my Grandchildren – The Truth About the Coming Climate Catastrophe and our Last Chance to Save Humanity.* Bloomsbury, New York, 303pp.

Haq, B.U., 1984. *Paleoceanography: A synoptic overview of 200 million years of ocean history.* In: B.U. Haq, J.D. Milliman (eds.) *Marine geology and oceanography of Arabian Sea and coastal Pakistan.* Van Nostrand Reinhold, New York, 201-231.

Hay, W., 1992. The cause of the late Cenozoic northern hemisphere glaciations; A climate change enigma. Terra Nova 4, 305-311.

Hays, J.D., 2009. CLIMAP. In: V. Gornitz (ed.) Encyclopedia of Paleoclimatology and

Ancient Environments. Springer, Dordrecht, pp.158-164.

Hays, J. D., Imbrie, J. and Shackleton, N. J., 1976. Variations in the Earth's orbit: pacemaker of the Ice Ages. Science, 194: 1121-1132.

Herbert, T.D., 1994. Reading orbital signals distorted by sedimentation: models and examples. Spec. Publs. Int. Assoc. Sediment. 19, 483-507.

Herbert, T.D., 1997. Climate periodicity in "icehouse" and "greenhouse" worlds. In: E.S. Kappel and J.W. Farrell (eds.) ODP's greatest hits. Joint Oceanographic Institutions, Washington, D.C., p. 10.

Herbert, T.D., and S.L. D'Hondt, 1990. Precessional climate cyclicity in Late Cretaceous-Early Tertiary marine sediments: A high resolution chronometer of Cretaceous-Tertiary boundary events. Earth Planet. Sci. Lett. 99, 263-275.

Herbert TD, Fischer AG (1986) Milankovitch climatic origin of mid-Cretaceous black shale rhythms in central Italy. Nature 321:739-743.

Herbert, T.D., R.F. Stallard, and A.G. Fischer, 1986. Anoxic events, productivity rhythms and the orbital signature in a mid-Cretaceous deep-sea sequence from central Italy. Paleoceanography 1, 495-506.

Herman, A.B., and R.A. Spicer, 1997. New quantitative palaeoclimate data for the Late Cretaceous Arctic: Evidence for a warm polar ocean. Palaeogeogr., Palaeoclimatol. Palaeoecol. 128, 227-251.

Hilgen, F.J., 1991. Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the geomagnetic polarity time scale. Earth Planet. Sci. Lett. 104, 226-244.

Hilgen, F.J., 1994. An astronomically calilbrated (polarity) time scale for the Pliocene-Pleistocene: a brief review. Spec. Publs. Int. Assoc. Sediment. 19, 109-116.

Huber, B.T., R.D. Norris, and K.G. MacLeod, 2002. Deep-sea paleotemperature record of extreme warmth during the Cretaceous. Geology 30, 123-126.

Imbrie, J., and K.P. Imbrie, 1979. Ice ages: solving the mystery. Enslow, Short Hills, New Jersey, 224pp.

Imbrie, J., J.D. Hays, D.G. Martinson, A. McIntyre, A.C. Mix, J.J. Morley, N.G. Pisias, W.L. Prell and N.J. Shackleton, 1984. The orbital theory of Pleistocene climate: Support from a revised chronology of the marine $\delta^{18}O$ record. In: Berger, A.L., Imbrie, J., Hays, J.D., Kukla, J. and Saltzman, J. (eds). Milankovitch and Climate (Part 1): 269-305, Hingham, Mass. (Reidel).

Imbrie, J., E.A.Boyle, S.C.Clemens, A.Duffy, W.R.Howard, G.Kukla, J.Kutzbach, D.G.Martinson, A.McIntyre, A.C.Mix, B.Molfino, J.J.Morley, L.C.Peterson, N.G.Pisias, W.L.Prell, M.E.Raymo, N.J.Shackleton, and J.R.Toggweiler, 1992. On the structure and origin of major glaciation cycles 1. Linear responses to Milankovitch forcing. Paleoceanography, 7:701-738.

Imbrie, J., A. Berger, E.A. Boyle, S.C. Clemens, A. Duffy, W.R. Howard, G. Kukla, J. Kutzbach, D.G. Martinson, A. McIntyre, A.C. Mix, B. Molfino, J.J. Morley, L.C. Peterson, N.G. Pisias, W.L. Prell, M.E. Raymo, N.J. Shackleton, and J.R. Toggweiler, 1993. On the structure and origin of major glaciation cycles 2. The 100,000-year cycle. Paleoceanography 8(6):699-735.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge (UK).

Izett, G.A., and J.D. Obradovich, 1991. Dating of the Matuyama-Brunhes boundary based on ^{40}Ar-^{39}Ar ages of the Bishop Tuff and Cerro San Luis rhyolite. Geological Society of America Abstracts with Programs, 23 (6), A106.

Jansen, E., and J. Sjøholm, 1991. Reconstruction of glaciation over the past 6 Myr from ice-borne deposits in the Norwegian Sea. Nature 349, 600-603.

Jansen, E., Mayer, L.A., Backman, J., Leckie, M. & Takayama, T. 1993. Evolution of climate cyclicity at ODP Site 806: oxygen isotope record. *Proc. ODP Scientific Res. Leg 130, 349-362*.

Jansen, E., T. Fronval, F. Rack, and J.E.T. Channell, 2000. Pliocene-Pleistocene ice rafting history and cyclicity in the Nordic Seas during the last 3.5 Myr. Paleoceanography 156, 709-721.

Johnson, R.G., 1982. *Brunhes-Matuyama magnetic reversal dated at 790,000 yr B.P. by marine-astronomical correlations.* Quat. Res. 17, 135-147.

Kennett, J.P., 1982. Marine Geology. Prentice-Hall, Englewood Cliffs, 813pp.

Kent, D.V., and P.E. Olsen, 1999. Astronomically tuned geomagnetic polarity timescale for the Late Triassic. J. Geophys. Res. 104, 12831-12841.

Köppen,W., 1931. Grundriss der Klimakunde. (2nd edition of Klimate der Erde). Walter de Gruyter, Berlin und Leipzig, 388pp.

Köppen,W., and A. Wegener, 1924, *Die Klimate der geologischen Vorzeit.* Bornträger, Berlin.

Kutzbach, J.E., 1994. Idealized Pangean climates: Sensitivity to orbital change. In: G.D. Klein (ed.) Pangea: Paleoclimate, Tectonics and Sedimentation during Accretion, Zenith and Breakup of a Supercontinent. Geol. Soc. America Special Paper 288, 41-55.

Lancelot, Y., J.C. Hathaway, and C.D. Hollister, 1972. Lithology and sediments from the western North Atlantic, Deep Sea Drilling Project, Leg 11. Initial Rpts. Deep Sea Drilling Project 11, 901-949.

Lisiecki, L.E., and M.E. Raymo, 2005: A Pliocene-Pleistocene stack of 57 globally distributed benthic ∂18O records. *Paleoceanography,* 20, PA1003, doi:10.1029/ 2004PA001071.

Larsen, H.C., A.D. Saunders, P.D. Clift, J. Beget, W. Wei, S. Spezzaferri, and ODP Leg 152 Scientific Party, 1994. Seven million years of glaciation on Greenland. Science 264, 952-955.

Laskar, J.T., 1988. Secular evolution of the solar system over 10 million years. Astron. Astrophys. 198, 341-362.

Laskar, J., T. Quinn, and S. Tremaine, 1992. Confirmation of resonant structure in the solar system. Icarus 95, 148-152.

Martinson DG, Pisias NG, Hays JD, Imbrie J, Moore Jr. TC, Shackleton NJ., 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. Quat. Research 27: 1-29.

Maslin, M.A., and A. Ridgewell, 2005. Mid-Pleistocene Revolution and the eccentricity myth. Spec. Publ. Geol. Soc. London, 247, 19-34.

Maslin, M.A., X.-S, Li, M.F. Loutre, A. Berger, 1998. The contribution of orbital forcing to the progressive intensification of northern hemisphere glaciation. Quat. Sci. Rev. 17, 411-426.

Mayer, L.A., Jansen, E., Backman, J. and Takayama, T. 1993. Climate cyclicity at ODP Site 806:: GRAPE record. *Proc. ODP Scientific Res. Leg 130, 623-639.*

McGowan, J.A., D. B. Chelton and A. Con.versi, 1996, Plankton patterns, climate, and change in the California Current. CalCOFI Report 37, 45-68.

Milanković, V. (ed.) Milutin Milanković 1879-1958. European Geophysical Society, Kaltenburg-Lindau, 181pp.

Milankovitch, M., 1930. Mathematische Klimalehre und astronomische Theorie der Klimaschwankungen. In: Köppen, W., Geiger, R. (Eds.), Handbuch der Klimatologie, Bd 1, Teil A. Bornträger, Berlin, 176pp.

Milankovitch, M. (1941). Kanon der Erdbestrahlungen und seine Anwendung auf das Eiszeitenproblem. [Canon of Earth's insolation and its application to the ice-age

problem.] Royal Serbian Academy Special Publication v.133, 1-633 pp.

Miller, K.G., Fairbanks, R.G., and Mountain, G.S., 1987. Tertiary oxygen isotope synthesis, sea-level history, and continental margin erosion. Paleoceanography, 2, 1-19.

Mix, A.C., 1989. Pleistocene Paleoproductivity: Evidence from Organic Carbon and Foraminiferal Species. In: W.H. Berger, V.S. Smetacek and G. Wefer (eds.), Productivity of the Ocean: Present and Past. Wiley, New York, pp. 313-340.

Mix, A.C., Pisias, N.G., Rugh, W., Wilson, J., Morey, A., Hagelberg, T.K., 1995. Benthic foraminifer stable isotope record from Site 849 (0-5 Ma): local and global climate changes. Proc. ODP, Scientific Results, 138. College Station, TX, Ocean Drilling Program, pp. 371-412.

Moore, R.C., 1931. Pennsylvanian cycles in the northern mid-continent regions. Illinois Geological Survey Bulletin 60, 247-257.

Mudelsee, M,, and M. Schulz, 1997. The Mid-Pleistocene climate transition: onset of 100 ka cycle lags ice volume build-up by 280 ka. Earth Planet. Sci. Lett. 151:117-123

Müller, P. J., and E. Suess, 1979. Productivity, sedimentation rate, and sedimentary organic matter in the oceans - I. Organic carbon preservation, Deep-Sea Research, 26A, 1347-1362.

Muhs, D.R., 2002. Evidence for the timing and duration of the last interglacial period from high-precision uranium-series ages of corals on tectonically stable coastlines. Quaternary Research 58, 36-40.

Muller, R.A, and G.J. MacDonald 1997. Glacial cycles and astronomical forcing. Science 277, 215-218.

Muller, R.A., and G.J. MacDonald, 2000. Ice Ages and Astronomical Causes – Data, spectral analysis and mechanisms. Springer Praxis, Chichester, UK, 318pp.

Norris, R.D., K.L. Bice, E.A. Magno, P.A.Wilson, 2002. Jiggling the tropical thermostat in the Cretaceous hothouse. Geology 30, 299-302.

Oerlemans, J., and C.J. van der Veen, 1984. Ice Sheets and Climate. Reidel, Dordrecht, 217pp.

Olausson, E., 1996. The Swedish Deep-Sea Expedition with the "Albatross" 1947-1948: A Summary of the Sediment Core Studies. E. Olausson, Göteborg, 98pp.

Olsen, P.E., and D.V. Kent, 1999. Long-period Milankovitch cycles from the Late Triassic and Early Jurassic of eastern North America and their implications for the calibration of the early Mesozoic time scale and the long-term behavior of the planets. Philos. Trans. Roy. Soc. London (A) 357, 1761-1787.

Palike, H., J. Laskar, and N.J. Shackleton, 2004. Geologic constraints on the chaotic diffusion of the solar system. Geology 32, 929-932.

Park, J., and R.J. Ogelsby, 1994. The effect of orbital cycles on Late and Middle Cretaceous climate: a comparative general circulation model study. Spec. Pubs. Int. Assoc. Sediment 19, 509-529.

Paul, A., and W.H. Berger, 1999. Climate cycles and climate transitions as a response to astronomical and CO_2 forcings. In J. Harff, W. Lemke and K. Stattegger (Eds) Computerized Modeling of Sedimentary Systems. Springer-Verlag, Berlin, Heidelberg, New York, pp. 223-245.

Paytan, A., M. Kastner, and F. Chavez, 1996. Glacial to interglacial fluctuations in productivity in the equatorial Pacific as indicated by marine barite. Science 274, 1355-1357.

Penck, A., and E. Brückner, 1909, *Die Alpen im Eiszeitalter*. 3 vols. C.H. Tauchnitz, Leipzig, 1199pp.

Peltier, W.R., and R.G. Fairbanks, 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. Quaternary Science Reviews, 25,3322-3337.

Petit, J.R., J. Jouzel, D. Raynaud, N.I. Barkov, J.-M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, M. Delmotte, V.M. Kotlyakov, M. Legrand, V.Y. Lipenkov, C. Lorius, L. Pépin, C. Ritz, E. Saltzman and M. Stievenard, "Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica." *Nature*, vol. 399, pp. 429-436, 1999.

Pettersson, H., 1953. Westward Ho with the Albatross. Dutton & Co., New York, 218pp.

Pisias, N.G., and T.C. Moore, 1981. The evolution of Pleistocene climate: a time series approach. Earth Planet Science Letters, 52, 450-456.

Pisias, N.G., L.A. Mayer, A.C. Mix, 1995. Paleoceanography of the eastern equatorial Pacific during the Neogene: Synthesis of Leg 138 drilling results. Proceedings Ocean Drill. Progr., Scientific Results, 138, 5-21.

Pollard, D., 1984. Some ice-age aspects of calving ice-sheet model. In: A. L. Berger et al. (eds.), Milankovitch and Climate, Part 2, 541-564. D. Reidel, Dordrecht.

Pratt, L.M., 1984. Influence of paleoenvironmental factors on preservation of organic matter in middle Cretaceous Greenhorn Formation, Pueblo, Colorado. Bull. Am. Assoc. Petrol. Geol. 68, 1146-1159.

Raymo, M.E., 1994. The initiation of northern hemisphere glaciation. Ann. Rev. Earth Planet. Sci. 22,353-383.

Raymo, M.E., 1997. The timing of major climate terminations. Paleoceanography 12, 577-585.

Raymo, M.E., and W.F. Ruddiman, 1992. Tectonic forcing of late Cenozoic climate. Nature 359, 117-122.

Rea, D. K., Chambers, L. W., Chuey, J. M., Janecek, T. R., Leinen, M., and Pisias, N. G., 1986, A 420,000-year record of cyclicity in oceanic and atmospheric processes from the eastern equatorial Pacific, Paleoceanogr., 1:577-586.

Rial, J.A., 1999. Pacemaking the ice ages by frequency modulation of the Earth's orbital eccentricity. Science 285, 564-568.

Ricken, W., 1994. Compex rhythmic sedimentation related to third-order sea-level variations: Upper Cretaceous, Western Interior Basin, USA. Spec. Publs. Int. Assoc. Sediment. 19, 167-193.

Roemmich, D., and J. McGowan, 1995. Climatic warming and decline of zooplankton in the California Current. Science 267, 1324-1326.

Ruddiman, W.F., 201. Earth's Climate: Past and Future. Freeman, New York, 465pp.

Ruddiman, W.F., and J.E. Kutzbach, 1991. Plateau uplift and climatic change. Scientific American 264, 66-75.

Ruddiman, W.F., Raymo, M.E., and McIntyre, A., 1986. Matuyama 41,000-year cycles: North Atlantic ocean and northern hemisphere ice sheets. Earth Planet. Sci. Lett. 80, 117-129.

Ruddiman, W.F., M.E. Raymo, D.G. Martinson, B.M. Clement, and J. Backman, 1989. Mid-Pleistocene evolution of Northern Hemisphere climate, Paleoceanography, 4, 353-412.

Saltzman, B., and A. Sutera, 1987. The mid-Quaternary climate transition as the free response of a three-variable dynamical model. J. Atmos. Sciences 44, 236-241.

Saltzman, B., A.R. Hansen, and K.A. Maasch, 1984. The late Quaternary glaciations as the response of a three-component feedback system to earth-orbital forcing. J. Atmos. Sciences 41, 3380-3389.

Sarnthein, M., K. Winn, J.-C. Duplessy, and M.R. Fontugne, 1988. Global variations of surface ocean productivity in low and mid latitudes: Influence on CO_2 reservoirs of

the deep ocean and the atmosphere during the last 21,000 years. Paleoceanography 3, 361-399.

Savdra, C.E., and D.J. Bottjer, 1994. Ichnofossils and ichnofabrics in rhythmically bedded pelagic/hemi-pelagic carbonates: recognition and evaluation of benthic redox and scour cycles. Spec. Publs. Int. Assoc. Sediment. 19, 195-210.

Schlanger, S.O., and H.C. Jenkyns, 1976. Cretaceous Oceanic Anoxic Events: causes and consequences. Geol. Mijnb. 55, 179-184.

Scholle, P.A., and M.A. Arthur, 1980. Carbon isotope fluctuations in Cretaceous pelagic limestones; potential stratigraphic and petroleum exploration tool, Am. Assoc. Petrol. Geol. Bull. 64, 67-87.

Schwarzacher, W., 1991. Milankovitch cycles and the measurement of time. In: G. Einsele, W. Ricken and A. Seilacher (eds) Cycles and Events in Stratigraphy. Springer, Berlin Heidelberg, pp. 855-863.

Schwarzbach, M., 1961. Das Klima der Vorzeit. Ferdinand Enke, Stuttgart, 275pp.

Shackleton, 2006. Formal Quaternary stratigraphy – What do we expect and need? Quaternary Science Reviews 25, 3458-3462,

Shackleton, N.J. and Opdyke, N.D., 1973. Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific Core V28-238: oxygen isotope temperatures and ice volume on a 10^5 year and 10^6 year scale. Quaternary Res., 3: 39-55.

Shackleton, N.J., Backman, J., Zimmerman, H., Kent, D.V., Hall, M.A., Roberts, D.G., Schnitker, D., Baldauf, J.G., Desprairies, A., Homrighausen, R., Huddlestun, P., Keene,J.B., Kaltenback, A.J., Krumsiek, K.A.O., Morton, A.C., Murray, J.W., and Westberg-Smith, J., 1984. Oxygen isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic region. Nature, 307, 602-623.

Shackleton, N.J., A. Berger, and W. R. Peltier, 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. Trans. Roy. Soc. Edinburgh: Earth Sci., 81, 251-261.

Shackleton, N. J., S. Crowhurst, T. Hagelberg, N. G. Pisias, and D. A. Schneider, 1995. A new late Neogene time scale: Application to Leg 138 sites, Proc. Ocean Drill. Program Sci. Results, 138, 73–101.

Shackleton, N.J., M.A. Hall, I. Raffi, L. Tauxe, and J. Zachos, 2000. Astronomical calibration age for the Oligocene-Miocene boundary. Geology 28, 447-450.

Shinn, E.A., 2001. Coral reefs and shoreline dipsticks. In: L.C. Gerhard, W.E. Harrison, and B.M. Hanson (eds) Geological Perspectives of Global Climate Change. Am. Assoc. Petrol. Geol., Tulsa, Okla., pp. 251-264.

Smith, D.G., 1994. Cyclicity or chaos? Orbital forcing versus non-linear dynamics. Spec. Publs. Int. Assoc. Sediment. 19, 531-544.

Tauxe L, Deino AD, Behrensmeyer AK, Potts R (1992) Pinning down the Brunhes/Matuyama and upper Jaramillo boundaries: A reconciliation of orbital and isotopic time scales. Earth Planet. Sci. Lett. 109:561-572.

Thiede, J., and Suess, E. (eds) 1983. Coastal upwelling its sediment record. Part B: Sedimentary records of ancient coastal upwelling. Plenum Press, New York and London, 610pp.

Tiedemann, R.M., M. Sarnthein and N.J. Shackleton, 1994. Astronomic calibration for the Pliocene Atlantic $\delta^{18}O$ and dust flux records of Ocean Drilling Program Site 659. Paleoceanography 9,619-638.

Toggweiler, J.R., and H. Bjornsson, 2000. Drake Passage and paleoclimate. J. Quaternary Sci. 15, 219-238.

Van Donk, J., 1976. O^{18} record of the Atlantic Ocean for the entire Pleistocene epoch. Geol. Soc. Am. Memoir 145, 147-163.

Von Koenigswald, W., 2002. Lebendige Eiszeit – Klima und Tierwelt im Wandel.

Wissenschaftliche Buchgesellschaft Theiss, Darmstadt, 190pp.

Wallace, A.R., 1895, *Island Life or the Phenomena and Causes of Insular Faunas and Floras Including a Revision and Attempted Solution of the Problem of Geological Climates*, 2nd ed., Macmillan, London, 563pp.

Weertman, J., 1976. Milankovitch solar radiation variations and ice age ice sheet sizes. Nature 261, 17-20.

Wefer, G., W.H. Berger, C. Richter, and Scientific Shipboard Party, 1998. Proceedings of the Ocean Drilling Program, Init. Rpts., vol. 175.

Wefer, G., W.H. Berger, J. Bijma and G. Fischer, 1999. Clues to ocean history: a brief overview of proxies. In: G. Fischer and G. Wefer (eds.), Use of Proxies in Paleoceanography: Examples from the South Atlantic. Springer-Verlag Berlin Heidelberg, pp. 1-68.

Wegener, A., 1929. Die Entstehung der Kontinente und Ozeane. 4te Ed. F. Vieweg, Braunschweig, (translated by J. Binram: "The Origin of Continents and Oceans," 1966, Dover, New York, 346pp.)

Whitman, J.M., and W.H. Berger, 1992. Pliocene-Pleistocene oxygen isotope record of Site 586, Ontong Java Plateau. Marine Micropal. 18, 171-198.

Winograd, I. J., T.B. Coplen, J.M. Landwehr, A.C. Riggs, K.R. Ludwig, B.J. Szabo, P.T. Kolesar, and K.M. Revesz, 1992. Continuous 500,000-year climate record from vein calcite in Devils Hole, Nevada. *Science* 258: 255-260.

Zachos, J., M. Pagani, L. Sloan, E. Thomas and K. Billups. 2001. Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present. Science, 292:686-693.

Zeuner, F.E., 1945. The Pleistocene Period, Its Climate, Chronology and Faunal Succession. Royal Society, London, 322pp.