The 41 kyr world: Milankovitch's other unsolved mystery

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[1] For most of the Northern Hemisphere Ice Ages, from ~3.0 to 0.8 m.y., global ice volume varied predominantly at the 41,000 year period of Earth's orbital obliquity. However, summer (or summer caloric half year) insolation at high latitudes, which is widely believed to be the major influence on high-latitude climate and ice volume, is dominated by the 23,000 year precessional period. Thus the geologic record poses a challenge to our understanding of climate dynamics. Here we propose that variations in the insolation gradient between high and low latitudes control high-latitude climate and ice volume during the late Pliocene and early Pleistocene. The differential heating between high and low latitudes, driven by obliquity, controls the atmospheric meridional flux of heat, moisture, and latent energy, which may exert the dominant control on high-latitude climate on Milankovitch timescales. In the two-dimensional zonal energy balance models typically used to study the long-term evolution of climate, the meridional atmospheric moisture flux is usually kept fixed. The hypothesis that insolation gradients control the poleward energy fluxes, precipitation, and ice volume at high latitudes has never been directly examined within the context of an ice sheet model. In light of what we know about modern energy fluxes and their relative influence on high-latitude climate, this possibility should be examined. *INDEX TERMS:* 4267 Oceanography: General: Paleoceanography; 1620 Global Change: Climate dynamics (3309); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; *KEYWORDS:* Milankovitch, orbital variations, ice ages, Pleistocene, obliquity, paleoclimate

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1. Introduction

[2] All serious students of Earth's climate history have heard of the "100 kyr problem" of Milankovitch orbital theory, namely the lack of an obvious explanation of the dominant ~100 kyr periodicity in climate records of the last 800,000 years. However, few have considered an equally perplexing characteristic of Earth's climate, one that similarly defies simple physical explanation yet dominates the Earth's recent geologic record. We call this the "Milankovitch 41 kyr problem." For the time interval extending back to the Brunhes-Matuyama boundary (0.78 Ma), an interval in Earth's climate history dominated by the large (and largely unexplained) 100,000 year periodicity, *Imbrie et al.* [1992] definitively showed that the obliquity (41,000 year) and precessional (23,000 year) frequencies observed in climate records were direct linear responses, with physically appropriate lags, to high-latitude summer insolation forcing. However, during the previous two million years of Northern Hemisphere ice sheet growth, from ~3 million years ago to about 0.8 million years ago, global ice volume varied almost exclusively at the 41,000 year obliquity period. Because high-latitude summer insolation is always dominated by precession, we argue that these earlier climate variations cannot be understood within the current framework of the Milankovitch Hypothesis. Finding an explanation for late Pliocene to early Pleistocene global climate variations represents one of the most interesting and challenging problems facing climate modelers today.

2. Ice Age Record

[3] The outlines of Earth's climate history for the last 3 million years have been known for nearly two decades. With an extremely low sedimentation rate piston core and then with longer Deep Sea Drilling Project cores, Nicholas Shackleton, and later William Ruddiman and others, measured oxygen isotopes in benthic foraminifera to derive a proxy for global ice volume over the last 3 million years. Many records generated since this time have confirmed their early observations, namely: (1) the main frequency of ice volume change from 3.0 to 0.8 m.y. was 41,000 years, the primary obliquity period; (2) after ~0.8 Ma, ice sheets varied predominately at the 100,000 year period and the amplitude of $\delta^{18}O$ variability increased implying growth of larger ice sheets.

[4] The double-cored and spliced benthic $\delta^{18}O$ record from DSDP607 nicely illustrates both these points (Figure 1a). Note that the isotope record is plotted with a paleomagnetic

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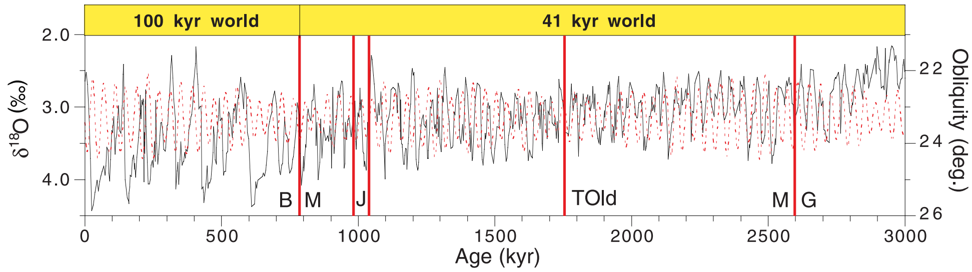

Figure 1. Benthic δ^{18}O record from DSDP Site 607 in the North Atlantic (solid line) plotted to a paleomagnetic timescale. The magnetic field reversals are marked, as well as the transition from a dominant 41 kyr to a 100 kyr world. B, Brunhes; M, Matuyama; J, Jaramillo; TOld, top of Olduvai; G, Gauss. Also shown is orbital obliquity (red dashed line).

timescale (Table 1) determined by the depth of magnetic field reversals recorded by ferromagnetic grains in the sediment core [*Clement and Kent*, 1986]. Constant sedimentation rates are assumed between these magnetic reversal events (shown on Figure 1) which are dated by interpolating seafloor magnetic anomalies between fixed calibration points [*Cande and Kent*, 1992, 1995]. The two calibration points used in the post-3.0 Ma section of the record are independently derived by both radiometric and astronomic tuning techniques [*Berggren et al.*, 1995].

[5] Using this simple timescale, which is not biased by orbital "tuning," one can clearly observe the dominant 41,000 year periodicity of the Matuyama and Gauss intervals [see also *Imbrie et al.*, 1993a; *Tiedeman et al.*, 1994]. The obliquity periodicity can be further illustrated by statistically filtering the data at 41,000 years or by Fourier analysis (Figure 2a). Note the near complete lack of variance at the 23,000 year precessional and 100,000 year eccentricity frequencies. Indeed, over long parts of the record the δ^{18}O curve looks almost sinusoidal. Nearly identical results are seen in many other deep sea isotope records including benthic δ^{18}O records from the Pacific plotted either to paleomagnetic or orbitally tuned timescales (e.g., Figure 2b).

[6] Because Site 607 is located in the subpolar North Atlantic (41°N, 33°W, 3427 mbsl), it also contains a record of ice-rafted detritus (IRD) delivered to the open ocean over the Plio-Pleistocene. Over the entire length of the glacial record (>125 m), the input of IRD covaries with δ^{18}O [*Raymo et al.*, 1989; *Ruddiman et al.*, 1989]. The sedimentological data thus demonstrates that variability observed in benthic δ^{18}O must derive in part from the waxing and waning of ice sheets bounding the North Atlantic.

3. Current Milankovitch Theory

[7] Based mainly on climate proxy records of the last 0.5 Ma, a general scientific consensus has emerged that variations in summer insolation at high northern latitudes are the dominant influence on climate over tens of thousands of years. The logic behind nearly a century's worth of thought on this topic is that times of reduced summer insolation could allow some snow and ice to persist from year to year, lasting through the "meltback" season. A slight increase in accumulation from year to year, enhanced by a positive snow-albedo feedback, would eventually lead to full glacial conditions. At the same time, the cool summers are proposed to be accompanied by mild winters which, through the temperature-moisture feedback [*Kallen et al.*, 1979], would lead to enhanced winter accumulation of snow. Both effects, reduced spring-to-fall snowmelt and greater winter accumulation, seem to provide a logical and physically sound explanation for the waxing and waning of the ice sheets as high-latitude insolation changes [e.g., see *Hartmann*, 1994, p. 310]. However, in this model, the seasonal contrast, which is controlled by obliquity, only changes systematically at the 41,000 year period only if the precessional effects on insolation are assumed to cancel out over the course of the annual cycle. This assumption has generally not been made due to the presence of a strong precessional signal in late Pleistocene records, hence the greater relative importance accorded summer insolation versus seasonal contrast in controlling past climate.

[8] Over the last two decades, countless research papers have plotted (or tuned) climate records to June 65°N or July 65°N insolation. Using many of these records, *Imbrie et al.* [1992] showed that climate variance at precessional and obliquity frequencies appeared to be linearly forced by and was coherent with northern summer insolation. Only the 100,000 year cycle is left unexplained by this model (the familiar "100,000 year problem") and it, typically, is ascribed to non-linear variability arising internally within the climate system. A comprehensive summary of work on this subject is given by *Imbrie et al.* [1992, 1993b] [see also *Peltier and Marshall*, 1995; *Gildor and Tziperman*, 2000; *Muller and MacDonald*, 2000].

[9] In the late Pliocene and early Pleistocene, no significant variance at the 100 kyr period is observed in benthic

Table 1. Age Control Points Used for Paleomagnetic Timescale at DSDP Site 607

Depth, mcd	Age, kyr	Magnetic Event
0.0	0	top of core
31.84	780	Brunhes/Matuyama
40.345	984	Jaramillo top
43.965	1049	Jaramillo bottom
73.655	1757	Olduvai top
111.58	2600	Matuyama/Gauss
129.50	3054	Kaena top

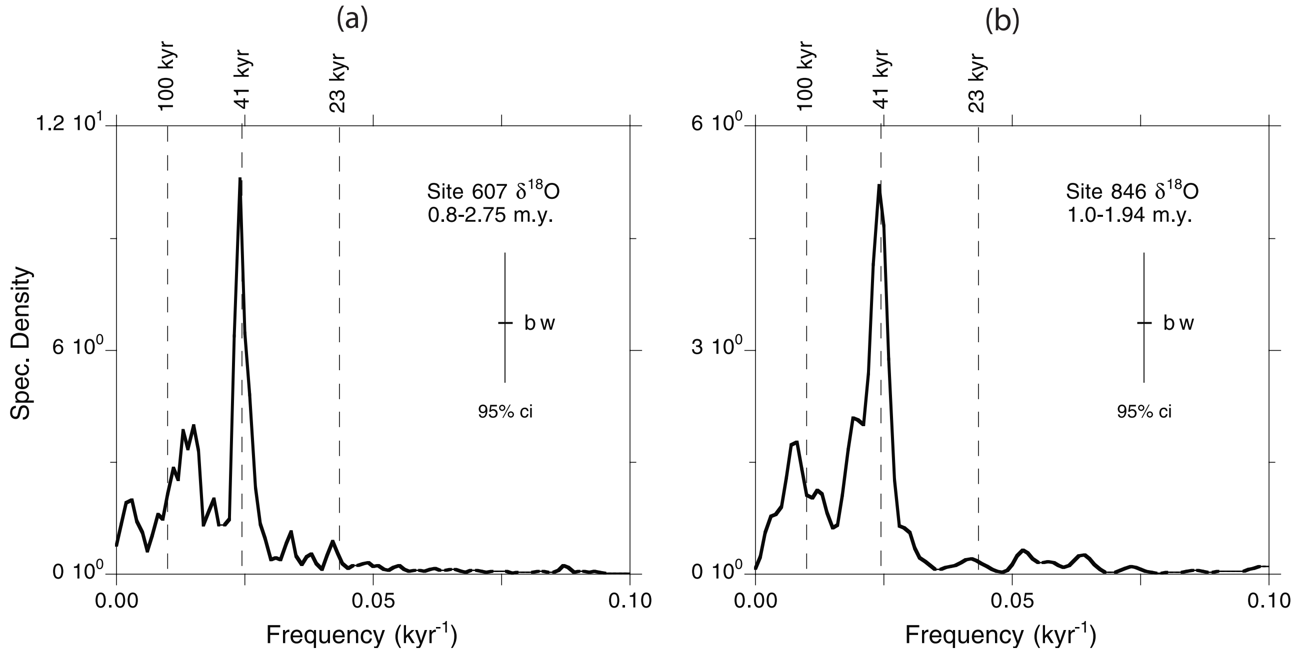

Figure 2. (a) Power spectra of Site 607 δ^{18}O plotted using timescale discussed in text (Table 1). The concentration of variance around 75–80 kyr is likely due to harmonics arising from the main obliquity frequency; (b) power spectra of the benthic δ^{18}O record of ODP Site 846 [*Mix et al.*, 1995] plotted to orbitally tuned timescale of *Shackleton et al.* [1990]. Bandwidths (bw) and confidence intervals (ci) shown on figure.

δ^{18}O records. Hence one might expect that the de facto implication of the "standard Milankovitch model" would be that global ice volume should vary linearly and coherently with high northern summer insolation. However, a comparison of δ^{18}O (ice volume; Figure 1) with various insolation records (Figure 3) clearly shows that while the ice volume proxies are dominated nearly exclusively by the 41,000 year obliquity periodicity, summer insolation is dominated, at nearly every latitude, by the 23,000 year period of precession. Any linear response to summer (or summer half year) insolation by high-latitude climate would require the strong presence of precession in the geologic record. In fact, this frequency is barely discernable in only a small stretch of the late Pliocene ice volume record and is absent over most (Figures 1 and 2). One must conclude that summer insolation at high northern latitudes does not exert a dominant (linear) influence on climate over most of the northern hemisphere Ice Ages.

4. The 41 kyr Problem

[10] While many investigators have attempted to model the 100 kyr world, few have focused their attention on the 41 kyr world. A notable exception is Andre Berger and colleagues who used a two dimensional ice sheet-climate model to try to simulate the growth and decay of ice sheets over the last 3 million years [e.g., *Berger et al.*, 1999]. While the obliquity period is present in the model output, precessional variance in ice sheet mass is also strongly present. In other words, although they successfully model the lack of the 100 kyr eccentricity cycle, they were not able to model an ice sheet that varies only at the obliquity frequency. This appears to be because the model is ultimately very sensitive to high-latitude summer insolation.

[11] Secondly, a discussion of the 41 kyr problem can be found in Richard Muller and Gordon MacDonald's book "Ice Ages and Astronomical Causes" [*Muller and Gordon*, 2000]. Following *Kukla* [1968], they propose that northern latitude winter insolation (e.g., January 65°N) may drive late Pliocene/early Pleistocene climate cycles, even though the total insolation received in January is a factor of 20 less than summer insolation at the same latitude. However, they go on to say this proposition is speculative and that the geologic record is posing a problem that needs to be solved.

5. Insolation Gradients

[12] Given that summer insolation has too much precession and (one could argue) winter insolation appears too weak to drive anything, what is left? We propose that the gradient in insolation between high and low latitudes may, through its influence on the poleward flux of moisture which fuels ice sheet growth, play the dominant role in controlling climate from ~3 to 1 million years ago. Summer half-year insolation, for instance, is calculated as the mean of insolation received between the vernal (0°) and autumnal (180°) equinoxes as defined by the longitude of the sun in degrees. The gradient (or difference) in summer half-year insolation between 25° and 70°N (Figure 3) is almost completely dominated by obliquity (spectra shown in Figure 4). It is this temperature gradient that drives the poleward heat, moisture, and momentum fluxes in the atmosphere; the

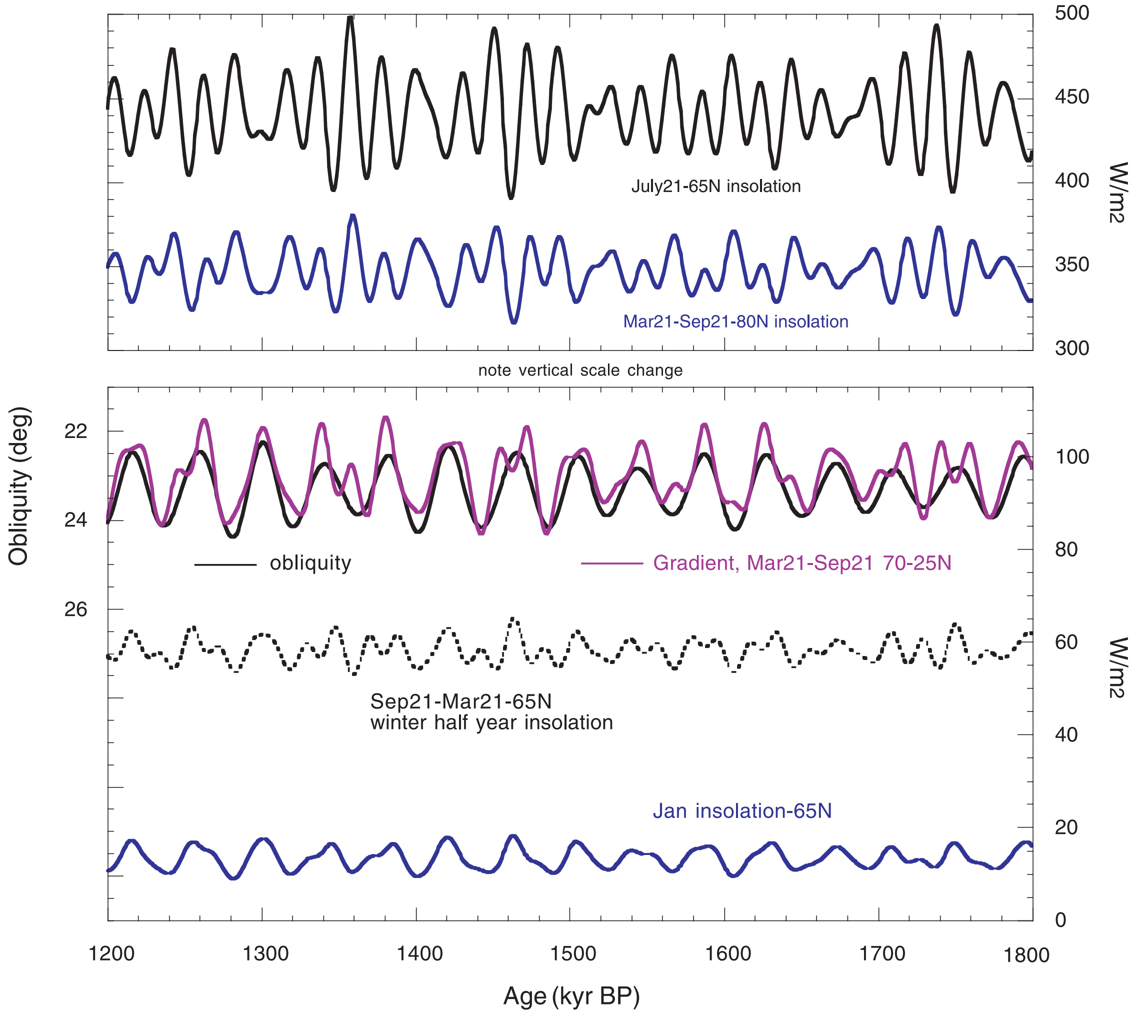

Figure 3. Various insolation and insolation gradient curves compared with obliquity. Curves derived using the *Laskar* [1990] orbital solution and Analyseries software of *Paillard et al.* [1996].

correlation between $\delta^{18}O$ and the insolation gradient (Figure 5) suggests that increased gradients promote ice sheet growth (although given the uncertainties in the timescale we cannot definitively rule out other possibilities). Note that the oxygen isotope record in Figure 5 has been shifted to an older age by 8 kyr, a reasonable lag to assume for the climate response to obliquity and consistent with late Pleistocene observations [e.g., *Imbrie et al.*, 1992]. Of course the true lag of response after forcing would be almost impossible to determine directly in sediments of this age.

[13] The idea that insolation gradients could exert an important control on climate on Milankovitch timescales is not new; *Young and Bradley* [1984] proposed that hemispheric insolation gradients may have contributed to the growth and decay of continental ice sheets through their modulating influence on the poleward transport of moisture. They, and previously *Berger* [1976], suggest that times of rapid ice growth and decay correspond to especially pronounced deviations in latitudinal insolation gradients. *Johnson* [1991] similarly invokes a decrease in the insolation gradient, rather than direct summer insolation at high latitudes, as the immediate cause of the deglaciation at Termination 2, offering this mechanism as the explanation for paleoclimate data which suggest that deglaciation occurred prior to the increase in summer insolation. This perplexing mismatch in timing between the deglaciation at Termination 2 and the timing predicted by Milankovitch theory has also been discussed by *Winograd et al.* [1992] and more recently by *Gallup et al.* [2002].

[14] It may be that we are underestimating the influence of meriodional fluxes of sensible and latent heat, driven by hemispheric temperature gradients, on continental ice sheet size. The mass balance of an ice sheet is set by the relative rates of accumulation and ablation. The rate of ablation is controlled by local incoming solar radiation and local atmospheric temperature. The rate of accumulation is controlled by the amount of moisture available for precipitation as well as the local temperature. As temperature and precipitation at high latitudes are strongly influenced by the magnitude of the atmospheric meridional heat and moisture fluxes, we would thus expect these fluxes to exert a strong influence on ice sheet mass balance. Today, annual mean poleward transports of heat by the atmosphere peak at about 5.0 PW in the mid-latitudes of both hemispheres [*Trenberth*

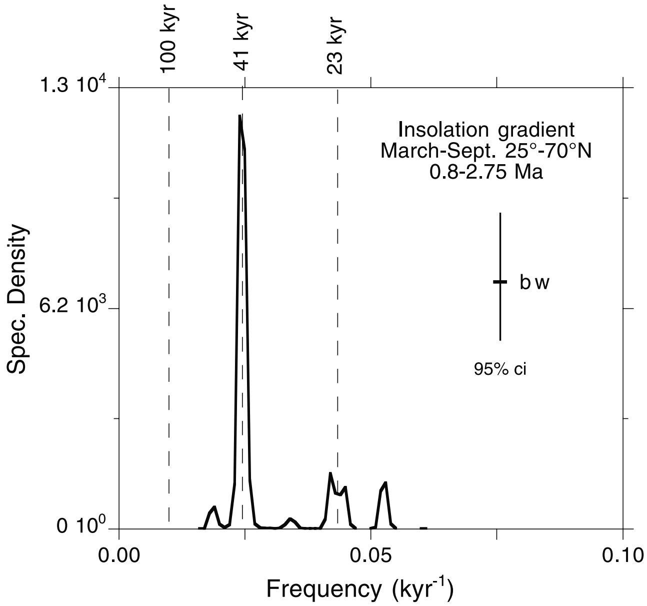

Figure 4. Power spectra of the gradient in insolation between 25° and 70°N for the summer half year between 0° (vernal equinox) and 180° (autumnal equinox). Bandwidth (bw) and confidence interval (ci) shown on figure.

and Caron, 2001], compensating the loss of heat to space from the polar regions. At high latitudes (>60°N) the Earth emits on an annual basis approximately twice as much energy (as long wave radiation) as it receives from absorbed solar radiation [*Hartmann*, 1994]; hence the meridional heat flux is comparable in magnitude to that received from high-latitude insolation. Lastly, recent studies suggest that a much greater portion of poleward energy transport occurs in the atmosphere, rather than the ocean which would be less directly affected by insolation gradients [*Trenberth and Caron*, 2001].

[15] All of the above observations suggest the possibility that variations in meridional heat and moisture fluxes (driven by orbital obliquity variations) could be large enough to override the effects of local insolation variations and imprint the dominant 41 kyr signal on the ice volume record. This seems especially plausible given the powerful ice-albedo feedback that would enhance the effects of insolation gradients on poleward energy transports. As the polar atmospheric temperature cooled at the onset of a glacial period, snow and ice would expand into regions previously covered by surfaces such as forests that have relatively low albedo. This increased snow/ice cover would raise the surface albedo dramatically, reflecting incoming radiation, and causing a further decrease in local temperature [e.g., *Bonan et al.*, 1992; *Kutzbach and Gallimore*, 1998]. Such an albedo change could have two effects: (1) act as a strong positive feedback on the meridional temperature gradients, further enhancing the poleward transport of the moisture that feeds ice sheet growth; and (2) act as a negative feedback by causing local cooling which decrease moisture availability through the temperature-precipitation feedback. Perhaps it is the interplay between these two feedbacks that determines the maximum ice sheet size (and perhaps the difference between the early and late Pleistocene climate behavior).

[16] Support for the idea that insolation gradients influence moisture flux to the ice sheets is found in the Antarctic deuterium excess record of the past 150 Ka which shows a strong correlation with the mean annual insolation gradient from 20°S to 60°S [*Vimeux et al.*, 1999]. As deuterium excess is a measure of the evaporative conditions of the oceanic source region for the moisture, this data indicates that there is a strong link between the insolation gradient and atmospheric moisture supply to the ice sheets. Note, that the deuterium excess values are high during glacial inception, a

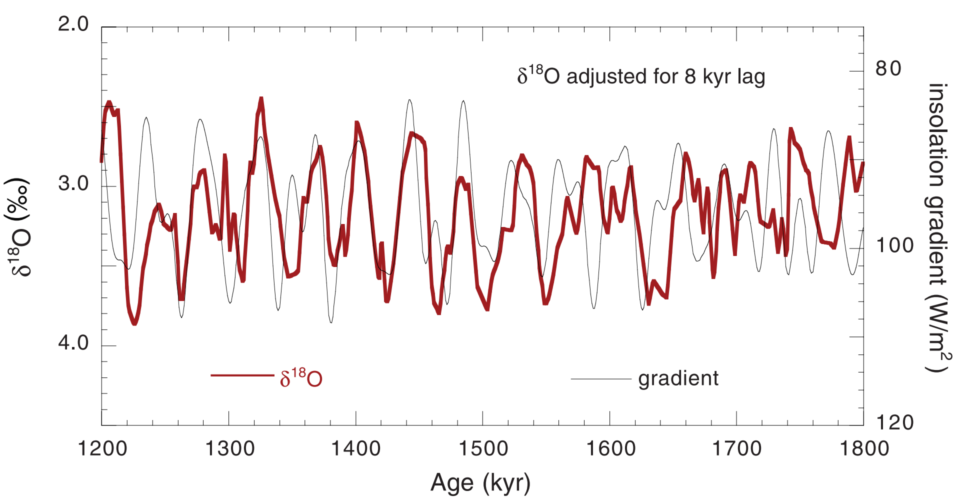

Figure 5. Site 607 benthic $\delta^{18}O$ record plotted versus the summer half-year gradient between 25° and 70°N. Isotope data is plotted to paleomagnetic timescale given in Table 1 and then shifted older by an assumed response lag of 8 kyr after the forcing [after *Imbrie et al.*, 1992] to better illustrate the correlation between the two parameters. The gradient in insolation is in phase with and shows a similar amplitude modulation as obliquity.

period characterized by low obliquity (cold high-latitude summers), and high meridional insolation gradient (e.g., a strong meridional atmospheric moisture flux).

[17] In most climate modeling studies of the long-term evolution of glacial-interglacial cycles (typically 2-D zonal energy balance models), the meridional atmospheric moisture flux has been kept fixed. Typically, models perturb the modern observed precipitation field according to changes in temperature. As a result, changes in atmospheric moisture flux have no impact on high-latitude precipitation and the accumulation of ice sheets. A notable exception is the study by *Gildor and Tziperman* [2000]. However, the hypothesis that insolation gradients as they control variations in poleward moisture fluxes and precipitation at high latitudes has never been directly examined within the context of an ice sheet model. In light of what we know about modern energy fluxes and their relative influence on high-latitude climate, this possibility should be examined.

6. Future Directions

[18] Above, we propose a "gradient hypothesis": that the strong obliquity signal imprinted on the Ice Age record is caused by the control meridional temperature gradients exert on the poleward transport of moisture. As obliquity decreases, cooling at high latitudes occurs and the gradient in solar heating between high and low latitude increases. Both effects, cooling polar regions and the enhanced delivery of moisture, promote ice sheet growth. The ice volume/ temperature history of the last few million years is now well known and, as discussed above, poses a challenge both to climate modelers and paleoclimatologists. Ultimately, ocean circulation and ice volume are being controlled by atmospheric dynamics that must be sensitive to Milankovitch variations in incoming solar radiation. These are the same physical processes that will determine the response of Earth's climate to rising greenhouse gases. Building a model which can reproduce the first-order features of the Earth's Ice Age history over the Plio-Pleistocene would be an important step forward in the understanding of the dynamic processes that drive global climate change.

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