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Is the spectral signature of the 100 kyr glacial cycle consistent with a Milankovitch origin?

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Abstract. Milankovitch theory seeks to explain the Quaternary glaciations via changes in seasonal insolation caused by periodic changes in the Earth's obliquity, orbital precession, and eccentricity. However, recent high-resolution spectral analysis of $\delta^{18}O$ proxy climate records have cast doubt on the theory [*Muller and MacDonald*, 1997a, b]. The spectral signature of the "100 kyr" component, which dominates the climate record over the past 0.6-0.8 Myr does not match the frequencies of the eccentricity variation. *Muller and MacDonald* [1997b, c] have therefore argued that a more likely pacemaker for the climate cycles is the variation in inclination of the Earth's orbit relative to the invariant plane of the solar system. Here we show that the spectral signature of $\delta^{18}O$ records are entirely consistent with Milankovitch mechanisms in which deglaciations are triggered every fourth or fifth precessional cycle. Such mechanisms may involve the buildup of "excess" ice due to low summertime insolation at the previous precessional "high."

Spectral analysis techniques traditionally applied to proxy climate records have involved the use of specialized windowing functions because of the finite length of the record available. These have the effect of artificially broadening the spectral peaks such that closely spaced peaks may not be fully resolved. Alternatively, use of a simple "boxcar" window following *Muller and MacDonald* [1997b] will maximize the spectral (frequency) resolution. This is achieved at the expense of potential truncation artifacts (manifested as "spurious" peaks in the spectra), although in the spectral analyses presented here, such additional peaks are not significant. In addition, simple methods like this are not able to place any confidence intervals on the results. Global ice volume proxy records obtained from deep-sea sediment cores, such as the SPECMAP $\delta^{18}O$ stack [*Imbrie et al.*, 1984] (Figure 1a), when analyzed in this way produce a narrow peak corresponding to a period of ~100 kyr that dominates the low-frequency (0-0.02 kyr^{-1}) part of the spectrum (Figures 2a, and 2b). This contrasts with the spectrum of orbital eccentricity variation, often assumed to be the main candidate to pace the glaciations [*Hays et al.*, 1980], which shows two distinct peaks near 100 kyr and substantial power near the 413 kyr period (Figure 2c). *Muller and MacDonald* [1997b, c] have interpreted the monochromatic nature of the $\delta^{18}O$ record at these low frequencies to indicate the existence of an extremely regular 100 kyr glacial cycle, which must therefore be driven by a non-Milankovitch astronomical mechanism. However, inspection of these records suggests that despite the sharpness of the 100 kyr spectral peak the relatively rapid deglaciations ("terminations") do not occur at regular intervals but tend to deviate from true 100 kyr intervals by up to ±20 kyr [*Raymo*, 1997].

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We suggest that glacial-interglacial terminations can be thought of as "quantum" in nature, with intervening periods corresponding to either four or five precessional insolation cycles [*Raymo*, 1997]. To test whether such a hypothesis would be spectrally consistent with $\delta^{18}O$ records, an artificial waveform was constructed comprising a repeated motif (Figure 1c). The individual motif was repeated with a period of either 4 or 5 complete cycles of June 21, 65°N insolation [*Laskar et al.*, 1993] (Figure 1b), which is largely determined by the precessional orbital component. We used a "sawtooth" motif for most of our studies because of its obvious superficial similarity with $\delta^{18}O$ deep-sea sediment core records, but our conclusions are insensitive to the actual shape; for example, a sinusoidal motif gives essentially the same result. Repeats were constrained to begin on insolation maxima, in line with the findings of modeling studies that the level of summer insolation is critical for the growth and decay of ice sheets [*Berger*, 1988; *Ledley and Chu*, 1995]. The integer number of insolation periods used for each sawtooth was chosen to give an approximate match of termination ages between the sawtooth and SPECMAP $\delta^{18}O$ stack [*Imbrie et al.*, 1984].

The power spectrum of our sawtooth waveform is shown in Figure 2d. At low frequencies this matches that of the $\delta^{18}O$ record (Figure 2b) extremely well; it exhibits a single sharp peak at around 100 kyr and has no power at 413 kyr, unlike models that seek to generate a match to the climate signal by nonlinear amplification of the eccentricity component of insolation, such as the classic ice volume model of *Imbrie and Imbrie* [1980] (Figure 2e). Our spectrum does not depend greatly on the precise timing of the motif repeats; for example, termination dates taken from orbitally tuned SPECMAP [*Imbrie et al.*, 1984] or untuned GSS97 [*Raymo*, 1997] timescales give the same conclusions as do repeats taken at 4 or 5 times a notional insolation period of 22 kyr. The close match between the low-frequency spectra of such quasi-periodic constructs and $\delta^{18}O$ records demonstrates that it is not necessary to

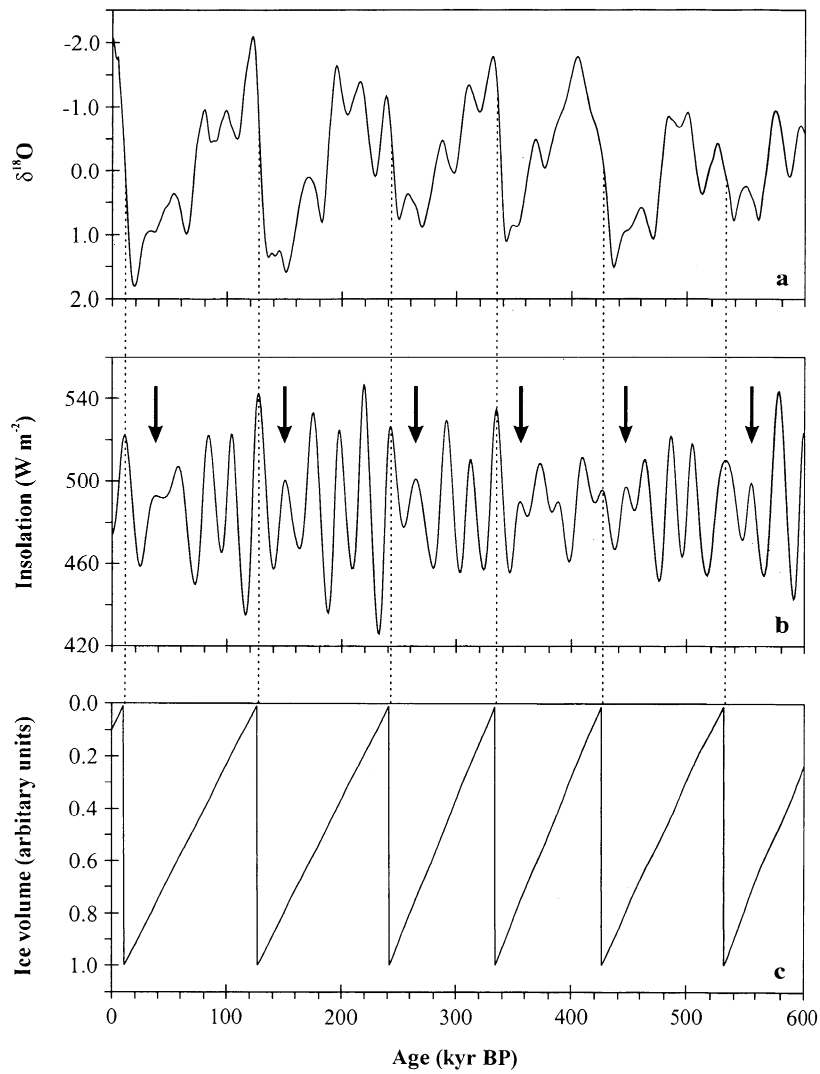

Figure 1. (a) SPECMAP stacked $\delta^{18}O$ composite; (b) insolation for 65°N, June 21, showing the quasi-periodic insolation maxima of unusually low strength (designated by arrows) preceding glacial-interglacial terminations by one precessional cycle in each case; and (c) sawtooth artificial ice volume signal.

hypothesize a truly periodic 100 kyr driving force to explain the sharpness of the 100 kyr peak in the $\delta^{18}O$ spectrum. A solution based upon the 100 kyr periodicity of the orbital inclination of the Earth [*Muller and MacDonald*, 1995, 1997b], which requires the existence of an interplanetary dust or meteoroid cloud in order to explain how the inclination might modulate climate, need not therefore be invoked.

We also investigated the hypothesis that climate cycles are triggered in a similarly quantum way by obliquity forcing occurring in multiples of 2 or 3 times the obliquity period of 41 kyr, i.e., at 82 or 123 kyr intervals. Its spectrum (Figure 2f) demonstrates that similarly large power corresponding to a period of ~100 kyr can be generated by selecting suitable multiples of the obliquity period so that the average period is ~100 kyr, although in this case, substantial spectral power is also observed in side bands. This appears to be a consequence of the larger difference between the two intervals used to make up the quasi-periodic waveform. Thus our investigations lead us to believe that if the 100 kyr climate cycle is paced by an integer number of Milankovitch oscillations, a match involving every fourth or fifth precessional cycle is the pattern most consistent with $\delta^{18}O$ spectra, although other permutations that generate a close spectral match are possible.

By itself this spectral analysis cannot determine the mechanism by which the climate cycles are paced, with terminations occurring only on every fourth or fifth insolation maximum. However, it has recently been noted that glacial-interglacial terminations tend to occur after the previous summer insolation maximum was unusually low at mid Northern Hemisphere latitudes [*Raymo*, 1997] (Figure 1b). If ice buildup in the Northern Hemisphere is normally limited by the periods of high summer insolation, then the episodic existence of these weak insolation maxima (caused by the superposition of periods of low obliquity and eccentricity) may allow a substantial buildup in Northern Hemisphere ice volume. The observed rapid ice sheet collapse at the next precessional high might then be triggered as a result of a threshold mechanism based upon "excess" ice volume, such as a critical level of isostatic bedrock

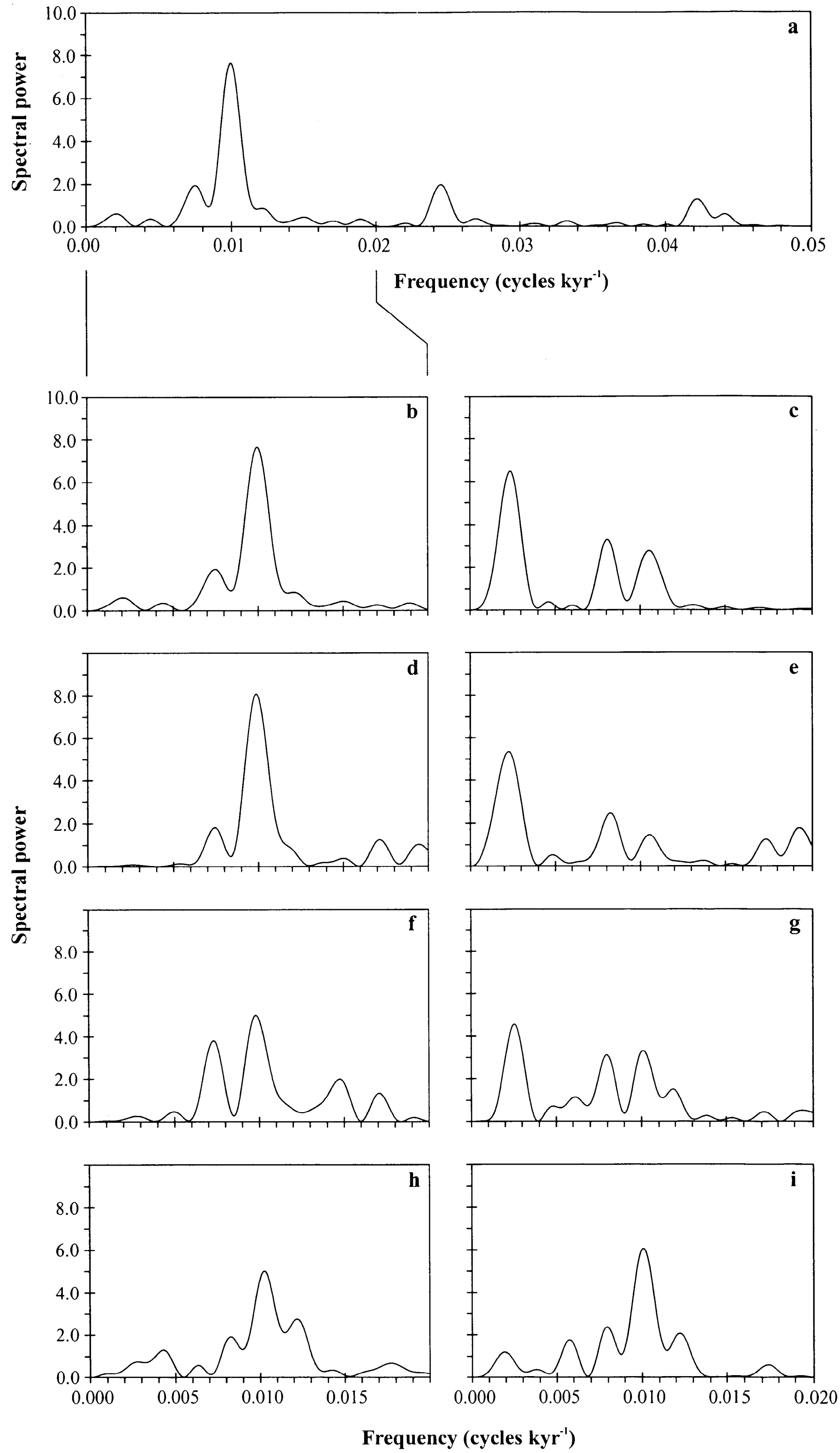

Figure 2. (a) Spectral power signature of SPECMAP stacked $\delta^{18}O$ composite together with expanded low-frequency spectra of (b) SPECMAP stacked $\delta^{18}O$ composite, (c) orbital eccentricity, (d) June 21, 65°N insolation-based sawtooth, (e) *Imbrie and Imbrie* [1980] nonlinear model, (f) obliquity-based sawtooth, (g) Louvain-la-Neuve two-dimensional (LLN 2-D) climate model with Milankovitch forcing only [*Berger et al.*, 1999], (h) *Paillard* [1998] threshold-based model, and (i) LLN 2-D model with Milankovitch and pCO_2 forcings [*Li et al.*, 1998]. All spectra are normalized with mean spectral power over the interval 0-0.02 kyr^{-1} set to unity.

adjustment, having been reached [*Oerlemans*, 1982; *Pollard*, 1982]. Indeed, models based either explicitly or implicitly on multiple thresholds in the climate system have been shown to produce reasonable simulations of the glacial-interglacial cycles in global ice volume [*Berger et al.*, 1999; *Paillard*, 1998]. For instance, the abstracted model of *Paillard* [1998], which is explicitly threshold-based, is conceptually similar to our sawtooth in as much as both "trigger" a deglaciation event in (delayed) association with excess ice volume buildup. In light of this it is not surprising that its spectral signature (Figure 2h) bears a reasonable resemblance to that of our sawtooth and SPECMAP.

Despite the many successes of relatively complex climate models that link together components of the atmosphere, ocean, cryosphere, and lithosphere, such as the Louvain-la-Neuve two-dimensional (LLN 2-D) climate model [*Berger et al.*, 1999, and references therein], the spectral signature of the simulated ice volume (Figure 2g) shows a distinct similarity with that of eccentricity and the simple nonlinear model of *Imbrie and Imbrie* [1980]. This suggests that the nonlinear amplification of eccentricity still represents a significant part of their model response at low frequencies. However, when the LLN 2-D model is forced with a reconstructed atmospheric CO_2 concentration (pCO_2) signal in addition to Milankovitch forcing [*Li et al.*, 1998], the spectral signature is dramatically transformed (Figure 2i) and takes on predominantly SPECMAP-like characteristics. Similarly, *Pisias and Shackleton* [1984] found that the *Imbrie and Imbrie* [1980] ice volume model adopted a $\delta^{18}O$-like spectral character when a reconstructed pCO_2 forcing was added. This confirms what has previously been suspected, that is, that the global carbon cycle is likely to be a critical component of the mechanism(s) controlling the 100 kyr cycles.

If the episodic occurrence of unusually low maxima in Northern Hemisphere summer insolation is indeed the single most critical factor in the timing of the 100 kyr cycle, then its periodicity would arise through a combination of all three Milankovitch periods (precession, obliquity, and eccentricity), rather than by a nonlinear amplification of orbital eccentricity alone. On this basis, phase locking of an internal climate oscillation directly by eccentricity can also be ruled out, although phase locking by the quasi-periodic low insolation maxima is still consistent with our analysis. Eccentricity only paces the glacial-interglacial cycles in the sense that it is the lowest frequency component that enables the reoccurrence of low summer insolation maxima. Its spectral signature does therefore not appear in the late Pleistocene proxy ice volume record.

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