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Pleistocene Climate: Deterministic or Stochastic?

Abstract. *Application of a simple linear model to the earth's ice volume record of the past 730,000 years indicates that although forcing by variations in the earth's orbital parameters of tilt and precession is real, it is small (less than 25 percent of the variance in the record). No relationship with the eccentricity is observed. This indicates that the Pleistocene glacial variations are largely stochastic in nature.*

Recently presented geologic evidence (*1, 2*) strongly supports the astronomical theory of climate change, which states that variations in the seasonal and latitudinal distributions of incoming solar radiation due to long-term variations in the earth's orbital parameters had a significant effect on global climate during the last 2 million years. However, the degree to which the climatic record of glacial and interglacial fluctuations is actually a direct result of orbital controls has not yet been determined (*3*). In addition, the orbital parameters that are expected to have a significant effect on climate are not always those that are actually reflected in the climatic record (*1*). This report addresses these two problems.

The distribution of the sun's energy with respect to latitude is controlled primarily by the tilt of the earth's axis. The distribution of insolation with respect to the seasons is controlled by the precession of the equinox about the sun. Both of these orbital parameters undergo long-term periodic variations caused by the gravitational attraction of other planets in the solar system. Detailed descriptions of these orbital parameters can be found in Chin and Yevjevich (*4*), Broecker and Van Donk (*5*), and Berger (*6*). Based on our precise knowledge of the solar system, the orbital variations have been determined for the past 5 million years, showing that tilt varies with an average period of 41,000 years and precession with an average period of 21,000 years (*6*). The application of spectral analytical techniques to paleoclimatic records obtained from deep-sea cores has identified these periodicities in the record of the earth's climate (*1, 2*).

In many cases most of the variance of these climatic records is centered at frequencies equal to periods of about 100,000 years. This corresponds to the periodicity of variations in the eccentricity of the earth's orbit. According to the astronomical theory of climate change, however, eccentricity influences the earth's insolation only by modifying the magnitude of the precessional effect.

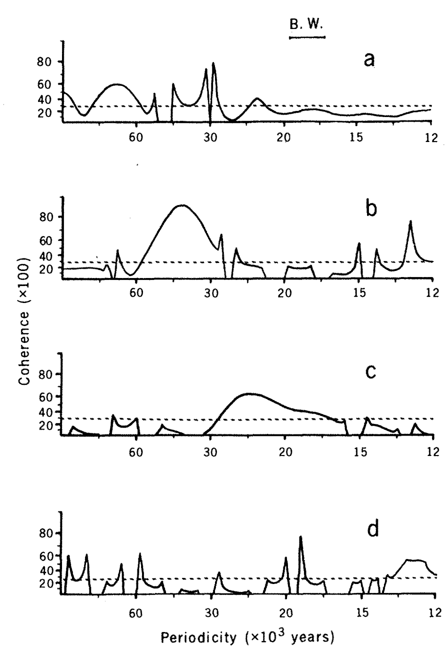

Fig. 1. Coherence spectra, plotted on an arc tangent scale (*9*), of the $\delta^{18}O$ record [TWEAQ time scale (*2*)] with (a) the eccentricity of the earth's orbit, (b) the tilt of the earth's axis, and (c) the precession of the equinox (*6*). The coherence spectrum of the tilt of the earth's axis with the precession of the equinox is shown in (d). All measures of coherence lying below the dashed line are not significantly different from zero at the 80 percent confidence level (16 lags or 20 degrees of freedom). Abbreviation: *B.W.*, bandwidth.

Thus, it should play, at most, a minor role in climatic change (*1*). If we are to understand the exact nature of long-term climatic change it is important to answer the question: How much of this or any other periodic component of the climatic record is attributable to forcing by variations in the earth's orbit?

The problem of the degree to which the climate of the late Pleistocene is either stochastic or deterministic has been approached by a number of authors. Hays *et al.* (*1*) assumed that all the variance in the peaks in the power spectrum of their climatic record, which correspond to the periodicities of precession, obliquity, and eccentricity, could be attributed to forcing. As a result, they concluded that about 80 percent of the variance in their 450,000-year climatic record was due to orbital forcing. Chin and Yevjevich (*4*) presented a mathematical model for long-term changes in the world's ice volume and described climate change as "an almost periodic stochastic process." They concluded that 59 percent of the variation in global ice volume is stochastic.

If variations in tilt and precession are the primary causes of climatic variation, we can calculate the deterministic component of the ice volume record through the use of a two-input, single-output linear time series model. This model considers two input time series $x_1(t)$ and $x_2(t)$ and one output $y(t)$. To get an estimate of the degree to which the output series is controlled by the input series, the pooled coherence function $C^2_{x_1x_2y}(f)$ is required (*7*). This function, which ranges in value from 0 to 1, is analogous to a simple squared correlation coefficient in that its value at a particular frequency f_0 indicates the amount of the variance contained in $y(t)$ at that frequency that can be explained in terms of simple forcing by $x_1(t)$ and $x_2(t)$. If $x_1(t)$ and $x_2(t)$ are independent—that is, if the coherence between them is zero for all frequencies—the expression for the total coherence function for $y(t)$ and both $x_1(t)$ and $x_2(t)$ is

$$C^2_{x_1x_2y}(f) = C^2_{x_1y}(f) + C^2_{x_2y}(f) \quad (1)$$

where $C^2_{x_1y}$ and $C^2_{x_2y}$ are the coherences of $y(t)$ with $x_1(t)$ and $x_2(t)$, respectively (*8*). The spectrum of the estimated output function $S_{x_1x_2y}$ is obtained from the product of the spectrum of $y(t)$, S_y, and the pooled squared coherence $C^2_{x_1x_2y}$

$$S_{x_1x_2y}(f) = S_y(f)\, C^2_{x_1x_2y}(f)$$

The integral of this function gives the amount of variance in $y(t)$ explained by the model.

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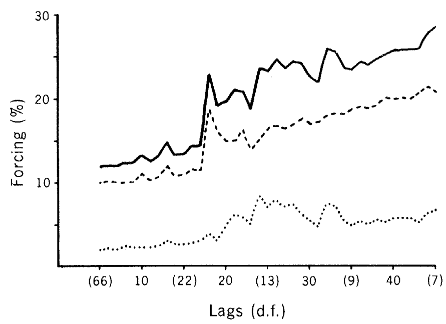

Fig. 2. Relationship between the number of lags used to calculate the autocorrelation function and the resulting degree of forcing calculated with a single-input, single-output model for precession (dotted line) and tilt (dashed line) and with the double-input, single-output model (solid line). Numbers in parentheses are degrees of freedom (*d.f.*).

For the output time series we use the $\delta^{18}O$ record of the Pacific sediment core V28-238 (*9*), which we assume represents the time series of global ice volume during the last 730,000 years. With this record we use the time scale of Kominz *et al.* (*2*), which is based on the "tune-up" time scale of Hays *et al.* (*1*) but extends the tuned relationship of the $\delta^{18}O$ record to the periodic changes in the tilt of the earth's axis and precession of the equinox back to 730,000 years before present.

The coherence spectra between the $\delta^{18}O$ record and eccentricity, tilt, and precession are presented in Fig. 1 (*9*). There is significant coherence (at the 80 percent confidence level) between the $\delta^{18}O$ record and eccentricity (Fig. 1a) at infinite periodicity [$C^2ey(f) = 0.23$] and at an 80,000-year periodicity [$C^2ey(f) = 0.38$]. Neither of these corresponds to peaks in the frequency spectra of either record. It is interesting to note that despite the presence of a prominent 109,000-year peak in the spectra of both records (*2*), there is no significant coherence at this frequency. Thus, there is no simple linear relationship between the eccentricity of the earth's orbit and the $\delta^{18}O$ variations at the dominant frequency of both records.

In contrast, tilt (Fig. 1b) and precession (Fig. 1c) show very strong coherences with the $\delta^{18}O$ record. These coherences correspond directly to the peak frequencies of the spectra. The significant portion of the graph of the coherence between precession and $\delta^{18}O$ appears to consist of a double peak containing the strong 23,000-year and the weaker 19,000-year peaks of precession. A peak centered at 38,000 years dominates the coherence spectrum comparing tilt to the $\delta^{18}O$ record. This corresponds well to the 40,700-year periodicity that dominates the frequency spectrum of tilt (*2*). When it is considered that the tuning of the time scale used in this analysis violates none of the radiometrically dated controls on the time scale, these coherence plots indicate that there is significant forcing of the $\delta^{18}O$ record by these parameters of the earth's orbit.

To determine the degree to which the $\delta^{18}O$ record is governed by the earth's orbital parameters, we assume a linear relationship between the ice volume record and the tilt and precession. We then apply the double-input, single-output model described above. Tilt and precession, the two input time series, must be independent in order to use this simple model. A plot of their coherence spectrum (Fig. 1d) indicates that there is no significant coherence between the two time series, and thus Eq. 1 holds true for the data set. Coherences not significantly different from zero at the 80 percent confidence level are set equal to zero in Eq. 1. This eliminates random coherences at frequencies where input functions have approximately zero variance. The resulting summations (using 16 lags or 20 degrees of freedom) indicate that 12 percent of the variance of the $\delta^{18}O$ record is due to forcing by the earth's tilt and 3 percent is due to forcing by the precession of the equinox.

Thus, by utilizing a time scale that has been tuned to maximize the relationship between the $\delta^{18}O$ record and the tilt of the earth's axis, about 15 percent of the variation in the global climate can be explained in terms of simple linear forcing. If a different time scale is used for this record, where constant sedimentation rates are assumed at the site of the core (*10*), the model calculations indicate that only 8 percent of the variance is accounted for by this model.

We emphasize that in using this model, the degree of forcing obtained is a function of the number of degrees of freedom retained by the modeler. In this model degrees of freedom $= 2.67\ N/L$, where N is the number of points in the time series ($\delta^{18}O$ record) and L is the number of lags used to create the autocorrelation function. As the number of lags decreases, the bandwidth in the frequency domain increases and the variance due to any one peak is distributed more widely to adjacent frequencies. As a result, both spectral peaks and coherence peaks are blurred, so that the calculated forcing decreases. Figure 2 shows the dependence of the degree of forcing on the number of lags. The peaked nature of the graph is due to random coherences that may surpass the 80 percent confidence level. Thus, it is evident that caution should be used in applying this model while using a set number of lags to determine the autocorrelation function.

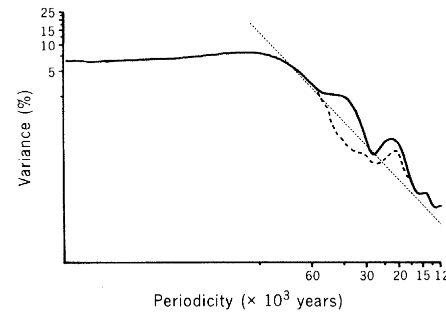

Fig. 3. Log-log plot of the spectrum of the $\delta^{18}O$ record of V28-238, using the TWEAQ time scale (*2*) and 16 lags (solid line), and of the residual spectrum (heavy dashed line) with the portion of the record forced by obliquity and precession removed. The thin dashed line indicates a slope of -2.

From the discussion above we conclude that more than 75 percent of the variance in the oxygen isotope record for the last 730,000 years is not linearly related to orbital variation. The spectrum for this residual time series is a red noise spectrum and displays a simple inverse square relationship with respect to frequencies (*2*) (see Fig. 3). Such a spectrum is predicted by many possible stochastic models. In particular, the stochastic model presented by Hasselmann (*11*) and Frankignoul and Hasselmann (*12*) predicts a climatic spectrum of this form.

We have not considered nonlinear models that have been suggested to explain the dominant 100,000-year component in the spectrum of climatic change (*1, 13*). But any nonlinear model relating eccentricity to this component of climatic change must satisfy the observation that the coherence at this frequency is very small and possibly zero.

In conclusion, on the basis of simple linear models we find that (i) less than 25 percent of the variation in global ice volume during the last 730,000 years is related to the tilt and precessional variations of the earth's orbit, (ii) there is no evidence for a linear relationship between eccentricity and global climates, and (iii) the spectrum of global ice volume with the linear effect of the earth's orbital variations removed is a red noise spectrum with a simple form.

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Warmth of the Subpolar North Atlantic Ocean During Northern Hemisphere Ice-Sheet Growth

Abstract. *Two 10,000-year periods of Northern Hemisphere continental ice-sheet growth stand out prominently within the last full interglacial-to-glacial cycle. During the first half of each rapid ice-growth phase, the subpolar North Atlantic from 40°N to 60°N maintained warm sea-surface temperatures comparable to those of today's ocean. The juxtaposition at latitudes 50°N to 60°N of an ''interglacial'' ocean alongside a ''glacial'' land mass, particularly along eastern North America, is regarded as an optimal configuration for delivering moisture to the growing ice sheets.*

Orbital variations are now clearly established as a significant primary cause of ice-age climatic cycles (*1*). The intermediate stages between cause and effect remain conjectural. How are orbital variations actually translated into regional climatic changes on the earth's surface? What is the mechanism of glacial growth and decay, and, more specifically, what is the mechanism by which water is extracted from the oceans and transported to growing ice sheets? This report addresses the latter question by focusing on the subpolar North Atlantic, the ocean closest to the Northern Hemisphere ice sheets.

Isotopic data from deep-sea cores with high accumulation rates (*2*) delineate two very large and rapid phases of ice growth during the last climatic cycle. One, the boundary between isotopic substages 5e and 5d at about 115,000 years before present (B.P.), marks the last glacial inception (increase of global ice above modern values). The second, the boundary between stages 5 and 4 at roughly 75,000 years B.P., can be regarded as the time of temperate-latitude transition into glacial conditions (*3*). During each of these intervals, roughly half the interglacial-to-glacial net ice mass accumulated within approximately 10,000 years (*4*).

Both ice-growth phases are closely related in time to Northern Hemisphere summer insolation minima (*1, 5*), substantiating Milankovitch's theory (*6*) that cool summers are critical in preserving large portions of the annual snowfall through the ablation season. As noted by numerous researchers, the growing glaciers provide positive feedback to enhance the high-latitude cooling by increasing the albedo over land. But the growth of these extensive bodies of ice also implies an expansion of the polar anticyclone normally positioned over ice cover in high latitudes of the Northern Hemisphere. This expansion of dry cold air would reinforce the normal high-Arctic aridity and slow or stop the rapid growth of ice sheets unless opposed by other parts of the climatic system (*7*). Specifically, the intervals of rapid ice growth that occurred twice during the last climatic cycle demand a significant moisture source for intervals of 10,000 years.

Ewing and Donn (*8*) hypothesized an ice-free Arctic Ocean to maintain the moisture supply to expanding ice sheets, but subsequent examination of Arctic sediments indicated no break in Arctic ice cover during the late Quaternary (*9*). Other paleoclimatologists have looked toward warm oceans at much lower latitudes (the Gulf of Mexico and western subtropical North Atlantic) as primary moisture sources (*10*). Recently, several papers have stressed the importance of the subpolar North Atlantic as the most proximal moisture source to the Laurentide Ice Sheet (*7, 11, 12*).

Our evidence (Fig. 1) shows that the subpolar North Atlantic (40°N to 60°N) maintained relatively warm ''interglacial'' sea-surface temperatures through much of the two major intervals of ice growth (*4*). This conclusion is based on oxygen isotopic evidence of ice growth from benthic Foraminifera and on transfer function estimates of sea-surface conditions derived from planktonic foraminiferal assemblages. The co-occurrence of these two separate signals within the same levels of deep-sea cores permits a precise comparison of their relative timing during intervals well beyond radiometric dating. To date, we have paired isotopic and faunal data across the stage 5-4 boundary from ten subpolar North Atlantic cores and across the substage 5e-5d boundary from five cores (*4*); two examples from each level are shown in Fig. 1.

During the substage 5e-5d transition, the sea surface in the subpolar Atlantic maintained temperatures as high as today's or 1° to 2°C warmer until about halfway into the ice-growth interval. The ocean surface finally cooled late in isotopic substage 5d, several thousand years after the midpoint of the ice-growth phase. This lag in ocean-surface cooling of about 3000 to 4000 years behind ice growth has been found so far in cores from 41°N to 54°N and from 15°W to 40°W.

During the stage 5-4 transition, the sea-surface temperatures again remained high during most of the period of rapid glacier ice accumulation (Fig. 1). Several cores even show increasing temperatures until the midpoint of ice growth. At this isotopic transition, the ocean cooling lags an estimated 4000 to 5000 years behind ice growth. This pattern has been observed in cores from 41°N to 59°N and from 15°W to 50°W (*4*).

As shown in Fig. 2, the subpolar North Atlantic at the midpoint of ice growth during the stage 5-4 transition was nearly as warm as today. Estimated sea-surface temperatures were generally within 1° to 2°C of modern values. We have detected marked oceanic warmth (19°C in summer) within 600 km of the present-day Newfoundland coast during the stage 5-4 transition (*4*).

There are two lines of evidence that much of the large ice volume indicated by the stage 5-4 isotopic data accumulated at the same longitudes as (and perhaps even directly alongside) this warm subpolar ocean: (i) ice-rafted detritus entered the subpolar Atlantic Ocean in great abundance late in this ice-growth transition (*3*), and (ii) end moraines from ice-growth phases on Baffin Island

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