Radiation windows as indicators of an astronomical influence on the Devil's Hole chronology

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ABSTRACT

Orbital explanations of paleoclimatic records traditionally focus on daily insolation at ~60°N. We exemplify how insolation at different latitudes and different times of day can explain the timing of the Devil's Hole $\delta^{18}O$ record. We combine winter tropical noontime insolation (associated with the source-region for wintertime precipitation) and summer extra-tropical noontime insolation (producing noontime heat to warm terrestrial surfaces). Periods of low winter and high summer insolation are called "radiation windows" and yield drier-warmer conditions in the Northern Hemisphere mid-latitudes. When radiation windows are compared with the DH-11 record, the apparent contradiction with Milankovitch (Winograd et al., 1992) may be resolved. The middle-latitude continental climate signal, as recorded by DH-11, tends toward a cooling state until interrupted by a termination. In every instance where the DH-11 record is warming before a radiation window, a termination occurs. If radiation windows occur with antecedent cooling, then there is a complex response of warming with a variable lag effect. Yet, there are no cases where cooling follows a radiation window.

INTRODUCTION

Although statistical evidence has been amassed demonstrating an astronomical influence on late Quaternary climate change (Berger et al., 1984), criticisms of Milankovitch orbital theory do exist. One recent challenge to the orbital theory stated that climatic changes recorded at Devil's Hole, Nevada, precede radiation changes at high northern latitudes (60°N), and as a consequence the Milankovitch theory is claimed to be an invalid explanation of climate change (Winograd et al., 1992).

Despite questions on the accuracy of the DH-11 record, it remains the best independently dated record of glacial-interglacial fluctuations currently available (Imbrie et al., 1993b; Ludwig et al., 1992, 1993a, 1993b; Winograd et al., 1992). However, other climate chronologies (e.g., SPECMAP and Vostok) remain widely used and accepted for studies of past climate change (Imbrie et al., 1993b). If climate proxy records are valid, how can the discrepancy between Milankovitch climate change theory and the physical evidence be resolved?

Several studies have attempted to explain the temporal discrepancy between Devil's Hole and 60°N radiation: (1) a change in the moisture source region and ground-water residence times (Johnson and Wright, 1989; Winograd and Coplen, 1989), (2) unaccounted contribution of excess ^{230}Th produced by the radioactive decay of ^{234}U caused by the calcite vein being continuously in water (Edwards and Gallup, 1993; Ludwig et al., 1993a, 1993b; Shackleton, 1993), (3) different sedimentation rates between deep sea cores and the calcite vein (Imbrie et al., 1993b), (4) adjusting the SPECMAP chronology to new high sea-level stands (Grootes, 1993), (5) adjusting the timing of the minima of the DH-11 curve to the low values of eccentricity and obliquity (Emiliani, 1993; Landwehr et al., 1994), and (6) the possibility that early timing of stage 6 is a regional signal due to the early retreat of the polar jet stream over the southwest United States (Crowley, 1994).

Although as explanations all of the above processes have their supporters and detractors, an alternative approach in addressing the discrepancies between the DH-11 record and Milankovitch theory is to fundamentally reexamine the role of orbital parameters on the DH-11 record. One possibility is to address an inherent regional signal in the Devil's Hole chronology through latitudinal variations in insolation.

Winograd et al. (1988) cited several factors that could have influenced $\delta^{18}O$ values in the DH-11 record, including air temperature during precipitation events and the moisture source region. Imbrie et al. (1993b, p. 532–533) proposed that these factors should be combined to create "a time-dependent model of processes governing the response of the climate to Milankovitch forcing, including those in the atmosphere over Nevada and in ground waters of the Great Basin." This study links these local influences to regional insolation variations.

Various paleoclimatic proxy records (i.e., ocean cores, ice cores, coral reefs, land-based records, and pollen records) have been compared to daily radiation variations for June or July radiation at high northern latitudes or high southern latitudes (Broecker, 1984; Emiliani, 1993; Hays et al., 1976; Imbrie et al., 1984; Lorius et al., 1985; Pons et al., 1992; Winograd et al., 1988, 1992). However, Crowley and Kim (1994) have suggested that a more complete understanding of the interaction between Milankovitch orbital variations and climate involves the consideration of more than just the insolation at high northern latitudes (e.g., 60°N and 65°N). This paper describes a simple algorithm consistent with Milankovitch theory that links the Devil's Hole chronology to insolation changes at latitudes different from 60°N.

METHODOLOGY

The Devil's Hole $\delta^{18}O$ record is primarily influenced by changes in wintertime precipitation (Winograd et al., 1988). Other influences on the $\delta^{18}O$ chronology include climate conditions at the moisture source regions and transport patterns of water vapor through the atmosphere (Rozanski et al., 1992). Previous research suggests that the vapor source region for the southwestern United States during glacial episodes is moisture drawn from tropical latitudes during the winter (Johnson and Wright, 1989; Winograd et al., 1988), related to the southward displacement of the polar jet stream (COHMAP Members, 1988). It is reasonable to assume, given the causative link between solar radiation and evaporation (Sellers, 1965), that variations in solar insolation forced by Milankovitch processes may impact tropical evaporation and, consequently, $\delta^{18}O$. We therefore compute December solstice radiation at the moisture source region of 20°N (a median value for the northern tropical latitudes) as a proxy for variations in moisture precipitated at Devil's Hole. All calculations of radiation values were made using the classical astro-trigometric expansions of eccentricity, obliquity, and precession given by Berger (1978).

Local air temperature is a second distinct factor that influences the Devil's Hole record (Winograd et al., 1992). If the DH-11 record represents local temperatures (Imbrie et al., 1993b; Johnson and Wright, 1989; Shackleton, 1993) in a combination with wintertime precipitation, a second proxy representing local temperatures is needed. The insolation over the Devil's Hole region could provide a surrogate for local temperature controls on the DH-11 chronology. A potential control on the δ^{18}O variations is the heating of ground water near the surface (Wang and Lewis, 1992).

We selected June solstice noontime insolation for the latitude centered over the Devil's Hole recharge area (37°N) for several reasons. First, June insolation provides the largest energy input into the northern middle latitudes, including Devil's Hole. Hence, it may represent the largest effect on local air and ground temperature. Second, because the timing of variations in June noontime insolation is the same for latitudes north of the tropic of cancer, June insolation addresses potential regional feedbacks. For example, the importance of high northern latitude June solstice insolation involves both complex ocean-atmosphere feedbacks and its coincidence with northern hemispheric ice-volume fluctuations (Broecker and Denton, 1989; Imbrie et al., 1992). Third, the δ^{13}C record from Devil's Hole (Coplen et al., 1994) argues for the importance of warm-period precipitation maxima in enhancing regional biomass, perhaps through "increased summer precipitation over the southwestern United States" (Coplen et al., 1994, p. 363). Hence, June insolation allows for the possible influence of monsoonal precipitation on the DH-11 record.

However, the use of summertime insolation as a proxy for the Devil's Hole chronology is debatable. Winograd et al. (1988) maintained that their record is a proxy of winter-spring paleotemperature. Unfortunately, since data are not available on the soil water balance during wetter periods, we feel the conservative approach would be to model the role of summer insolation.

In addition, radiation curves for this study are separated into two parts: noontime (defined as the radiation received within 5° of the maximum zenith angle of record) and daily minus noontime ($D - N$). Justification for using two curves is twofold: evaporative processes and spectral analyses. First, different radiation spectral signals are present in distinct elevation angle classes (90° minus the zenith angle) (Cerveny, 1991). Simple daily radiation curves can be misleading when used to analyze evaporation rates over a moisture source region and differential heating over the proxy record location. Little evaporation of source-region moisture occurs at low sun angles because of higher reflection (Cogley, 1979). Second, there is a strong correlation between the insolation computed for specific elevation angle classes and the prominent cycles of radiation, 41 k.y. (obliquity) and 23 k.y. (precession) (Cerveny, 1991). Obliquity strongly influences solstice noontime radiation (Berger et al., 1993), and precession controls radiation at times other than noon ($D - N$) (Cerveny, 1991). Therefore, obliquity and precessional components of radiation curves could be compared to the DH-11 chronology. And, indeed, a previous study (Imbrie et al., 1992) has identified the influence of the precessional and obliquity cycles on the δ^{18}O record. The insolation curves were calculated for noontime and $D - N$ radiation.

As stated above, the DH-11 record is a combination of wintertime moisture and summertime temperature. To represent these physical processes in a single time series, a composite curve is created by subtracting the winter-tropical insolation (December solstice radiation at 20°N) from the summer-extratropical (June solstice radiation at 37°N) radiation curve. Separate curves were calculated for noontime and $D - N$ radiation following the rationale given above (Fig. 1). Subtraction of these two insolation curves creates a time series in which cool, moist climates are represented by higher values and warm, drier climates by lower values in Figure 1. Lower values occur when summertime radiation is maximized and wintertime evaporation of source-region moisture is minimized. Conversely, higher values are represented by maximizing winter radiation over the moisture source and minimizing summer radiation. Consequently, a high value of this index may be associated with increased water vapor and perhaps increased precipitation over the proxy site. The signature of this precipitation is found in the evaporation from the tropical source region. Additionally, a high index value represents the effects of less summertime radiation at the proxy site.

"Radiation windows" for climate change occur during periods of negative slope for both noon and $D - N$ curves (Fig. 1). Negative slopes indicate warmer and drier conditions caused by (1) increasing summertime radiation over the recharge area and (2) a reduction in wintertime moisture availability.

RESULTS

A climatic trend can be amplified or reversed by a radiation window. If the preceding climate trend in the DH-11 record is warming, the desiccating influence of less wintertime moisture and increased summer radiation, produced by a radiation window, precedes an abrupt transition in the climate to a full interglacial. These transitions occur within 1 to 6 k.y. after the start of a radiation window. This coincides with a variety of pa-

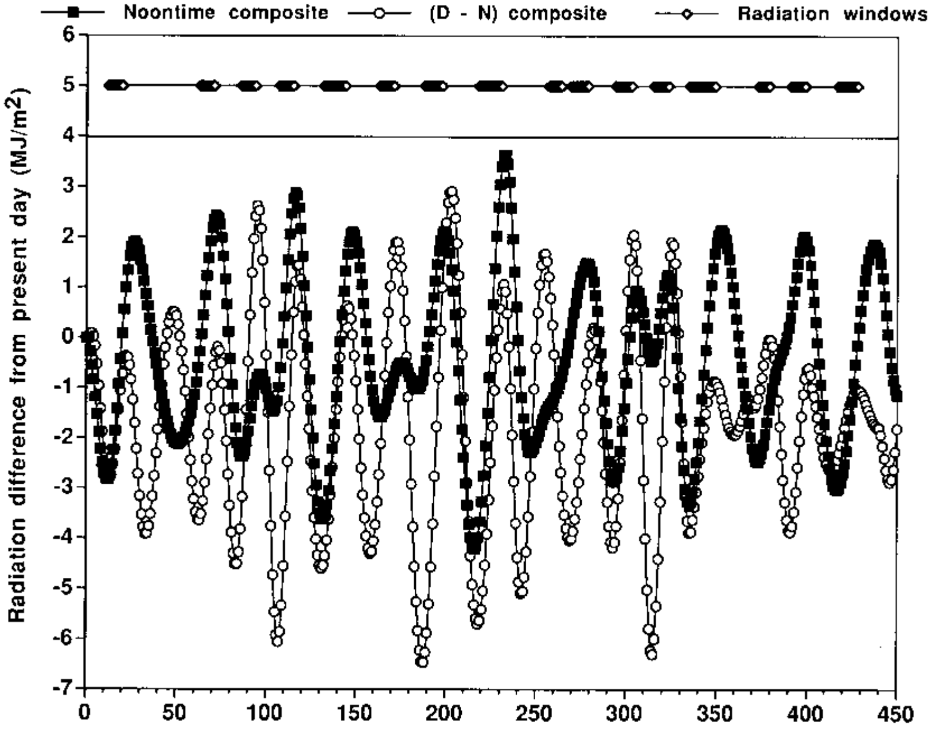

Figure 1. Composite curves for noontime and daily minus noontime ($D - N$) radiation for the past 450 k.y. The composite curves are calculated by subtracting the December solstice radiation at 20°N from the June solstice radiation at 37°N. The past 100 k.y. of DH-11 record (450 to 550 ka) are not used because of large uncertainty in numerical ages (Winograd et al., 1992). Radiation values plotted are difference-from-present-day values. Radiation windows occur when both curves have negative slope, producing a tendency toward deglaciation by reducing wintertime moisture and increasing summertime radiation.

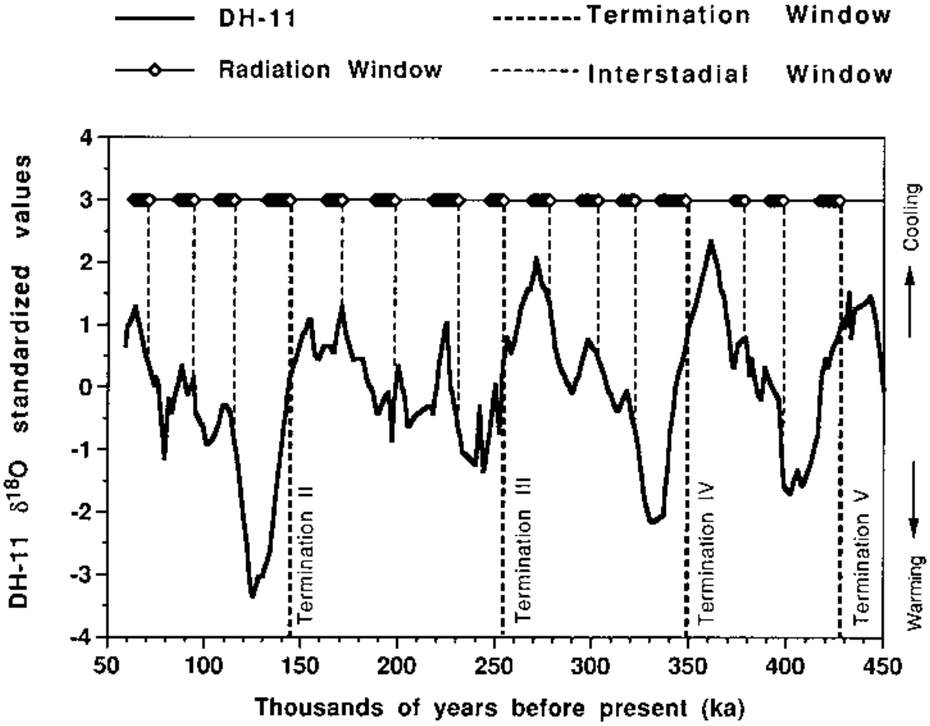

Figure 2. DH-11 curve of $\delta^{18}O$ values for 60 to 450 ka with radiation (interstadial and termination) windows imposed on graph. The "value" on the plot (3.0) assigned to the radiation windows is arbitrarily selected for graphical purposes. DH-11 curve was digitized from Figure 2 of Winograd et al. (1992) and is standardized.

leoclimatic records that demonstrate lag relationships (2 to 8 k.y.) with Milankovitch radiation (e.g., Hays et al., 1976; Ruddiman and McIntyre, 1981; Prell, 1984; Martinson et al., 1987).

The superposition of the beginning of a radiation window on a preexisting warming is termed a "termination window." Four termination windows occur in the DH-11 record from 450 to 60 ka (Fig. 2). All four correspond with the refined termination dates of Winograd et al. (1992). No radiation window occurred from 60 (the end of the DH-11 record) to 22 ka (Fig. 1). The last radiation window (22 to 13 ka) occurred during the latest glacial termination (Broecker and Denton, 1989; Dansgaard et al., 1993; Dorn et al., 1991; Martinson et al., 1987).

If the start of a radiation window is superimposed on a preexisting cooling trend in the DH-11 chronology, limited short-term warming follows and results in an interstadial climate or what we speculatively call a "failed termination." The superposition of a radiation window and preexisting cooling is termed an "interstadial window." For the DH-11 chronology over the past 450 k.y., there are 11 interstadial windows.

Terminations always occur in the DH-11 record when the start of a radiation window coincides with a preexisting warming trend. The paleoclimatic significance of a radiation window in times of antecedent cooling, however, is slightly more ambiguous. Timing of the interstadial warming, in relation to the timing of the radiation window, is more variable. Slight warming occurs with time lags of 1 to 6 k.y., and two interstadial events are not explained: at 380 and 235 ka (Fig. 2). With these exceptions, the onset of interstadial episodes does not occur without a preceding radiation window.

DISCUSSION OF RESULTS

The question of long-term control on climate, which is key to discrimination between an interstadial window and a termination window, has long been debated. The $\delta^{18}O$ record at DH-11 exemplifies Broecker and Van Donk's (1970) observation that Pleistocene climate slowly builds toward a cooler and, eventually, glacial world, punctuated by interstadials, until a glacial termination occurs. Superposition of long-term climate variations, together with the occurrence of a radiation window, coincides with all glacial terminations and all but two warming trends (360 ka, 155 ka) in the DH-11 record. The warming trends at 360 and 155 ka have not been explained by the Milankovitch theory. In addition, terminations in DH-11 have a larger amplitude than radiation curves can explain.

Research continues to examine specific internal feedback mechanisms (Gallimore and Kutzbach, 1996) or more generalized nonlinear dynamic behaviors of the ocean–ice sheet–atmosphere system (Imbrie et al., 1993a) to account for these signals. For example, atmospheric enhancement of CO_2 (Gallee et al., 1992), reorganization of ocean circulation (Broecker and Denton, 1989), or Antarctic ice-cap dynamics (Pollard, 1982) could account for climate trends that are not a function of orbital mechanisms such as the preexisting temperature trends found in the Devil's Hole record.

Radiation windows alone do not explain when glacial terminations and interstadials occur in the DH-11 record. Instead, we argue that radiation windows supplement preexisting climatic conditions. Both precession ($D - N$ curve) and obliquity (noontime curve) work in tandem to produce a radiation signal that precedes the DH-11 record. We speculate that radiation windows may act as an "insolation warm-dry shock" to the middle-latitude paleoclimatic system.

Although this study has focused on comparing the new concept of "radiation windows" to the Devil's Hole chronology, the application of radiation windows is not limited to this individual record. The main idea of this paper is to link the tropical and middle-latitude insolation curves to a specific proxy record. We acknowledge that the combined effect of precession and obliquity is half that of the amplitude observed in the 100 k.y. cycle and that this methodology does not provide the answer for the origin of 100 k.y. glacial cycles. However, we do address the specific problem of linking orbital cycles to the last 16 major glacial terminations and interstadials in the DH-11 record.

Winograd et al. (1992) noted the close correspondence in the peaks and troughs of parts of the Devil's Hole chronology to other proxy records (Imbrie et al., 1984; Jouzel et al., 1987). This is not surprising as Milankovitch insolation exhibits similar variations over time. However, the temporal differences between Devil's Hole and other proxy records, we suggest, may arise from regional effects that are to some extent captured in our concept of radiation windows.

We suggest that insolation gradients between latitudes may account for some of the hitherto unexplained variance in specific proxy records. Consequently, insolation algorithms computing radiation variations at different latitudes, different times of day, and different seasons can be adapted to other locations. Linkage of composite radiation curves to climatic processes may be applied to other paleoclimate records (Jouzel et al., 1993; Martinson et al., 1987; Pokras and Mix, 1987).

A skeptical view is that we might be able to fit any climate proxy record to a combination of insolation curves. We answer this perspective first deductively and then inductively. First, our approach, of combining extratropical summer and tropical winter insolation at noon, is not happenstance but instead is based on linking insolation time series to temperature and moisture processes influencing the DH-11 chronology. Second, we obtain a similar timing for radiation windows by using insolation values from latitudes in the same region as those discussed above. For example, similar tropical insolation time series are obtained for latitudes between 0° and 23.5°N, and, for the extratropical latitudes, north of the tropical of cancer. In other words, we are exploring whole classes of insolation curves, and not simply randomly selected combinations to fit the dataset.

Inductively, Kuby et al. (in press) used linear programming to identify all possible matches between combinations of 342 insolation curves and four different paleoclimatic proxy records. Although the inductive linear programming methodology could have combined any or all curves, 4 insolation curves accounted for 29% of the total variance.

CONCLUSIONS

Radiation curves, representing processes inherent in the DH-11 record, produce unique signals termed "radiation windows." When superimposed on preexisting temperature trends over the past half million years, radiation windows are followed by interstadials and glacial terminations identified in the DH-11 chronology (Winograd et al., 1992). Sixteen radiation windows occurred during the past 450 k.y. Eleven occurred during a cooling trend and are followed by short-term interstadial warming conditions in the DH-11 chronology. Four radiation windows are linked to long-term warming trends and correspond in time to glacial terminations identified in the DH-11 record. A fifth termination window occurs, outside the limits of the DH-11 record, during the accepted timing of termination I.

Radiation windows (termination and interstadial) may thus resolve the apparent temporal discrepancy in the timing of the Devil's Hole chronology (Winograd et al., 1992) and the Milankovitch theory of climate change. Both precession and obliquity orbital cycles work in tandem with preexisting climatic feedbacks to drive when major climate oscillations occur in the Devil's Hole record. Insolation variations as computed in this study are used as proxies for regional climate processes. Although the concepts of radiation windows and, consequently, Milankovitch orbital theory do not provide a complete explanation of the DH-11 chronology of the past 500 k.y., we suggest that radiation windows do serve to link Milankovitch climate theory to many of the events identified in Devil's Hole chronology.

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