PALEOCEANOGRAPHY, VOL. 17, NO. 2, 10.1029/2000PA000571, 2002

On the 1470-year pacing of Dansgaard-Oeschger warm events

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Received 31 July 2000; revised 15 August 2001; accepted 17 September 2001; published 1 May 2002.

[1] The oxygen isotope record from the Greenland Ice Sheet Project 2 (GISP2) ice core was reanalyzed in the frequency and time domains. The prominent 1470-year spectral peak, which has been associated with the occurrence of Dansgaard-Oeschger interstadial events, is solely caused by Dansgaard-Oeschger events 5, 6, and 7. This result emphasizes the nonstationary character of the oxygen isotope time series. Nevertheless, a fundamental pacing period of $\sim$1470 years seems to control the timing of the onset of the Dansgaard-Oeschger events. A trapezoidal time series model is introduced which provides a template for the pacing of the Dansgaard-Oeschger events. Statistical analysis indicates only a $\leq$3% probability that the number of matches between observed and template-derived onsets of Dansgaard-Oeschger events between 13 and 46 kyr B.P. resulted by chance. During this interval the spacing of the Dansgaard-Oeschger onsets varied by ±20% around the fundamental 1470-year period and multiples thereof. The pacing seems unaffected by variations in the strength of North Atlantic Deep Water formation, suggesting that the thermohaline circulation was not the primary controlling factor of the pacing period. *INDEX TERMS:* 4267 Oceanography: General: Paleoceanography; 1620 Global Change: Climate dynamics (3309); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; *KEYWORDS:* late Pleistocene climate, Dansgaard-Oeschger events, GISP2, nonstationarity

1. Introduction

[2] Oxygen isotope (δ^{18}O) data from Greenland ice cores reveal that large and rapid temperature fluctuations dominated climate in Greenland between $\sim$11 and 74 thousand years before present (kyr B.P.) [*Johnsen et al.*, 1992; *Dansgaard et al.*, 1993; *Grootes et al.*, 1993]. Nitrogen and argon isotope data from the Greenland Ice Sheet Project 2 (GISP2) ice core indicate that transitions between cold stadials and warm interstadials, the so-called Dansgaard-Oeschger events, took place within some decades and were accompanied by warmings of $\sim$10°C [*Severinghaus and Brook*, 1999; *Lang et al.*, 1999]. The significance of these warming events is corroborated by similar climate variations on a global scale, which can be correlated to the Dansgaard-Oeschger events [e.g., *Clark et al.*, 1999; *Sarnthein et al.*, 2000].

[3] The recurrence time between Dansgaard-Oeschger warming events, as recorded in the δ^{18}O time series from the GISP2 ice core [*Grootes and Stuiver*, 1997] (Figure 1) varied considerably, ranging from $\sim$1 to 12 kyr during the last 90 kyr [*Bond et al.*, 1999]. The variability of the pacing was greatly reduced between 25 and 60 kyr B.P., when the spacing between the warming events was $\sim$1–5 kyr [*Bond et al.*, 1999]. In the interval 12–50 kyr B.P. the power spectrum of the δ^{18}O time series reveals a statistically significant peak at a periodicity of 1470 years, which is thought to reflect the pacing of the Dansgaard-Oeschger events [*Grootes and Stuiver*, 1997]. Some Dansgaard-Oeschger events encompass two or three half cycles of the 1470-year pacing cycles; hence the time between subsequent warming events may differ from the pacing [*Schulz et al.*, 1999]. In contrast, *Wunsch* [2000] argued that the sharp 1470-year spectral peak found in the ice core records is caused by aliasing spectral variance from "annual" cycles to frequencies in the millennial band. Moreover, since the prominent Dansgaard-Oeschger events do not disappear after subtracting a $\sim$1500-year signal component from the time series, *Wunsch* [2000] refuted the idea of a regular pacing of these events.

[4] The origin of the Dansgaard-Oeschger events remains controversial, ranging from internal oscillations of the ocean-atmosphere system [*Broecker et al.*, 1990; *Winton*, 1993; *Sakai and Peltier*, 1997] to periodic calving of the Greenland ice sheet [*van Kreveld et al.*, 2000] and to external forcing mechanisms [*van Geel et al.*, 1999; *Keeling and Whorf*, 2000]. It was also suggested that millennial-scale climate variability is not restricted to the last glacial period but is a pervasive feature of Holocene climate variability, although with much smaller amplitude [*Bond et al.*, 1997, 1999; *Bianchi and McCave*, 1999; *deMenocal et al.*, 2000]. The possible interference of anthropogenic climate perturbations with natural climate fluctuations on a millennial timescale poses a challenging task for predicting future climate change. To gain better insight into these natural climate variations, the relation between the timing of the onset of Dansgaard-Oeschger events and a data-derived 1470-year template, which is intended to predict their pacing over the last 80 kyr, was investigated. This analysis reveals that between 13 and 46 kyr B.P. the start of all but one Dansgaard-Oeschger events are in phase with a coherent 1470-year signal. Before 46 kyr B.P. the spacing between Dansgaard-Oeschger events is considerably more irregular, which may be due to larger stratigraphic uncertainties.

2. Origin of the 1470-year Spectral Peak

[5] The fact that the waiting time between Dansgaard-Oeschger events has not always been 1470 years [*Bond et al.*, 1999] is contradictory to the notion that the 1470-year spectral peak might be linked to the pacing of the Dansgaard-Oeschger interstadials. Time-frequency analysis of the GISP2 δ^{18}O records reveals that the amplitude of the 1470-year signal component was not constant throughout the last 100 kyr and reached its maximum amplitude between 31 and 36 kyr B.P. [*Schulz et al.*, 1999], that is, during the time of Dansgaard-Oeschger events 5–7 (see Figure 1). Hence one of the fundamental assumptions of spectral analysis is violated, namely, that the statistical properties of the time series under consideration have to be invariant with respect to time (second-order stationary) [e.g., *Percival and Walden*, 1993]. To assess the effect of this nonstationarity on the estimated power spectrum, the GISP2 δ^{18}O time series in the interval 13–50 kyr B.P. was

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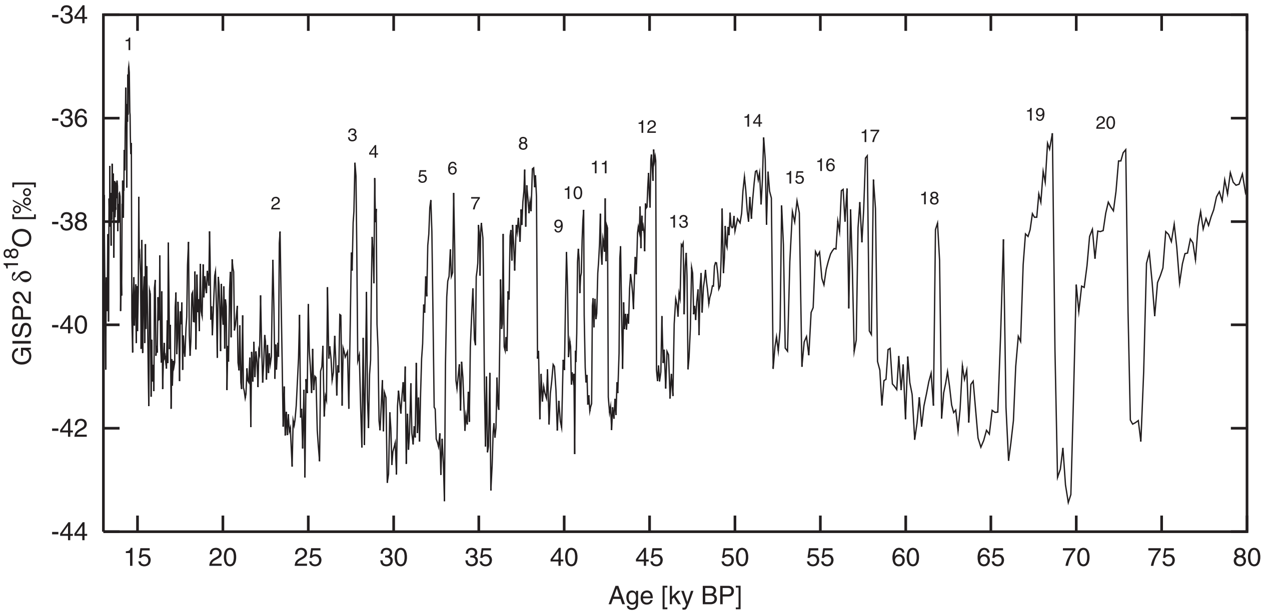

Figure 1. Oxygen isotope (δ^{18}O) record from Greenland (GISP2 ice core [*Grootes and Stuiver*, 1997]). Numerals above δ^{18}O maxima denote the "classical" Dansgaard-Oeschger interstadial events [*Johnsen et al.*, 1992; *Dansgaard et al.*, 1993].

reanalyzed using the software REDFIT [*Schulz and Mudelsee*, 2002]. The power spectrum of the unevenly spaced time series shows the expected peak at a frequency of 1/1470 years^{-1} which is statistically significant at the 99% level (Figure 2a). REDFIT as well as all other time series analysis methods employed in this study can process unevenly spaced time series directly, without the requirement of interpolation in the time domain, which may significantly bias spectral analysis results [*Schulz and Stattegger*, 1997]. Accordingly, one can simply remove the 31–36 kyr section from the time series and repeat the spectral analysis. Surprisingly, the removal of Dansgaard-Oeschger events 5–7 yields a spectrum which lacks a statistically significant 1470-year spectral peak (Figure 2b). It should be noted that the spectral amplitude at the frequency 1/1470 years^{-1} does not drop to zero (Figure 2b), indicating small variance contributions from time intervals outside the 31–36 kyr section at this frequency [cf. *Schulz et al.*, 1999, Figure 1a]. These are, however, too small to result in a discernable spectral peak at this frequency.

[6] This result can be easily understood if one considers the addition of a time-limited sinusoidal wave to red noise, produced

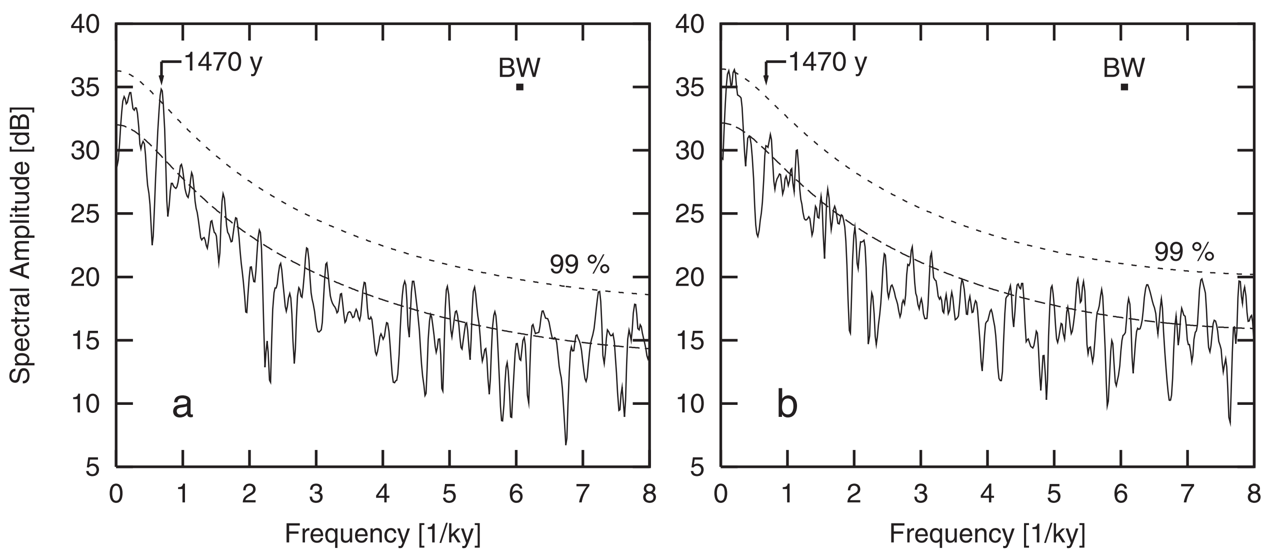

Figure 2. (a) Power spectrum of the 13–50 kyr B.P. section of the GISP2 δ^{18}O time series (solid line), theoretical red noise spectrum (long-dashed line) and false alarm level for 99% significance (short-dashed line). Spectral peak at period of 1470 years (arrow) is inconsistent with red noise origin. Note logarithmic ordinate scale (decibels, dB). Horizontal bar indicates 6-dB bandwidth (BW). (b) Power spectrum as in Figure 2a but omitting the interval 31–36 kyr B.P. in the calculation.

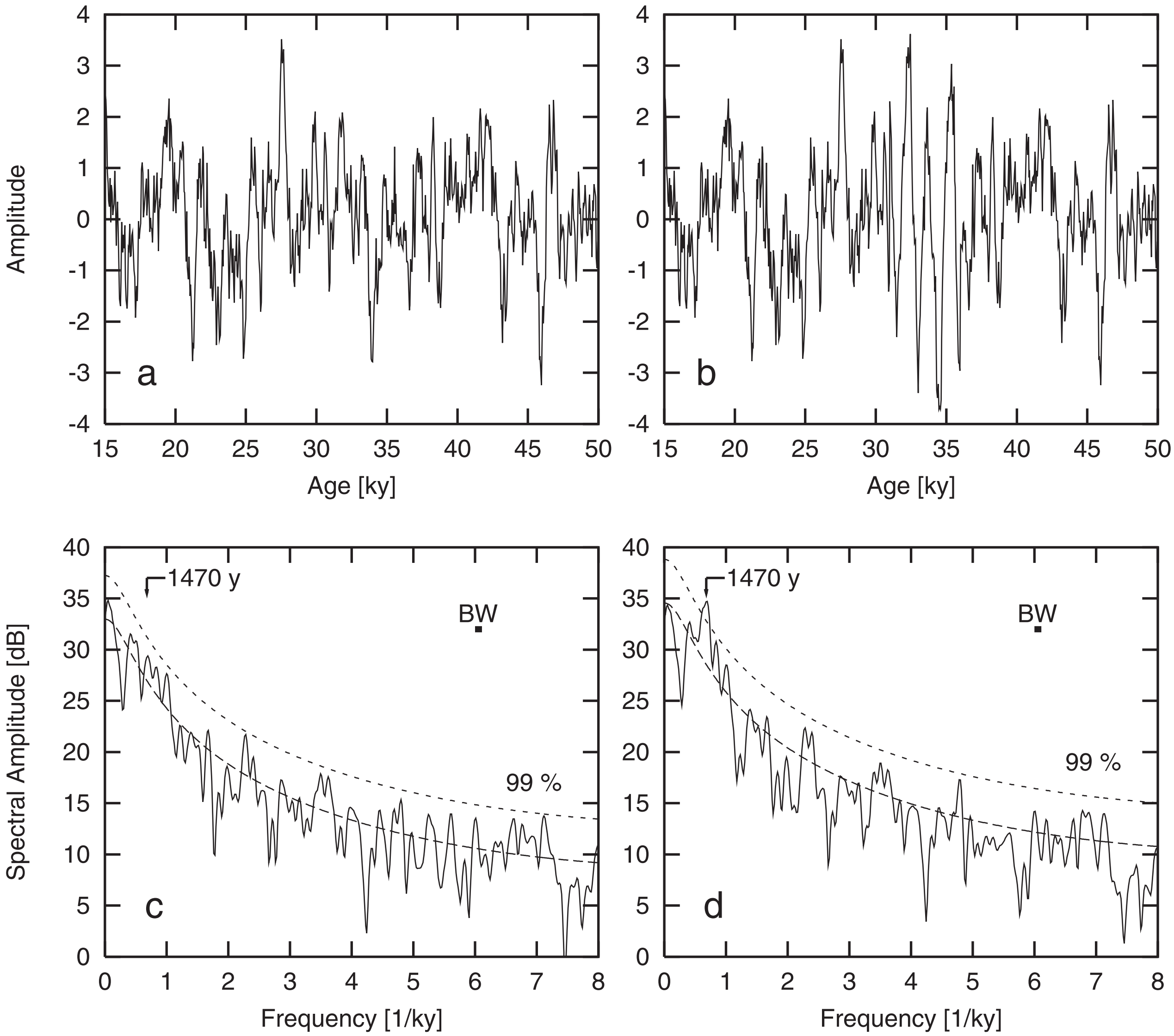

Figure 3. (a) Realization of an unevenly spaced first-order autoregressive process. (b) The same data as in Figure 3a with added sinusoidal signal between 31 and 36 kyr (signal-to-noise ratio of 4). (c) Power spectrum of the red noise time series in Figure 3a (thin solid line), theoretical red noise spectrum (long-dashed line), and false alarm level for 99% significance (short-dashed line). Note logarithmic ordinate scale (dB). Horizontal bars indicate 6-dB bandwidth (BW). (d) As in Figure 3c but for the red noise plus sine wave data in Figure 3b.

by a first-order autoregressive (AR1) process. An unevenly spaced AR1 time series was generated [*Schulz and Stattegger*, 1997], with unit variance, average sampling interval of 50 years, and characteristic timescale of 300 years (Figure 3a). These parameter values ensure that the power spectrum of the AR1 time series is similar to the red noise spectral background of the GISP2 δ^{18}O record. As expected, the power spectrum of the AR1 time series exhibits no statistically significant peak (Figure 3c). Adding a sinusoidal wave between 31 and 36 kyr with periodicity of 1470 years and signal-to-noise ratio of 4 to the AR1 time series (Figure 3b) drastically alters the resulting power spectrum, which shows a significant peak at a frequency of 1/1470 years^{-1} (Figure 3d). The spectral peak is, however, smaller than expected from the prescribed signal-to-noise ratio since the estimated spectral amplitude reflects the average value of the signal amplitude in the entire time series. (The signal amplitude is zero outside the 31–36 kyr interval and $\sqrt{8}$ within this interval.) This example demonstrates that it might be misleading to conclude from a statistically significant spectral peak that the corresponding harmonic signal component is present in the entire time series. Such conclusion is only justified if the underlying assumption of stationarity is met.

[7] Since the sharp 1470-year spectral peak in the spectrum of the GISP2 δ^{18}O time series is obviously caused solely by Dansgaard-Oeschger events 5–7, it is unnecessary to invoke aliasing [*Wunsch*, 2000] to account for it. The nonstationary character of the δ^{18}O time series also explains why the Dansgaard-Oeschger events cannot be removed from the record by subtracting a ~1500-year signal component [*Wunsch*, 2000]. The amplitude of the ~1500-year signal to be filtered out is an average value, estimated from the entire time series, and is smaller than the average value of the δ^{18}O anomalies associated with Dansgaard-Oeschger events [cf. *Schulz et al.*, 1999, Figure 1c]. Hence its subtraction fails to remove the full amplitude range of the Dansgaard-Oeschger events. Moreover, by subtracting a slowly varying sinusoidal wave

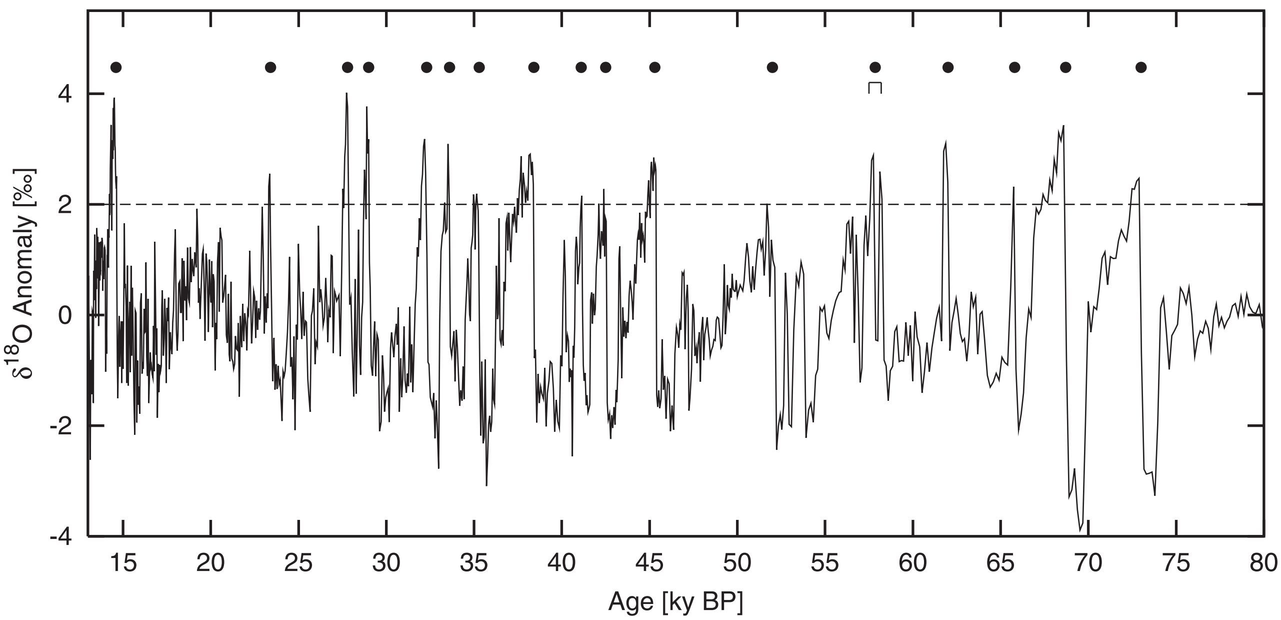

Figure 4. High-pass filtered GISP2 δ^{18}O data. Cutoff frequency of filter is 1/12 kyr^{-1}. Bullets indicate "canonical" Dansgaard-Oeschger events, defined by δ^{18}O anomalies $\geq$2‰ (dashed line). The two closely spaced δ^{18}O anomalies at $\sim$58 kyr B.P. are regarded as single event.

from a time series with sharp transitions, as associated with the beginning and end of Dansgaard-Oeschger events, it is impossible to eliminate the sharp transitions completely.

3. A Template for the Onset of Dansgaard-Oeschger Events

[8] Although the statistical significance of the 1470-year spectral peak must be questioned, owing to the nonstationary character of the δ^{18}O time series, there is, nevertheless, a good correspondence between the timing of Dansgaard-Oeschger events and a 1470-year pacing [*Schulz et al.*, 1999]. This raises the question if the onset of Dansgaard-Oeschger events since 80 kyr B.P. can be predicted based on the 1470-year pacing cycle which appears to be so well expressed during Dansgaard-Oeschger events 5–7. To answer this question, the strategy is as follows: A time series model, which can follow the characteristic course of Dansgaard-Oeschger events, is fitted to the δ^{18}O data in the interval 31–36 kyr B.P. Extrapolation of this pacing template to the entire time series allows one to evaluate if the timing of the Dansgaard-Oeschger events agrees with the predictions of the template.

[9] The definition of Dansgaard-Oeschger interstadial events was based on visual identification of large-amplitude and abrupt isotopic anomalies in the δ^{18}O ice core records [*Johnsen et al.*, 1992; *Dansgaard et al.*, 1993]. The resulting enumeration of the events includes slight inconsistencies, which have their origin in the recently extended resolution of the records. For example, while the small Dansgaard-Oeschger event 13 was enumerated, the large anomaly at 66 kyr B.P. was not (Figure 1). Similarly, the δ^{18}O spike between events 14 and 15 was not counted as Dansgaard-Oeschger event. To avoid such ambiguities, a somewhat more quantitative definition of Dansgaard-Oeschger events is adopted here, which is based on the δ^{18}O anomaly associated with the stadial-to-interstadial transition. Since the long-term trend in the GISP2 δ^{18}O series (Figure 1) hinders a quantitative identification of Dansgaard-Oeschger events, a high-pass filter [*Rybicki and Press*, 1995] with cutoff frequency of 1/12 kyr^{-1} is first applied to the unevenly spaced δ^{18}O data to remove all low-frequency components. The filtered time series is then used to identify Dansgaard-Oeschger events by δ^{18}O anomalies which exceed the somewhat arbitrary value of 2‰ (Figure 4). In contrast to the "classical" Dansgaard-Oeschger events [*Johnsen et al.*, 1992; *Dansgaard et al.*, 1993], these events will be referred to as "canonical" Dansgaard-Oeschger events. With the exception of the classical Dansgaard-Oeschger events 9, 13, 15, and 16, all events are distinguished in this way. An additional canonical Dansgaard-Oeschger event is identified at 66 kyr B.P.

[10] The spacing of the canonical Dansgaard-Oeschger events, defined by the time between the midpoints of the stadial-to-interstadial transitions, shows a distinct pattern between 15 and 80 kyr B.P. (Figure 5). The spacing decreases upon entering the glacial around 75 kyr B.P., rebounds slightly around 50–55 kyr B.P., reaches the lowest values between 27 and 45 kyr B.P., and

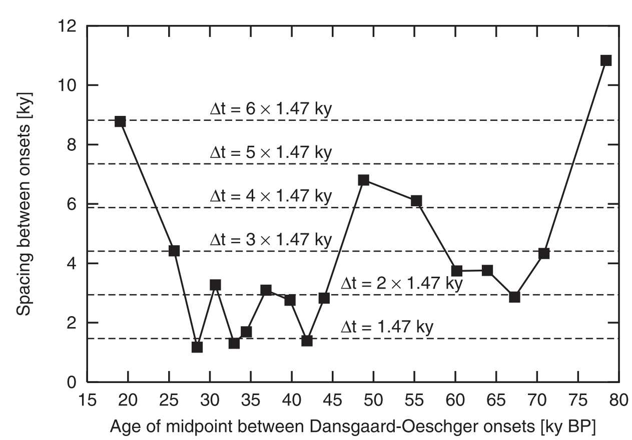

Figure 5. Spacing (Δt) between the onsets of subsequent canonical Dansgaard-Oeschger events. Ages are assigned to each onset at the point where the corresponding δ^{18}O increase reaches 50% of its full range. Dashed horizontal lines mark fundamental 1470-year spacing and its multiples.

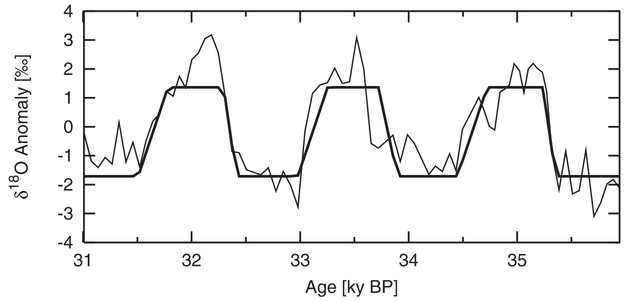

Figure 6. Fit of the trapezoidal time series model (thick line) to the filtered δ^{18}O data (thin line) in the interval 31–36 kyr B.P. Slight differences in appearance of the three cycles of the model result from the uneven spacing of the δ^{18}O time series.

increases again thereafter. A particular feature in the evolution of the event spacing is the clustering around a spacing of either 1470 or 2940 years between 27 and 45 kyr B.P., that is, once or twice the apparent pacing of the Dansgaard-Oeschger events. It is also noteworthy that the spacing increases to >8000 years across the last glacial-to-interglacial transition. If this increase continued into the Holocene as well as previous interglacials, the expected spacing is of the same length than the duration of an interstadial, making it unlikely that glacial-type Dansgaard-Oeschger events ever occurred during interglacials. To test if the spacing pattern is indeed compatible with an underlying 1470-year pacing mechanism or should be regarded as series of random events, it is necessary to establish a template for the pacing, which can be compared with the actual timing of the Dansgaard-Oeschger events.

[11] In order to build such a template for the onset of Dansgaard-Oeschger events a time series model is required, which can follow the rapid transitions, delineating the Dansgaard-Oeschger events in the δ^{18}O record. Since a sinusoidal wave is inappropriate for this purpose, a trapezoidal wave is used instead (see Appendix A for details). The time series model was fitted to the high-pass filtered δ^{18}O data in the interval 31–36 kyr B.P., that is, the time interval during which the 1470-year cycle is best expressed. The most significant fit (in terms of the F statistic, see Appendix A) results for a period of 1470 years, and the fitted trapezoidal wave approximates the course of Dansgaard-Oeschger events 5–7 reasonably well (Figure 6). In particular, none of the observed stadial-to-interstadial transitions starts before the corresponding transition commences in the time series model. Moreover, during all three interstadials the maximum δ^{18}O value is reached within the "upper plateau" of the trapezoidal wave. To obtain a template for the timing of Dansgaard-Oeschger events in the interval 13–80 kyr B.P., the fitted trapezoidal wave was extrapolated to the entire period of observations (Figure 7).

4. Testing the Pacing of Dansgaard-Oeschger Events

[12] The objective is to test if the observed Dansgaard-Oeschger events coincide with the prediction of the 1470-year template or occur randomly. This question can be translated into a statistical problem by considering the following null hypothesis: the observed Dansgaard-Oeschger events are regarded as "bullets" which are fired at random at the interstadial "targets," predicted by the template. How many "hits" can be expected under the null hypothesis? A Bernoulli trial constitutes a reasonable approximation of this problem [cf. *Wigley*, 1988]. This statistical model allows us to estimate the probability that the actual number of matches between observed and predicted Dansgaard-Oeschger events occurs by chance. The target area of the template is taken as the upsloping segment and upper plateau of the trapezoidal wave (Figure A1), which together encompass 630 years of the full period of 1470 years. Accordingly, the probability of hitting the target by chance is (630 years/1470 years) = 0.43; that is, there is a 43% probability that a Dansgaard-Oeschger event will match an interstadial predicted by the template by chance. For a hit to occur, the following two conditions must be met: (1) The stadial-to-interstadial transition in the δ^{18}O record starts after or coincides with the corresponding transition in the template, and (2) the maximum of the δ^{18}O anomaly of a Dansgaard-Oeschger event is reached before the end of the upper plateau of the corresponding trapezoidal wave. This set of rules thus allows for slight variations in the pacing of Dansgaard-Oeschger events. It should be noted that the resulting distinction between match and mismatch is only determined by the onset of a Dansgaard-Oeschger event and not by the end of the interstadial.

[13] The spacing of the Dansgaard-Oeschger events suggests a shift toward more regular and shorter intervals between 45 and 50 kyr B.P. (Figure 5). Accordingly, the time series is split, somewhat arbitrarily, at 46 kyr B.P., and the test for the applicability of the 1470-year pacing template is carried out separately in the younger and older part of the record. Between 13 and 46 kyr B.P. the number of independent canonical Dansgaard-Oeschger events is eight (Figure 7). (The total number of events is reduced by three because Dansgaard-Oeschger events 5, 6, and 7 have been used to construct the template.) Seven out of the eight events hit the target, that is, match the template (Figure 7). It follows from the binomial distribution that the probability that this high degree of coincidence occurs by chance is only 1%. In contrast, between 46 and 80 kyr B.P. the number of independent canonical Dansgaard-Oeschger events is six, and only two of them agree with the predictions of the template. The probability that two out of six events match the template by chance is 29%. Similar results are obtained if the classical definition of Dansgaard-Oeschger events is used instead. In this case the probability for the observed number of matches by chance is 3% between 13 and 46 kyr and 18% in the older part of the record.

[14] Hence it is unlikely that the good agreement between the 1470-year template and onset of the Dansgaard-Oeschger events between 13 and 46 kyr B.P. arises out of happenstance. During this interval the 1470-year pacing, derived from Dansgaard-Oeschger events 5–7, is reflected in all but one Dansgaard-Oeschger event (Figure 7). However, the Dansgaard-Oeschger interstadials do not respond to each 1470-year pacing cycle. Instead, as indicated by the spacing between the stadial-to-interstadial transitions, the waiting time between the onset of two subsequent Dansgaard-Oeschger events may, to a first approximation, be regarded as multiple of the 1470-year cycle (Figure 5). Accordingly, the 1470-year pacing can be considered as the fundamental period of the pacing of Dansgaard-Oeschger events between 13 and 46 kyr B.P. The situation is markedly different in the interval 46–80 kyr B.P., when no significant 1470-year pacing of the Dansgaard-Oeschger onsets is indicated. During this interval the occurrence of Dansgaard-Oeschger events cannot be distinguished from a series of random events.

[15] For ages to ~50 kyr B.P. the stratigraphy of the GISP2 δ^{18}O record is based on counting annual layers, whereas older ages were assigned by correlating the δ^{18}O of O_2 in gas bubbles in the GISP2 ice core to that of the Antarctic Vostok ice core, which was dated by flow modeling and a match to the marine SPECMAP timescale [*Meese et al.*, 1994; *Bender et al.*, 1994, and references therein]. Accordingly, the relative uncertainty of the GISP2 timescale shows a distinct break at ~50 kyr B.P. from 1–2 to 5–20% [*Meese et al.*,

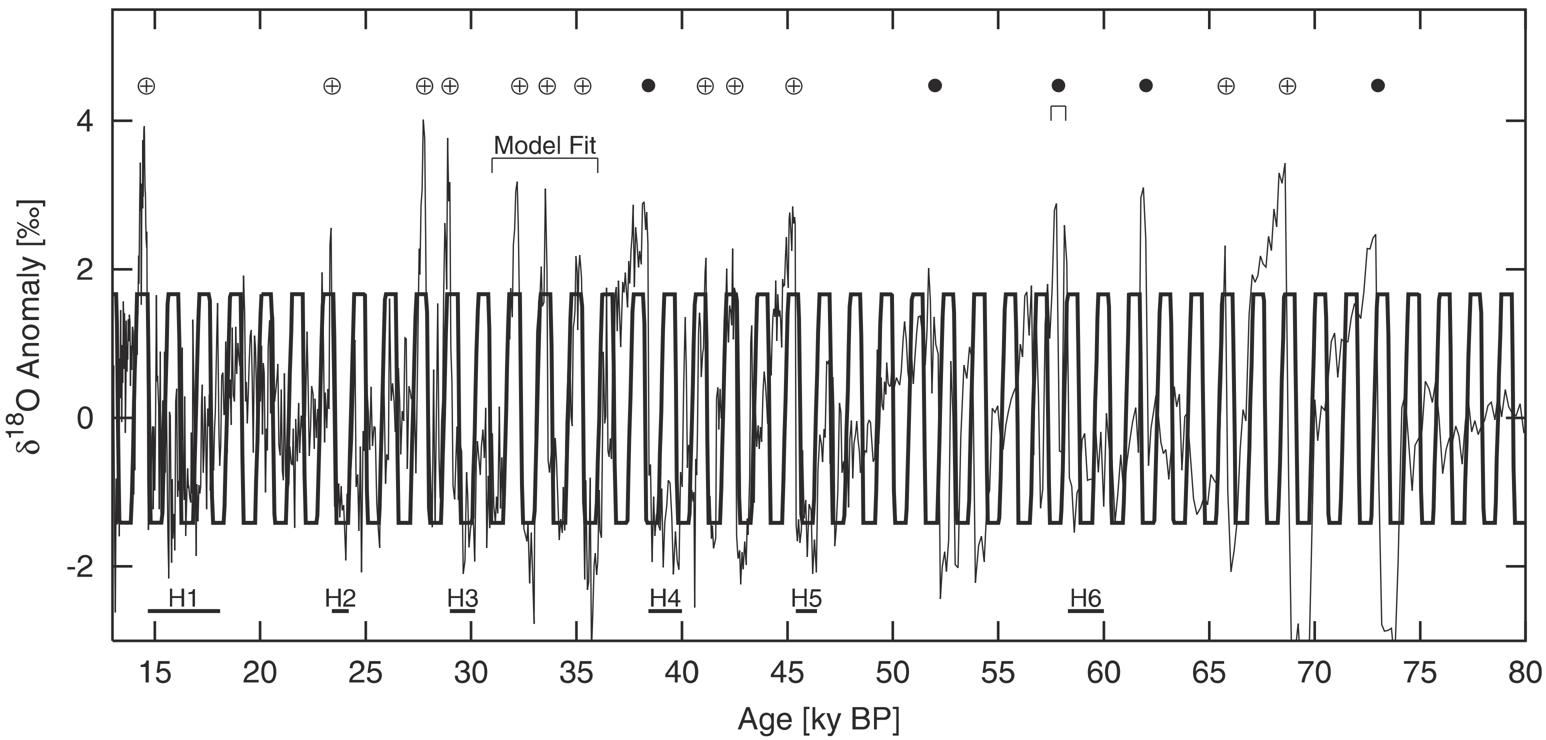

Figure 7. Filtered δ^{18}O time series (thin line) and 1470-year pacing template (thick line). The template is derived from the time series model depicted in Figure 6. Bullets mark canonical Dansgaard-Oeschger events, and circled pluses denote those events which are consistent with the pacing predicted by the template (see text for details). Timing and duration of Heinrich events (H1. . .H6) are indicated by horizontal bars [*Sarnthein et al.*, 2001]. Interval where time series model was fitted to the data is indicated.

1997]. The identified shift in the pacing of the Dansgaard-Oeschger events at ∼46 kyr B.P. thus coincides with a significant change in the uncertainty of the GISP2 timescale. Hence it cannot be ruled out that the mismatch between the 1470-year template and the Dansgaard-Oeschger events between 46 and 80 kyr B.P. arises from errors in the timescale. This implies that the fundamental 1470-year cycle may have acted before 46 kyr B.P. as pacemaker of the Dansgaard-Oeschger events as well.

5. Inferences About the Pacing Mechanism

[16] By itself the evidence for a fundamental 1470-year pacing of the Dansgaard-Oeschger events between 13 and 46 kyr B.P. does not reveal the mechanism which generates the pacing. Nevertheless, the above findings can be compared with predictions of conceptual models, which have been suggested to account for Dansgaard-Oeschger events [e.g., *Winton*, 1993; *van Kreveld et al.*, 2000; *Keeling and Whorf*, 2000]. The pacing of the Dansgaard-Oeschger events implies a remarkable stability of the 1470-year forcing period (see Figure 7). The spacing Δt of the Dansgaard-Oeschger events (Figure 5) can be used to estimate the variability of the inferred 1470-year pacing using the transformation $\Delta t' = (\Delta t - n)$ 1470 years, where n is chosen such that $0 \leq \Delta t' < 2 \times 1470$ years. Restricting the analysis to ages < 46 kyr B.P., that is, the interval with significant 1470-year pacing, reveals that $\Delta t'$ deviates by less than approximately ±20% from the mean spacing of 1470-year and its multiples. The variability of the time lag between the onset of a Dansgaard-Oeschger event and the corresponding onset in the 1470-year template provides another measure of the stability of the pacing cycle. If the pacing would be exact, the onsets of all Dansgaard-Oeschger events would be synchronous with the template, resulting in a zero lag. In the interval 13–46 kyr B.P. a positive lag ensues in all but one case (Figure 8). In no instance does the lag exceed the uncertainty imposed by the relative error of the GISP2 timescale (1–2%). These results suggest that the variability of the pacing period varied less than can be resolved, given the stratigraphic uncertainties of the GISP2 timescale. As pointed out by *Wunsch* [2000], it is unlikely that a pacing signal with only negligible variations in its period can be generated within a fluid-dynamical system, such as the climate system, because of the large number of degrees of freedom being involved. Future modeling studies may be able to test if the estimated small degree of variability can be reconciled with internal oscillations, generated within the climate system. Particular emphasis should be placed on the possible role of continental ice sheets in generating the pacing [*Greve*, 1997; *van Kreveld et al.*, 2000].

[17] A simplified atmosphere-sea ice-ocean model can generate internal oscillations with a period of 1600–2000 years [*Paul and Schulz*, 2002]. In this model the period of the oscillation is partly determined by the strength of the meridional overturning in the Atlantic Ocean, which is closely linked to the rate of North Atlantic Deep Water formation; the period increases as the meridional overturning weakens. Applying this concept to the pacing of the Dansgaard-Oeschger events, one would expect that the period of the pacing, that is, the period of the internal oscillation, would increase during time intervals when the formation of North Atlantic Deep Water was extremely weak or even ceased completely, as during Heinrich events [*Sarnthein et al.*, 1994, 2001]. However, the five Heinrich events which occurred between 15 and 47 kyr B.P. [*Sarnthein et al.*, 2001] did not perturb the match between the 1470-year template and the onset of the Dansgaard-Oeschger events significantly (Figure 7), as one might expect if the pacing period would be closely linked to the strength of the meridional overturning in the Atlantic Ocean. It seems therefore likely that the mechanism responsible for generating the 1470-year pacing is not primarily controlled by the rate of North Atlantic Deep Water formation.

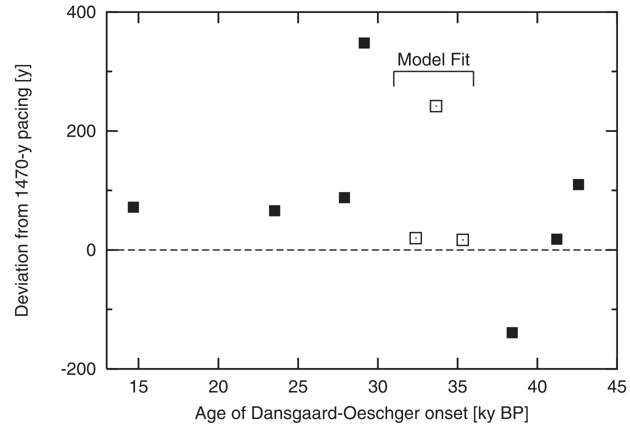

Figure 8. Lag between the onset of the stadial-to-interstadial transitions in the 1470-year template and the corresponding onset of a canonical Dansgaard-Oeschger event in the filtered $\delta^{18}O$ time series. Solid squares indicate points which are independent of fitting the time series model to the data.

[18] If the 1470-year pacing cycle would originate from astronomical fording, the long-term stability of the orbital elements within the solar system make them a prime candidate for generating the 1470-year pacing cycle. So far, a periodicity of ∼1800 years has been identified [*De Rop*, 1971; *Keeling and Whorf*, 2000], which arises from the periodic motions of Earth and Moon and may modulate large-scale oceanic mixing by variations in the strength of oceanic tides. *Keeling and Whorf* [2000] proposed a mechanism by which these tidal variations induce changes in climate and suggest that they might be responsible for the Dansgaard-Oeschger events. However, given that the uncertainty of the GISP2 timescale is <5% during the last 50 kyr or so, the observed 1470-year pacing is incompatible with the 1800-year tidal cycle. Nevertheless, other orbital elements may hold the key to explain the 1470-year cycle. Independent of the astronomical pacemaker that might be suggested in the future, it will be challenging to conceive a physical link between the external forcing and climate variations. Given the great many orbital periods associated with the largest bodies of the solar system [e.g., *Fairbridge and Sanders*, 1987], it is likely to find a "combination tone" of these periods that comes close to 1470 years. However, one then has to ask why other combination tones, with possibly larger amplitudes, have not been recorded by the climate system.

[19] Finally, the "quantum" nature of the spacing of the Dansgaard-Oeschger events calls for an explanation. If one accepts the existence of the fundamental 1470-year pacing period, a mechanism is required which allows the climate system to skip up to five pacing cycles before a new Dansgaard-Oeschger event is triggered (Figure 5). Stochastic resonance [*Alley et al.*, 2001, and references therein] is an appealing concept to account for this observation. In its simplest form a system consisting only of a threshold and a subthreshold pacing cycle with added white noise can generate the observed quantum spacing. The general course of the spacing during a glacial-interglacial cycle (Figure 5) may then be due to a change in the noise amplitude or the threshold value, which may be linked to continental ice mass. Although attractive, this conceptual model does not solve the problem of identifying the origin of the pacing cycle as well as the physics underlying the threshold behavior.

[20] Alternatively, the quantum spacing may be linked to changes in the stability of the oceanic thermohaline circulation. *Ganopolski and Rahmstorf* [2001] suggested that the Dansgaard-

Oeschger interstadials are perturbations of a stable stadial climate state, triggered by an external pacing cycle. In their model experiments the interstadial state is marginally unstable and decays until the climate system finally falls back into the stable stadial state. It can be shown that the rate by which the interstadial state decays is linked to the amount of continental ice volume [*Schulz*, 2002]. Only decay rates associated with intermediate ice volume allow the climate system to respond to succeeding trigger events of the 1470-year cycle and result in stadials/interstadials of approximately the same duration (such as Dansgaard-Oeschger events 5–7). In contrast, smaller ice volume goes along with lower decay rates and results in interstadials which last longer than 1470 years. Hence the climate system cannot respond to each 1470-year pacing event but has to skip some pacing cycles before a new interstadial can be triggered. This ensures that the time span between the onsets of the Dansgaard-Oeschger interstadials occurs in multiples of the 1470-year pacing period.

6. Conclusions

[21] 1. The distinct 1470-year spectral peak in the nonstationary GISP2 $\delta^{18}O$ time series is caused solely by Dansgaard-Oeschger events 5, 6, and 7. It is therefore unnecessary to invoke aliasing to account for it.

[22] 2. The waiting time between the onset of two subsequent Dansgaard-Oeschger events varies by less than approximately ±20% around a value of 1470 years and multiples thereof. The inconstant spacing of Dansgaard-Oeschger events is sufficient to mute any significant 1470-year spectral peak outside the time interval of Dansgaard-Oeschger events 5–7.

[23] 3. Between 13 and 46 kyr B.P. the onset of Dansgaard-Oeschger events was paced by a fundamental period of ~1470 years. Uncertainties in the GISP2 timescale preclude inferences regarding the pacing for times before ~50 kyr B.P. If future studies approve the existence of the 1470-year pacing cycle, it may be used for fine tuning timescales, by matching the onset of Dansgaard-Oeschger events to a 1470-year template.

[24] 4. The match between the onset of Dansgaard-Oeschger events and the pacing cycle persists during five Heinrich events. Therefore it seems likely that the generation of the 1470-year pacing period was largely decoupled from the rate of North Atlantic Deep Water formation.

Appendix A

[25] The course of the Dansgaard-Oeschger events in the GISP2 $\delta^{18}O$ record deviates strongly from a sinusoidal wave and is better described by a square wave pattern with sharp transitions. Other paleoclimatic time series show saw-tooth patterns on various timescales. In situations like these it might not be optimal to analyze a time series in terms of sinusoidal waves (Fourier analysis) since many sinusoids are required to construct such signals. Moreover, Fourier analysis may even produce misleading results. Consider a pulse train and a saw-tooth wave of the same frequency. The phase between the signals is set such that each pulse is centered on the rapid transitions of a saw tooth. A straightforward interpretation of the relation between the two signals is that they are in phase. In contrast, a Fourier-based phase spectrum will indicate a 90° phase offset between the two signals. This result can be understood if one examines the Fourier series of the pulse train and the saw-tooth wave, respectively. Whereas the fundamental frequency appears in a cosine term in the pulse train series, it is associated with a sine term in the saw-tooth series, leading to the apparent phase shift of 90°. As a remedy it might be advantageous to use nonsinusoidal waveforms for time series analysis. Although wavelets [e.g., *Torrence and Compo*, 1998] appear to be well suited for this purpose, they might not be flexible enough because all frequencies are analyzed using the same mother wavelet, that is, with the same waveform. The following approach, which is based on a trapezoidal waveform, comes without this restriction since the shape of the trapezoidal wave is allowed to vary within bounds.

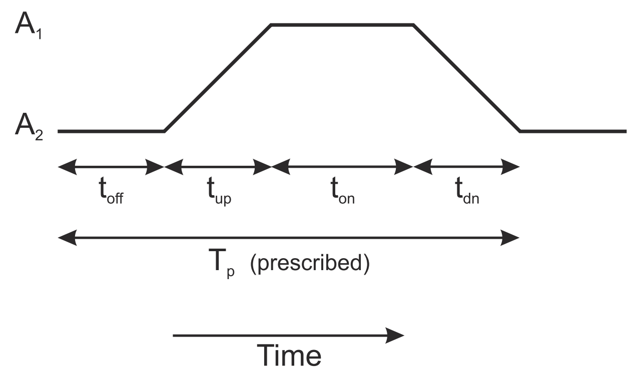

Figure A1. Trapezoidal waveform used by the time series model (see text for explanation of symbols).

[26] The trapezoidal wave (Figure A1), with period T_p, is composed of four segments: off phase of length t_{off}, upsloping segment t_{up}, upper plateau t_{on}, and downsloping segment t_{dn}. The amplitude range is given by A_1 and A_2. Other waveforms can be derived from the generic trapezoidal base wave as well: square wave ($t_{\mathrm{up}} = t_{\mathrm{dn}} = 0$; $t_{\mathrm{on}} = t_{\mathrm{off}}$), pulse train ($t_{\mathrm{up}} = t_{\mathrm{dn}} = 0$; $t_{\mathrm{on}} < t_{\mathrm{off}}$), triangular wave ($t_{\mathrm{up}} = t_{\mathrm{dn}}$; $t_{\mathrm{on}} = t_{\mathrm{off}} = 0$), saw-tooth wave ($t_{\mathrm{up}} \gg t_{\mathrm{dn}}$; $t_{\mathrm{on}} = 0$; $t_{\mathrm{off}} \geq 0$). Prescribing T_p and introducing a phase shift τ yields a set of six independent parameters $\mathbf{P} = (t_{\mathrm{off}}, t_{\mathrm{up}}, t_{\mathrm{dn}}, \tau, A_1, A_2)$ which determine the shape of the trapezoidal wave $\Phi(t, \mathbf{P})$ as function of time t. Imposing T_p on a prescribed grid, the time series model $\Phi(t, \mathbf{P})$ is fitted to a data set $x(t)$ by minimizing $L = (\Phi(t, \mathbf{P}) - x(t))^2$ for each T_p, using a conjugate direction set algorithm [*Press et al.*, 1992]. For each value of T_p the statistical significance of the resulting fit is evaluated using a standard F test as in multiple regression analysis. A plot of $(|A_1| + |A_2|)$ versus $1/T_p$ yields a "fit spectrum," while plotting the F statistic versus $1/T_p$ allows us to identify periods where the fit is significant. A Fortran 90 implementation of this curve-fitting procedure is available upon request.

[27] **Acknowledgments.** I am grateful to M. Sarnthein, A. Paul, W. Berger, P. Grootes, and T. Kiefer for numerous stimulating discussions about the origin of Dansgaard-Oeschger events. Comments by an anonymous reviewer helped to improve the manuscript. This study was supported by EU project "Climate variability—How unusual is the Holocene?".

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