Timing of abrupt climate change: A precise clock

Stefan Rahmstorf
Potsdam Institute for Climate Impact Research, Potsdam, Germany

Received 12 February 2003; revised 27 March 2003; accepted 10 April 2003; published 21 May 2003.

[1] Many paleoclimatic data reveal a ~1,500 year cyclicity of unknown origin. A crucial question is how stable and regular this cycle is. An analysis of the GISP2 ice core record from Greenland reveals that abrupt climate events appear to be paced by a 1,470-year cycle with a period that is probably stable to within a few percent; with 95% confidence the period is maintained to better than 12% over at least 23 cycles. This highly precise clock points to an origin outside the Earth system; oscillatory modes within the Earth system can be expected to be far more irregular in period. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 1650 Global Change: Solar variability; 3367 Meteorology and Atmospheric Dynamics: Theoretical modeling; 1635 Global Change: Oceans (4203). **Citation:** Rahmstorf, S., Timing of abrupt climate change: A precise clock, *Geophys. Res. Lett.*, *30*(10), 1510, doi:10.1029/2003GL017115, 2003.

1. Introduction

[2] Global climate during the last glacial (~120,000–10,000 years before present) has experienced at least twenty abrupt and large-amplitude shifts called Dansgaard-Oeschger (DO) events. These dramatic climate events are most clearly seen in Greenland ice cores [*Dansgaard et al.*, 1993; *Johnsen et al.*, 1992], but have also been recorded in many other places [*Voelker*, 2002]. Early analyses have found a periodicity around 1,500 years for these events; power spectra of the GISP2 ice core record show a prominent peak at a period of 1,470 years [*Grootes and Stuiver*, 1997]. Further statistical analysis has shown that the "waiting times" between consecutive DO events are most often close to 1,500 years, with further preferred intervals around 3,000 and 4,500 years [*Alley et al.*, 2001a, 2001b]. This suggests that the events are triggered by an underlying cycle of ~1,500 year period, but that sometimes a beat or two is skipped. By fitting a trapezoidal wave to the time series, [*Schulz*, 2002] concluded that the onset of DO events varied by ±20% around multiples of the 1470-year period. Here we show with an improved analysis method that this variation is only ±8%, and we analyze the different contributions to this variation - in particular, the precision of the underlying cycle.

[3] Simulations with a coupled climate model have led to the proposal of a mechanism for DO events: these can be understood as a state change in the thermohaline ocean circulation of the Atlantic, more specifically a shift in the latitude of North Atlantic Deep Water (NADW) formation [*Ganopolski and Rahmstorf*, 2001]. Such a shift in convection location can explain many observed features of DO events (e.g., their spatial pattern and time evolution), and it can be triggered by small cyclic variations in the freshwater budget of the Nordic Seas. This is a threshold process; if the freshwater variations are not strictly periodic but include a random component ("noise"), stochastic resonance [*Gammaitoni et al.*, 1998] can occur, explaining why not each oscillation triggers an event [*Ganopolski and Rahmstorf*, 2002].

[4] While this mechanism explains how these events are triggered and how they evolve, it does not explain what the cause of the underlying cycle might be. There is some evidence that this cycle may also be present in the Holocene but does not trigger DO events then [*Bond et al.*, 1997], possibly because the Atlantic ocean circulation is not close to a threshold in a warm climate [*Ganopolski and Rahmstorf*, 2001]. The so-called "little ice age" of the 16th–18th century may be the most recent cold phase of this cycle. The origin of the "mystery 1,500 year cycle" is thus one of the key issues in climatology that needs to be explained.

[5] Two types of explanations have been advanced: periodic external forcings (e.g., variations in the luminosity of the sun) or internal oscillations in the climate system (e.g. in the ocean circulation [*Broecker et al.*, 1990]). A key to distinguish hypotheses is the regularity of the oscillation. For several reasons oscillation modes within the climate system (such as the Southern Oscillation and the North Atlantic Oscillation) tend to be highly irregular. These reasons include the complexity of the climate system, its large number of degrees of freedom, and the unstable nature of the atmospheric circulation causing ubiquitous stochastic variability. If the 1,500-year cycle originated in the Earth system, we would also expect the period to change as the background climate moves between full glacial and interglacial conditions. In contrast, orbital cycles are highly regular.

2. An Objective Event Detection Algorithm

[6] Several δ^{18}O time series from the GISP2 and GRIP ice cores were analysed; we will mainly discuss the GISP2 series sampled at 2m intervals shown in Figure 1. This ice core is dated by layer-counting back to 51 kyr b.p. [*Meese et al.*, 1997]; this well-dated part of the time series provides the best opportunity to analyse the regularity of DO events.

[7] First, we need to define an objective method to identify DO events and determine their timing. In contrast to [*Schulz*, 2002] no particular time series model is fitted to the events. A much simpler event detection algorithm is applied here which requires fewer assumptions: each warming by more than ΔT (in units of δ^{18}O) within a time interval Δt is considered a DO event. The unfiltered GISP2 data were scanned on a point-by-point basis with these criteria. Since the DO events stand out very clearly from the background variability, the choice of the threshold values is

0094-8276/03/2003GL017115$05.00

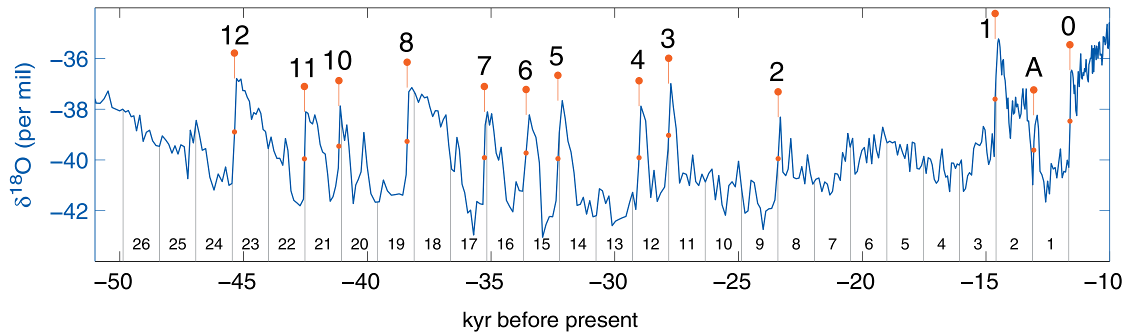

Figure 1. The GISP2 climate record for the second half of the glacial. Dansgaard-Oeschger warming events found by the objective detection algorithm are labeled with red flags. The grey vertical lines show 1,470-year spacing, small numbers at the bottom count the number of 1,470-year periods from DO event 0.

not critical. The only two debatable events are the Allerød event (labelled A in Figure 1), not previously counted as a DO event, and event 9, which is not accepted by the algorithm as a DO event. By adapting the thresholds event 9 could be included, but with almost the same amplitude as the Allerød it is much slower (2.80‰ warming in 312 years, compared to 2.74‰ warming in 172 years). The Allerød thus fits in with the other events, all faster than 200 years, better than event 9. We used $\Delta T = 2$‰ and $\Delta t = 200$ years; the events identified in this way are marked in Figure 1. The numbering corresponds to the traditional numbering of these events as they were identified by eye [*Dansgaard et al.*, 1993; *Johnsen et al.*, 1992]. The algorithm identifies the deglacial warming (the end of the Younger Dryas) as a DO event; following an earlier suggestion [*Rahmstorf*, 2002] this is labeled DO event 0.

[8] The timing of the events is defined as the time when the $\delta^{18}O$ value is half way between the start value and the peak value and is shown as red dots in Figure 1. (The algorithm defines the start of an event as the first data point of a pair that meets the criteria.) Table 1 provides a list of DO events and their timings as found by the algorithm.

[9] The method was also applied to two higher resolution data sets from GISP2, sampled at 1m intervals and at 20 yr intervals. These data sets are 'noisier' (more short-term fluctuations) and the algorithm as described above gives a number of 'false alarms' (identifying additional DO events) when applied unaltered to the higher resolution data. Making the detection algorithm more complex to reject brief fluctuations is one way to rectify this. Alternatively, the unaltered simple detection criteria can be used on smoothed versions of the higher resolution data. E.g., after applying a simple 5-point running average on the 20-yr resolution data, almost identical results are obtained as with the 2-m sampled data. Nothing is gained in this way; we show the results for the 2-m sampled time series here since this allows the most simple data treatment without any filtering.

[10] Figure 1 includes lines spaced $P = 1{,}470$ years apart, and it is apparent that most of the DO events fall very close to these lines. Figure 2 shows the distance (in time) of each event from such a line. For randomly timed events these should be roughly randomly distributed between $\pm P/2$. In fact, 11 of the 13 events fall within ±10% of the full period, the remaining two within 20%, and the standard deviation of the 13 events is only 125 years (8% of the period). This is the puzzling regularity in the timing of DO events that we want to examine in more detail.

[11] When doing this, we have to keep in mind that the phase and the period P of the cycle can be tuned to fit the data, so that two degrees of freedom have been used up. Different ways of deriving P from the data all result in periods within a few years of 1,470 yr and hardly affect the further results; for simplicity I have used the classical value of $P = 1{,}470$ yr. The phase was chosen to reduce the mean deviation of all 13 events to zero.

[12] The deviation δ_i of each event i from "perfect timing" (i.e., multiples of P) can be decomposed into three components:

$$\delta_i = \delta_i^t + \delta_i^c + \delta_i^d, \tag{1}$$

Table 1. Listing of DO Events as Analyzed in This Study

Event number	Time (years b.p.)	Cycles before event 0	Deviation δ_i (years)
0	11,605	0	−45
A	13,073	1	−48
1	14,630	2	40
2	23,398	8	−12
3	27,821	11	1
4	29,021	12	−269
5	32,293	14	63
6	33,581	15	−119
7	35,270	16	100
8	38,387	18	277
10	41,143	20	93
11	42,537	21	17
12	45,362	23	−98

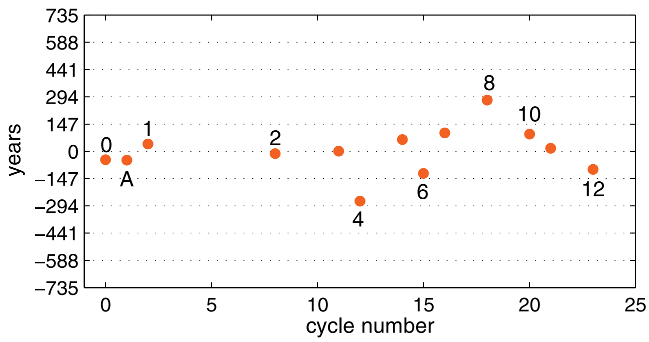

Figure 2. Time deviation δ_i for each DO event from the grey lines in Figure 1, labelled with event number.

where δ_i^t is the "triggering error" of an event, δ_i^c is the "clock error", and δ_i^d is the dating error. We will consider these in turn. This decomposition is based on the idea that there is an underlying cycle (a "clock") that triggers the DO events. One example is the ocean circulation mechanism mentioned above; other mechanisms are possible.

3. The Triggering Error

[13] Even if the underlying clock is completely regular, events could vary in time by being triggered sometimes slightly earlier or slightly later in the clock cycle. This is for example the case for a stochastic resonance mechanism, where random noise and a clock cycle combine to trigger events. This not only leads to some cycles without any events being triggered, it also leads to variations in the timing of the events. The characteristic of this *triggering error* is that it is not cumulative; a delayed start of one event does not affect the timing of subsequent events. Unless there is a systematic effect (perhaps due a change in background climate), each δ_i^t is independent of all others:

$$\delta_i^t = \sigma_t \xi_i, \quad (2)$$

where ξ_i is a white noise process with unit standard deviation. If we assume the triggering error is indeed random and is the main source of the observed variance, the data in Figure 2 provide an upper estimate for the standard deviation σ_t of this random process. For example, in a stochastic resonance mechanism the relative amplitudes of the clock cycle and the noise, as well as the shape of the cycle, determine the deviation of the events from perfect periodicity. A strong role of noise would lead to large deviations from perfect timing; the data show however that these deviations are remarkably small at σ_t = 8% of the period. This provides quite a stringent constraint for a possible mechanism and for future model simulations.

4. The Clock Error

[14] As discussed in the introduction, probably the most interesting aspect of the regularity of DO events is the accuracy of the underlying clock. This *clock error* is treated differently here since for most conceivable clocks the error will be accumulating: if at one point in time the clock is running late, all subsequent times will be affected. (Irrespective of the physical motivation for the decomposition (equation (1)), we could have formally decomposed the error into a non-cumulative and a cumulative component.)

[15] If we assume a random, but accumulating error (with standard deviation σ_c) in the length of each clock cycle, the resulting deviation of the clock after *n* cycles is the result of a Wiener process [*Gardiner*, 1985]:

$$\delta_{i+1}^c = \delta_i^c + \sigma_c \xi_i. \quad (3)$$

[16] We can then provide an upper estimate for the clock accuracy σ_c from the data in Figure 2. The upper limit on σ_c is more stringent than on the triggering error, since the error accumulates and the clock would lose its phase relation in this way after a number of cycles. (The standard deviation of a Wiener process after n steps grows proportional to $\sqrt{n}$.) The fact that this does not happen even over 23 cycles is one of the most remarkable aspects of the GISP2 data shown in Figure 1. Having fitted the period and phase of the cycle is equivalent to subtracting a linear trend and the mean from the particular realisation of the Wiener process. Also, we are not interested in the standard deviation after n steps, but in the standard deviation of all steps from this linear trend. This problem is hard to treat analytically; we have therefore numerically generated 10,000 realisations of such a Wiener process with 23 steps (clock cycles); from each realisation its linear trend and mean were removed. A random sample of 5 such realisations is shown in Figure 3.

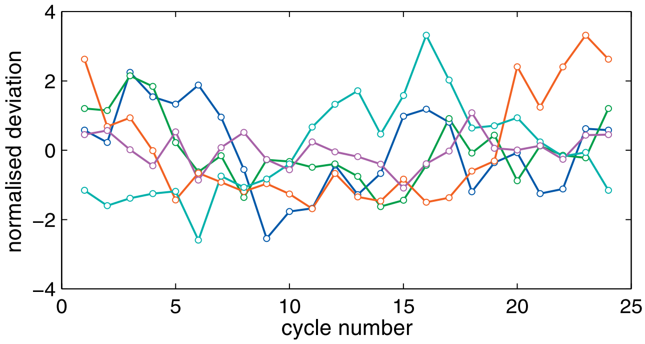

Figure 3. Five realizations of a Wiener process with unit standard deviation and 23 steps, with linear trend and mean removed.

[17] The average standard deviation of these synthetic data that corresponds directly to Figure 2 (i.e., computed from a subsample of 13 "events" from the 25 cycles just as in the Greenland data) was found to be 1.27 σ_c. This means that the observed standard deviation of 125 years found in the data would on average be produced by a clock with accuracy σ_c = 99 years (125/1.27). This is a remarkably small value at less than 7% of the period *P*.

[18] However, this is only one realization sampled with 13 data points, so the observed standard deviation could be low by sampling chance, even if the clock error σ_c is in fact larger. Our numerical simulations show that in 95% of all simulated realizations, the standard deviation of the 13-point subsample is greater than 0.69 σ_c. This means that with 95% confidence we can conclude from the observed 13 DO events that the underlying clock is more accurate than σ_c = 181 years or 12% of the period.

5. The Dating Error

[19] The third potential cause of the deviations seen in Figure 2 is the *error in the dating* of the ice core. Since the analyzed core section is dated by layer-counting, this error is cumulative and behaves like the clock error. To derive an upper limit we can assume again that all the observed deviations are completely caused by dating error. This leads to the conclusion that the random dating error of these data is less than 7% during the ~40 kyr considered. This is not the total error since systematic errors cannot be detected in this way; if the number of layers was systematically under-counted by 5% percent, this would simply lead to a period *P* that was underestimated by 5% but not to random variations around this period.

[20] The same analysis technique was applied to the older part of GISP2 (>51 kyr b.p.), which was not dated by layer counting but by correlation with the Antarctic Vostok ice

core [*Meese et al.*, 1997]. The regularity of DO events is lost in this part of the core, probably because the dating accuracy is not sufficient to detect it. The same is true for a data set from the GRIP core, which was not dated by layer counting during the glacial period [*Grootes et al.*, 1993]. The same 13 DO events as used for the above analysis are also found when the detection algorithm is applied to this GRIP series, but shifted in time enough to destroy the regularity found in GISP2. This strongly suggests that the GISP2 time scale is more accurate than the original GRIP time scale, as is also shown by [*Wang et al.*, 2001].

6. Conclusions

[21] In summary, the key concept behind this analysis is that Dansgaard-Oeschger events are discrete events paced by a regular cycle, rather than being cycles themselves. This is evident by visual inspection of Figure 1; it is also supported by mechanistic simulations of these events [*Ganopolski and Rahmstorf*, 2001, 2002] and by the fact that analysing these events with methods appropriate for cycles fails to reliably detect the regularity that is so striking in Figure 1 [*Wunsch*, 2000]. Instead of using such methods, a very simple event detection algorithm was used here. 13 DO events were identified and timed during the time interval 51–10 kyr b.p. in the GISP2 ice core in this way. It was found that 11 of these events fall within an interval of ±10% of multiples of a 1,470-year period; the remaining 2 events fall within 20%. This strongly supports the idea that the events are paced by a regular 1,470-year cycle.

[22] When analyzing three possible components causing deviations from this period, three powerful conclusions can be drawn.

[23] 1. If the deviations are entirely caused by the events being triggered slightly earlier or later in each cycle, e.g. due to the presence of climatic "noise", then our best estimate for this "triggering error" is 8% (standard deviation) of the period.

[24] 2. If the deviations are entirely caused by a random variation in the underlying regular cycle or "clock", then the best estimate for this "clock error" is less than 7% of the period (or 99 years). With 95% confidence we can say that the clock error is smaller than 12% of the period.

[25] 3. The most accurate of the various dating methods applied to Greenland ice cores, at least in terms of random errors, is layer-counting. Only layer-counted portions of the ice cores show the regularity analysed here.

[26] Conclusion (2) is the most remarkable and far-reaching one. It is rare that such a stringent quantitative measure can be determined at such a high confidence level in paleoclimatic data. Given the pessimistic assumptions that were made to derive an upper limit estimate of the clock error (in reality, both the core dating error and the triggering error can be expected to significantly contribute to the total deviations), it is likely that the clock error is in fact much smaller still than the estimates given above. The five most recent events, arguably the best-dated ones, have a standard deviation of only 32 years (2%). While the earlier estimate of ±20% [*Schulz*, 2002] is consistent with a solar cycle (the 11-year sunspot cycle varies in period by ±14%), a much higher precision would point more to an orbital cycle. The closest cycle known so far is a lunar cycle of 1,800 years [*De Rop*, 1971], which cannot be reconciled with the 1,470-year pacing found in the Greenland data. The origin of this regular pacing thus remains a mystery.

[27] **Acknowledgments.** I thank Till Kuhlbrodt for helpful discussions on stochastic processes.

References

Alley, R. B., S. Anandakrishnan, and P. Jung, Stochastic resonance in the North Atlantic, *Paleoceanography*, *16*, 190–198, 2001a.
Alley, R. B., S. Anandakrishnan, P. Jung, and A. Clough, Stochastic resonance in the North Atlantic: Further insights, in *The Oceans and Rapid Climate Change: Past, Present and Future*, *Geophys. Monogr. Ser.*, vol. 126, edited by D. Seidov, M. Maslin, and B. J. Haupt, pp. 57–68, AGU, Washington, D. C., 2001b.
Bond, G., W. Showers, M. Cheseby, R. Lotti, P. Almasi, P. deMenocal, P. Priore, H. Cullen, I. Hajdas, and G. Bonani, A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates, *Science*, *278*, 1257–1266, 1997.
Broecker, W. S., G. Bond, M. Klas, G. Bonani, and W. Wolfi, A salt oscillator in the glacial northern Atlantic?: 1, The concept, *Paleoceanography*, *5*, 469–477, 1990.
Dansgaard, W., S. J. Johnsen, H. B. Clausen, N. S. Dahl-Jensen, N. S. Gundestrup, C. U. Hammer, C. S. Hvidberg, J. P. Steffensen, A. E. Sveinbjörnsdottir, J. Jouzel, and G. Bond, Evidence for general instability of past climate from a 250-kyr ice-core record, *Nature*, *364*, 218–220, 1993.
De Rop, W., A tidal period of 1800 years, *Tellus*, *23*, 261–262, 1971.
Gammaitoni, L., P. Hanggi, P. Jung, and F. Marchesoni, Stochastic resonance, *Rev. Mod. Phys.*, *70*, 223–287, 1998.
Ganopolski, A., and S. Rahmstorf, Rapid changes of glacial climate simulated in a coupled climate model, *Nature*, *409*, 153–158, 2001.
Ganopolski, A., and S. Rahmstorf, Abrupt glacial climate changes due to stochastic resonance, *Phys. Rev. Lett.*, *88*(3), 038501, 2002.
Gardiner, C. W., *Handbook of Stochastic Methods*, 444 pp., Springer-Verlag, New York, 1985.
Grootes, P. M., and M. Stuiver, Oxygen 18/16 variability in Greenland snow and ice with 10^{-3}- to 10^{5}-year time resolution, *J. Geophys. Res.*, *102*(C12), 26,455–26,470, 1997.
Grootes, P. M., M. Stuiver, J. W. C. White, S. Johnsen, and J. Jouzel, Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores, *Nature*, *366*, 552–554, 1993.
Johnsen, S. J., H. B. Clausen, W. Dansgaard, K. Fuhrer, N. Gundestrup, C. U. Hammer, P. Iversen, J. Jouzel, B. Stauffer, and J. P. Steffensen, Irregular glacial interstadials recorded in a new Greenland ice core, *Nature*, *359*, 311–313, 1992.
Meese, D. A., A. J. Gow, R. B. Alley, G. A. Zielinski, P. M. Grootes, M. Ram, K. C. Taylor, P. A. Mayewski, and J. F. Bolzan, The Greenland Ice Sheet Project 2 depth-age scale: Methods and results, *J. Geophys. Res.*, *102*(C12), 26,411–26,423, 1997.
Rahmstorf, S., Ocean circulation and climate during the past 120,000 years, *Nature*, *419*, 207–214, 2002.
Schulz, M., On the 1470-year pacing of Dansgaard-Oeschger warm events, *Paleoceanography*, *17*(2), 1014, doi:10.1029/2000PA000571, 2002.
Voelker, A. H. L., Global distribution of centennial-scale records for marine isotope stage (MIS) 3: A database, *Quat. Sci. Rev.*, *21*, 1185–1214, 2002.
Wang, Y. J., H. Cheng, R. L. Edwards, Z. S. An, J. Y. Wu, C. C. Shen, and J. A. Dorale, A high-resolution absolute-dated Late Pleistocene monsoon record from Hulu Cave, *China, Science*, *294*, 2345–2348, 2001.
Wunsch, C., On sharp spectral lines in the climate record and the millennial peak, *Paleoceanography*, *15*, 417–424, 2000.

S. Rahmstorf, Potsdam Institute for Climate Impact Research, PO Box 601203, 14412 Potsdam, Germany. (rahmstorf@pik-potsdam.de)