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Ice-age variability from the Vostok deuterium and deuterium excess records

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Abstract. The four climatic cycles obtained from the Vostok ice core offer a unique opportunity to study the high-frequency paleoclimatic variability, i.e., on time scales smaller than 15 kyr. We focused our study on the deuterium (δD) and deuterium excess (d) records, which are proxies for local temperature and remote evaporation source temperature and hence give us access to spatial climatic variations. Spectral analyses of paleoclimatic records have shown that the last glacial period (110–15 kyr before present) is characterized by large and fast temperature oscillations. Examples of such variations in the Northern Hemisphere are the so-called Dansgaard-Oeschger oscillations and Heinrich events. At Vostok, these oscillations are also imprinted in the ice, with broadband periodicities between 5 and 8 kyr and between 1.4 and 1.8 kyr. Scenarios for this behavior have recently been developed and argued, as well as connections with the Northern Hemisphere. We now can investigate the stability of the fast spectral features in the previous ice ages recovered in the Vostok isotopic records. This allows us to document the different types of climatic behavior under glacial conditions and hence connect the fast variation statistics with the slower ones controlled by insolation and sea level change. Our results show that δD and d do have a distinct spectral behavior. We discuss the implications on the ocean circulation from such a difference.

1. Introduction

The Vostok ice core provides, to date, the longest ice record in terms of depth and time span, since it reached a depth of 3623 m and over 450,000 years in the past. The Vostok project is a cooperative effort among Russia, the United States, and France [*Vostok Project Members*, 1995]; it was drilled in East Antarctica (78°28'S, 106°48'E), where the annual average temperature is $\approx -55°$C. The project involved drilling several holes [*Lorius et al.*, 1985; *Jouzel et al.*, 1987, 1993; *Vostok Project Members*, 1995; *Petit et al.*, 1999], for which the data were compared and found in good agreement.

From the ice core, climatic information was retrieved through isotopic measurements of deuterium [*Petit et al.*, 1999] and deuterium excess [*Vimeux et al.*, 1999], greenhouse gases (CO_2 [*Barnola et al.*, 1987; *Petit et al.*, 1999] and CH_4 [*Chappellaz et al.*, 1990; *Petit et al.*, 1999]), dust content [*Petit et al.*, 1990], and various chemical species [*Legrand et al.*, 1992]. We focused on the isotopic measurements (δ^{18}O and δD), expressed in per mil with respect to the standard mean ocean water (SMOW). These two isotopes mainly account for the local temperature variations at the top of the inversion layer, where the precipitation formed [*Jouzel and Merlivat*, 1984; *Jouzel et al.*, 1997]. The δ^{18}O and δD were both measured at 5 m increment samples from 0 to 150 kyr B.P., and 1 m beyond 150 kyr B.P., by *Vimeux et al.* [this issue], independantly from the δD measurements of *Petit et al.* [1999]. The deuterium profile is shown in Figure 1. The comparison between the two isotopes is interesting, so we also used the linear residual between δD and δ^{18}O, the deuterium *excess* d defined by [*Craig*, 1961; *Dansgaard*, 1964]

$$d = \delta\mathrm{D} - 8\delta^{18}\mathrm{O}. \quad (1)$$

The deuterium excess is controled by kinetic isotopic effect differences between δD and δ^{18}O during evaporation. Thus the water vapor at the source of evaporation is richer in δD when the temperature is higher. Hence the deuterium excess index at Vostok accounts for nonlocal or remote information on the oceanic moisture source that precipitates at the site [*Craig*, 1961; *Dansgaard*, 1964]. We used the deuterium excess profile of *Vimeux et al.* [this issue] on the four cycles (Figure 2). Previous studies have shown that d in precipitation reflects meteorological moisture source properties, i.e., mainly sea surface temperature and relative humidity [*Merlivat and Jouzel*, 1979; *Jouzel and Merlivat*, 1984; *Johnsen et al.*, 1989]. Moreover, both Rayleigh-type models [*Vimeux*, 1999] and general circulation models [*Delaygue et al.*, 2000] have shown that d at Vos-

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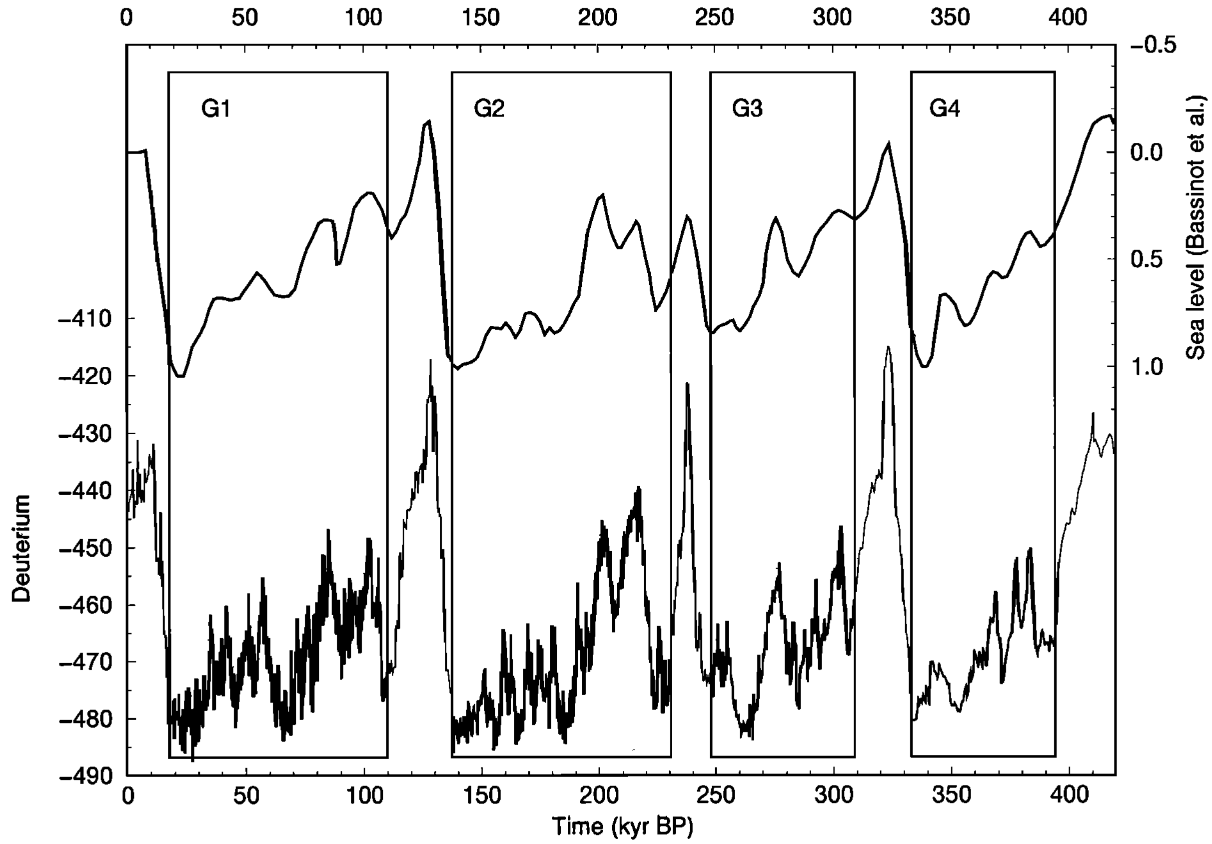

Figure 1. Deuterium δD variations in the Vostok ice core for the top 3305 meters. Time is expressed in thousands of years before present (kyr B.P.). Deuterium values are normalized by SMOW and expressed in per mil. The four ice ages are numbered from G1 to G4, and emphasized by boxes. The upper panel shows the sea-level change curve from the *Bassinot et al.* [1994] data.

tok roughly increases by 1 per mil when source regions warm up by 1°C.

The accumulation rate at Vostok is about 2 cm/yr; this means that the annual layers are too thin for visual detection and models of chronologies have to be used to date the samples [*Lorius et al.*, 1985; *Jouzel et al.*, 1993; *Waelbroeck et al.*, 1995]. *Parrenin et al.* [this issue] provide a methodology that combines and improves the chronologies. Other approaches have been followed, using markers like methane [*Blunier et al.*, 1998] or δ^{18}O [*Bender et al.*, 1994] in the air bubbles to correlate Vostok with better dated records, such as the Greenland Ice core Project (GRIP) ice core or marine records. In this study we will restrict our investigation to the extended glaciological timescale (EGT4) of *Petit et al.* [1999]. The EGT4 chronology is based on ice flow modeling, with the constrain of a few control points (at 110 and 390 kyr B.P.) which put Vostok in phase with marine isotopic records [*Petit et al.*, 1999; *Parrenin et al.*, this issue]. An important caveat is that EGT4 is slightly different from the time scale of *Lorius et al.* [1985] which was used for the first climatic cycle and only had one control point at 110 kyr B.P. Such a change does have an impact on the exact location of the spectral peaks. Hence this is a way of obtaining error bars on the frequency analysis [*Yiou et al.*, 1994, 1997].

The time series derived from the experimental measurements are generally irregular but bear many resemblances and recurring patterns embedded in noise. These patterns cover the well-documented glacial-interglacial cycle and the abrupt oscillations during the last ice age which are found in all cores. Our challenge is then to decipher the climatic information from these apparently noisy signals and assess the statistical significance of the near periodicities in order to infer plausible physical mechanisms.

The purpose of the paper is to compare the statistical features of the four ice ages imprinted in the Vostok ice core. Ice ages are allegedly more variable than interglacials (e.g., the Holocene) and exhibit fast and large-scale variations (see *Broecker* [2000] for a recent review). These variations occur on centennial to millenial time scales and are particularly prominent in Greenland records and marine records of the North Atlantic. Spectral analyses of those records have shown broadband periodicities near 1.5 kyr and 5 kyr (1 kyr = 1000 years), which are respectively associated with Dansgaard–Oeschger (DO) oscillations and Heinrich events (HE). Such fast variations are explained by the instability of northern ice sheets which (more or less) regularly collapse into the ocean and modify its thermohaline circulation (THC). *Blunier et al.* [1998]

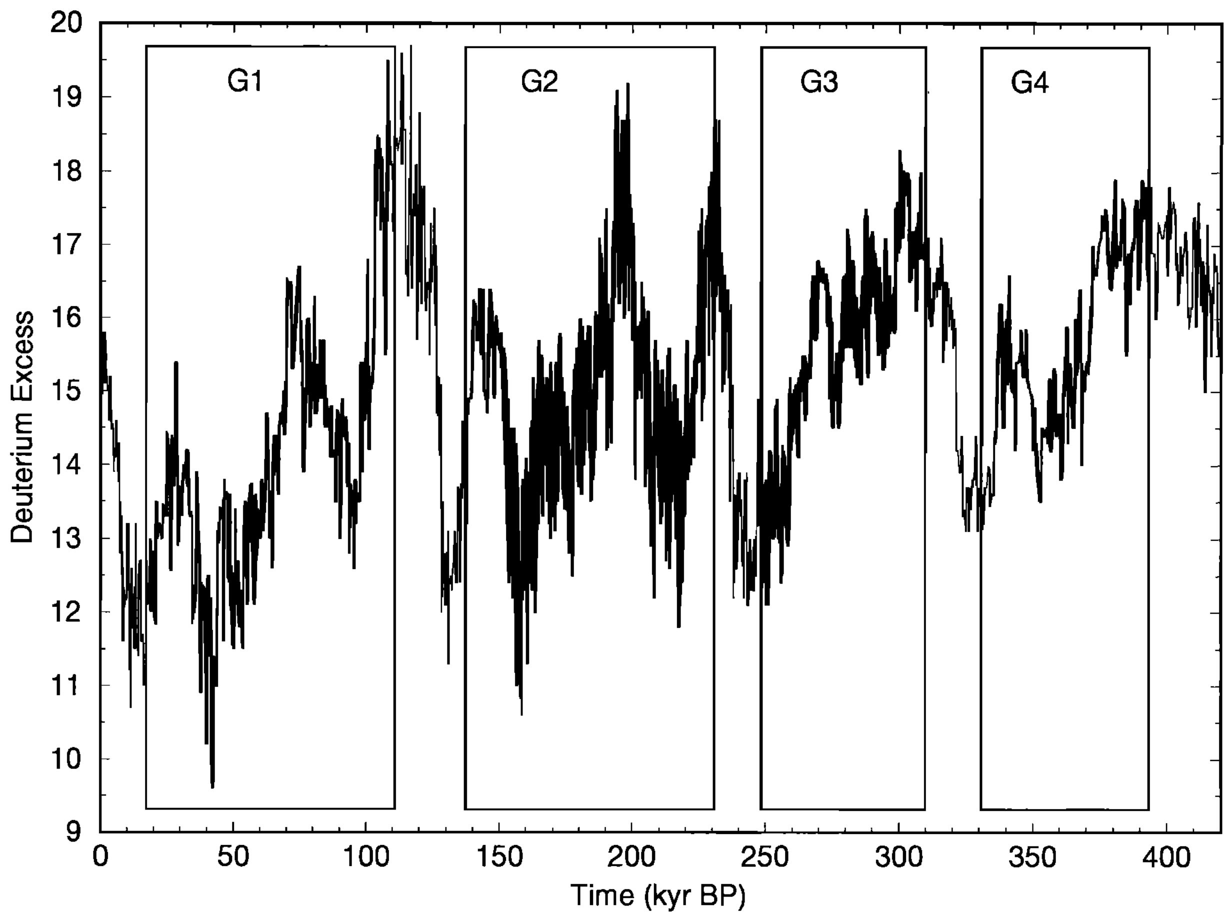

Figure 2. Deuterium excess d variations in the Vostok ice core. The four ice ages G1–4 are emphasized by boxes.

and *Broecker* [1998] give a mechanism through which anomalies of the ocean circulation in the North can transmit "information" to the Southern Hemisphere, by connecting energy transport changes to collapses of the thermohaline circulation.

The joint study of the deuterium and deuterium excess records provides an opportunity to evaluate the respective behavior of high and lower latitudes on several climatic cycles (assuming that moisture source regions are located in middle and low latitudes) and hence obtain a better statistical stability than with a single climatic cycle. Thus we will be able to detect some generic features of temporal and spatial ice age variability felt at Vostok.

We isolated the four glacial ages and numbered them G1 to G4. These periods were heuristically chosen from low δD values (Figure 1). The four glacial boxes cover the same periods for the two records (Figures 1 and 2). Our strategy is thus to determine the common stable frequency patterns of the four ice ages in the isotopic records, assuming that such patterns characterize a glacial period.

Note that we only considered the data down to 420 kyr before present (B.P.), i.e., 3305 m, since the isotopic content beyond that depth is likely to be affected by the underlying Vostok lake [*Jouzel et al.*, 1999]. This truncation also ensured that we had a good time resolution for the high-frequency analysis.

Data treatment and spectral analyses will be discussed in section 2. Results will be discussed in section 3.

2. Spectral Analysis

The data obtained from the ice core is roughly regular in depth (some intervals benefited from a more intense sampling), but the depth–age relationship is not linear since the ice thinning varies with depth. Apart from a few outliers, the deuterium profile has a sampling rate that varies between $\approx$ 0.1 kyr and 0.5 kyr (i.e., sampling every meter); the deuterium excess profile sampling varies between $\approx$ 0.2 kyr and 0.5 kyr. Hence the data have to be interpolated at regular intervals in order to retrieve a *time* series. In this paper we elected to use the finest possible time step, δt = 100 years, so we follow the original data as closely as possible. On the other hand, since the data time step is much larger toward the bottom of the core, we decided to conservatively cut the frequency analyses at 1 cycle/kyr to avoid problems near the Nyquist frequency. The last part of the record will be cut at 0.6 cycles/kyr.

In this paper we used the multitaper method (MTM) of *Thomson* [1982] and the statistical tests developed by *Mann and Lees* [1996]. We also tested other spectral analysis methods [*Dettinger et al.*, 1995; *Yiou et al.*, 1996; *Ghil et al.*, 2001] in order to cross-check our results; we used the SSA-MTM Toolkit v3 (available on the Web at http://atmos.ucla.edu/tcd). We will only show the MTM results in order not to overload the paper.

The purpose of MTM [*Thomson*, 1982; *Percival and Walden*, 1993] is to circumvent the problem of the variance of spectral estimates; indeed, the variance of the Fourier spectrum of a random process equals the spectrum itself [*Jenkins and Watts*, 1968], which means that the potential errors can be as large as the calculation itself. A set of independent estimates of the power spectrum is computed, by premultiplying the data by K orthogonal tapers, i.e., functions that are built to minimize the spectral leakage outside a scaled bandwidth $N\Omega$ (Ω is a frequency bandwidth) due to the finiteness (N) of the data. Then, averaging over this ensemble of spectra yields a better and more stable (with lower variance) estimate than with single-taper methods [*Thomson*, 1990]. Detailed algorithms for the calculation of those tapers are given by *Thomson* [1990] and *Percival and Walden* [1993]. The choice of K and $N\Omega$ is a trade-off between stability and frequency resolution, so several values should be tested [*Yiou et al.*, 1996; *Mann and Park*, 2000]. Here we chose a conservative set of $N\Omega = 4$ and $K = 7$ tapers for the four glacial periods.

Harmonic analysis (estimate of line frequencies and their amplitude) can be performed by MTM, with a statistical F test on the amplitude; this test uses the ratio of the variance explained by a line frequency to the residual variance [*Thomson*, 1982]. One of the main assumptions of MTM harmonic analysis is that the signal must yield periodic and separated components. If not, a continuous spectrum (from a colored noise or a chaotic system) will be broken down to spurious lines with arbitrary frequencies and possibly high F values. The power spectrum is then "reshaped" near the found line frequencies, hence representing the time series spectrum as the sum of discrete line spectra and continuous broadband spectra [*Percival and Walden*, 1993; *Ghil et al.*, 2001].

In addition, *Mann and Lees* [1996] provided a method to detect significant narrow band, "quasi-oscillatory" signals that may exhibit phase and amplitude modulation as well as intermittently oscillatory behavior. Their method combines the harmonic analysis test and a "robust" estimate of the background noise. Here the background noise is assumed to be red noise (i.e., an autoregressive process of the first order [*Chatfield*, 1984; *Ghil et al.*, 2001]):

$$X(t+1) = aX(t) + b(t), \qquad (2)$$

where $0 < a < 1$ and $b(t)$ is a Gaussian white noise. The retained features will be those for which the red noise null hypothesis can be rejected with a sufficient confidence. Discrimination against a red-noise background is particularly important in climate studies, where the system under investigation always contains longer time scales than those of immediate interest. This leads to greater power at lower frequencies and greater likelihood of prominent peaks in the spectrum, these, even in the absence of any signals [e.g., *Hasselmann*, 1976].

To summarize, significance levels for harmonic or narrow band spectral features relative to the estimated noise background can be determined from the appropriate quantiles of the chi-square distribution, by assuming that the spectrum as being distributed with $\nu = 2K$ degrees of freedom [*Mann and Lees*, 1996; *Mann and Park*, 2000]. A reshaped spectrum is determined in which the contributions from harmonic signals are removed [*Thomson*, 1982], based on their passing significance threshold for the F variance-ratio test described above. In this way, noise background, harmonic, and narrow band signals are isolated in two steps. The harmonic peak detection procedure provides information as to whether the signals are best approximated as harmonic or narrow band, i.e., as phase-coherent sinusoidal oscillations or as amplitude and phase modulated, possibly intermittent oscillations. In either case, they must be formed to be significant relative to a specified noise hypothesis such as that of red noise (2) used above.

3. Results and Discussion

The first exercise we performed was to obtain the spectra of the δD and d time series of Figures 1 and 2. The MTM spectrum of the deuterium shows prominent peaks near 40, 23, and 18 kyr, i.e., near obliquity and precessional peaks (not shown) [see also *Petit et al.*, 1999]. A peak near 100 kyr also emerges and is connected with the glacial to interglacial cycles. This completes the findings of *Jouzel et al.* [1987] and *Yiou et al.* [1991], who only analyzed the first climatic cycle. The presence of these periodicities is a strong argument in favor of the orbital forcing theory [*Hays et al.*, 1976]. However, it should be noted that the 100 kyr peak has a broad band, which corresponds to the fact that the interval between interglacials increases with time (i.e., between G3–4 and G1–2), hence yielding longer and longer ice ages. This feature has been observed by *Birchfield and Ghil* [1993] who observed the progressive appearance of a 100 kyr cycle, near 700 kyr B.P., in a marine sediment core covering the Late Pleistocene.

The deuterium excess d time series yields a rather different spectrum, with more pronounced peaks near 40, 18, and 100 kyr [*Vimeux et al.*, this issue]. Moreover, it is also clear from a visual inspection that the peaks are broadband and nonstationary, since the precessional peak disappears before 250 kyr B.P., as discussed by *Vimeux et al.* [this issue].

Prior to further statistical analyses of the higher frequencies, a few features can be pointed out on the four ice ages G1–4. Figure 1 also shows the sea level variations estimated from the isotopic record of *Bassinot et al.* [1994]. It is clear that the low-frequency variations of the deuterium record are parallel to the sea level change curve, apart from a phase lag which can be attributed to the timescale uncertainties or a delayed response of Antarctica to a northern signal. This similarity emphasizes the two-step feature of G1 and G2, with high δD (or temperature) during the first parts of the ice ages, and low δD thereafter. On the other hand, G3 and G4 show an oscillating decrease of δD values. Moreover, the durations of the ice ages are not similar: G1 and G2 last for around 90 kyr, while G3 and G4 last about 60 kyr. Thus we can a priori classify the four last ice ages (at least in the Vostok data) into two categories: the long two-stepped ones and the short ones. Such a distinction does not appear with lower latitude sediment data [*Schneider et al.*, 1995, 1996; E. Bard, Personal Communication, 2000]; therefore there are differences in the spatial variability from one ice age to another, which would justify a separate study of each of them. Here we will focus on their common properties, which seem to prevail in the high latitudes.

The MTM spectral analyses of δD during the four glacial periods G1–4 are displayed in Figure 3. Since G4 has a looser sampling rate than G1–3, we truncated the analyses at $f = 0.6$ cycles/kyr (bottom panel of Figure 3). The overall shapes of the spectra are close to red noise processes (thick continuous solid lines in Figure 3), but a few features stand out of the confidence intervals. On the one hand, the "orbital" low frequencies account for the trends in all the four series. On the other hand, the four series show lines between periods of 5 and 10 kyr. This is about the time scale of periodic ice sheet instabilities predicted by the simple models of *Ghil and Le Treut* [1981] or *MacAyeal* [1992], and used by *Paillard and Labeyrie* [1994] to evaluate the impact of the Heinrich events on the THC and climate. *Yiou et al.* [1994] found similar oscillations in marine sediments from various ocean basins, so this periodicity range can be considered a generic glacial feature. The results found for G1 slightly differ from the ones of *Yiou et al.* [1997], due to local changes in the chronology (these differences were anticipated by *Yiou et al.* [1997] who tested a GRIP-tuned Vostok timescale). It is clear, however, that such peaks are not constant through time within each ice age, and they only account for an average periodicity (hence the sensitivity of the actual frequency to the timescale).

Other groups of harmonic peaks appear significant in the higher-frequency domain, with consistent properties between G2 and G3 ($T \approx 2.3$ kyr) and G1–3 ($1.6 < T < 1.8$ kyr). The latter range is robust (to method and parameter changes) and close to the conspicuous 1.5 kyr periodicity found in many Northern Hemisphere high resolution sediment records [*Mayewski et al.*, 1997; *Hendy and Kennett*, 2000; *Schulz et al.*, 1999; *Hinnov et al.*, 2001], albeit with a very small explained variance (less than 1% of the total variance).

The deuterium excess time series behaves quite differently. When looking at the time domain (Figure 2), the glacial periods are characterized by global negative trends, although the trend in G2 is much less pronounced than for the others. This trend can be interpreted as a progressive cooling of the source regions at lower latitudes [*Vimeux*, 1999]. As a consequence, the power spectra are dominated by low-frequency variance, and the high-frequency parts are akin to red noise (Figure 4). The ice ages bear some similarities in the 4–5 kyr and $\approx$ 2 kyr bands (G1 and G4) and in the 2.5–3 kyr band (G1–4). We note that the line frequencies never fall in the 5–8 kyr range found in the deuterium records.

However, we find an intriguing difference between G1 and the other ice ages. The G1 d record *does* yield a cycle near 1.5 kyr, as well as the δD record, albeit not at the same exact frequency. The excess time series in G2–4 do not have this peak. This finding is consistent with the observation of *Mazaud et al.* [2000], who correlated minute d minima with some δD maxima, and cold periods preceding a Heinrich event, in the GRIP δ^{18}O record. Their result was obtained on a Vostok chronology tuned to GRIP with methane content [*Blunier et al.*, 1998], during the younger half of G1. Thus such a correlation might be real throughout the whole ice age G1, but the absence of a 1.5 kyr cycle in the preceding ice ages suggests that this correlation is no longer valid (provided we accept the present Vostok chronology). Yet, one should keep in mind that the 1.5 kyr cycle and observed d minima have a very small amplitude ($\approx$ 1 per mil) compared to the total variations ($\approx$ 10 per mil). Therefore it cannot be excluded that the match came by pure chance; a thorough study of d negative peaks on the full ice age in Greenland, and possibly on other ice ages, would be necessary to settle this discrepancy.

The spectral differences between the deuterium and excess glacial records suggest that the underlying dynamics that control both proxies are distinct. It is important to note that these differences are meaningful since both profiles share the *same* timescale and the same time resolution, so the differences would persist after a chronology change. There is some evidence that the fast variability in the deuterium record is connected to northern ice sheet instabilities and the THC [*Blunier et al.*, 1998; *Ganopolski and Rahmstorf*, 2001]. The conventional "seesaw" scenario is that when salinity and temperature anomalies occur in the high latitudes of the Northern Hemisphere (e.g., due to D-O or HEs), they hinder the global THC and affect climate near the upwelling zones in the Southern Hemisphere [*Broecker*, 1998]. Thus a reduced THC would lower the northward energy transport that cools Antarctica. Such a transport process would, of course, smooth out

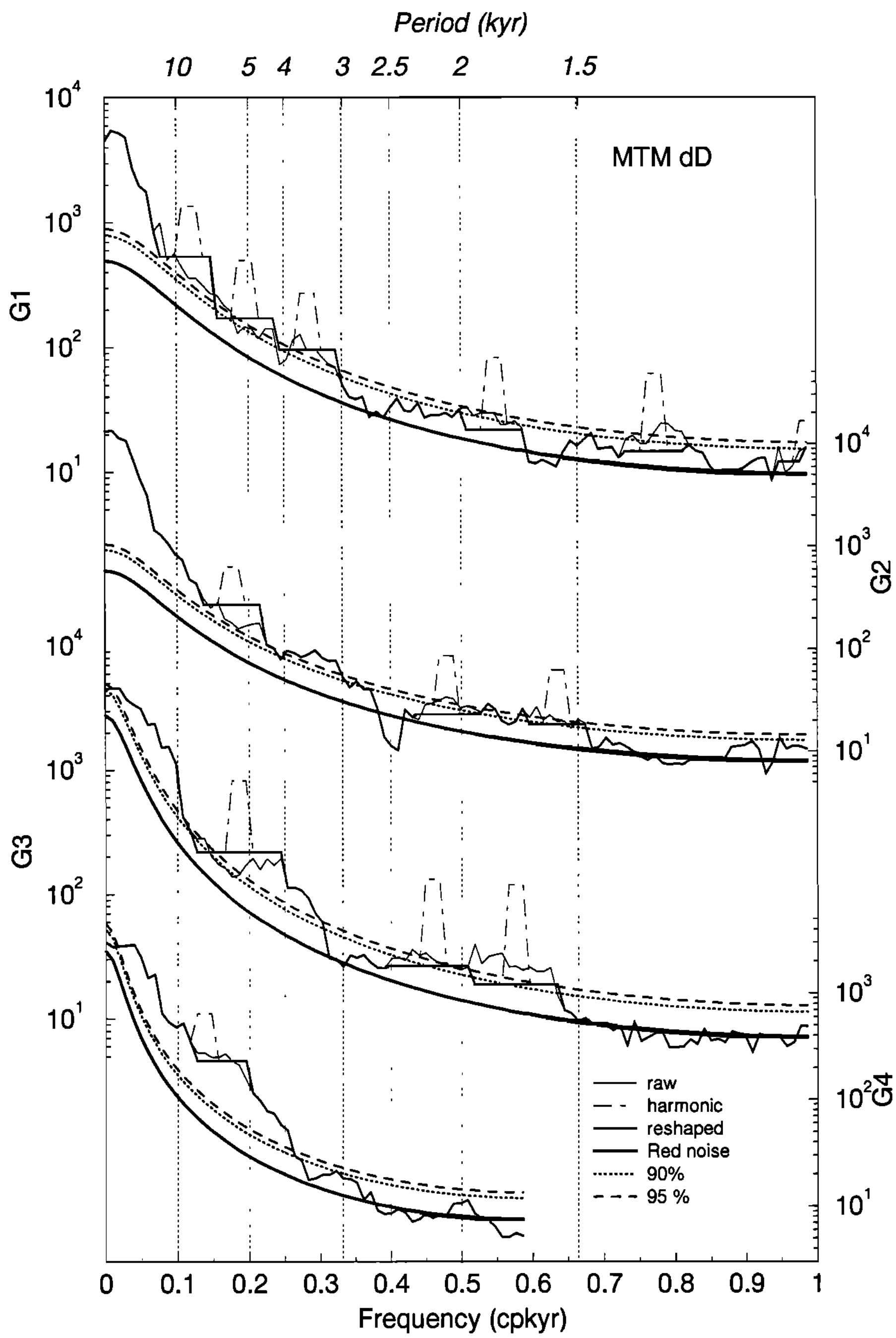

Figure 3. MTM spectral analyses of the four glacial δD records. The four ice ages G1–4 go from top to bottom. The G4 spectrum is truncated at 0.6 cycles/kyr because of its poorer resolution. The MTM parameters are a $NW = 4$ bandwidth and $K = 7$ tapers (see *Yiou et al.* [1996] for methodological details). The thin wiggly lines represent the raw spectra; the thin dash-dotted lines, the harmonic peaks detected by the F-test [*Mann and Lees*, 1996]; the thick wiggly line, the reshaped spectra, after removal of the harmonic components [*Thomson*, 1982; *Mann and Lees*, 1996]; the thick continuous line is the equivalent red noise spectrum obtained by robust median testing [*Mann and Lees*, 1996]; the dotted and dashed lines are the 90% and 95% confidence intervals for the red noise null hypothesis.

extremely fast variations, so only the large and long variations will be efficiently propagated [*Blunier et al.*, 1998]. This is what is observed between the Greenland and the Antarctic ice cores [*Bender et al.*, 1994; *Blunier et al.*, 1998]. If we make the hypothesis that the signature of these glacial anomalies is quasi-periodic peaks between intervals $5 < T < 10$ kyr and $1.4 < T < 1.8$ kyr, then such a "seesaw" scenario is consistent with the statistical analysis of Greenland [*Yiou et al.*, 1997] and the Vostok ice cores. This scenario is also supported by marine sediment cores in the North Atlantic (albeit during marine isotopic stage (MIS) 3 only) where benthic

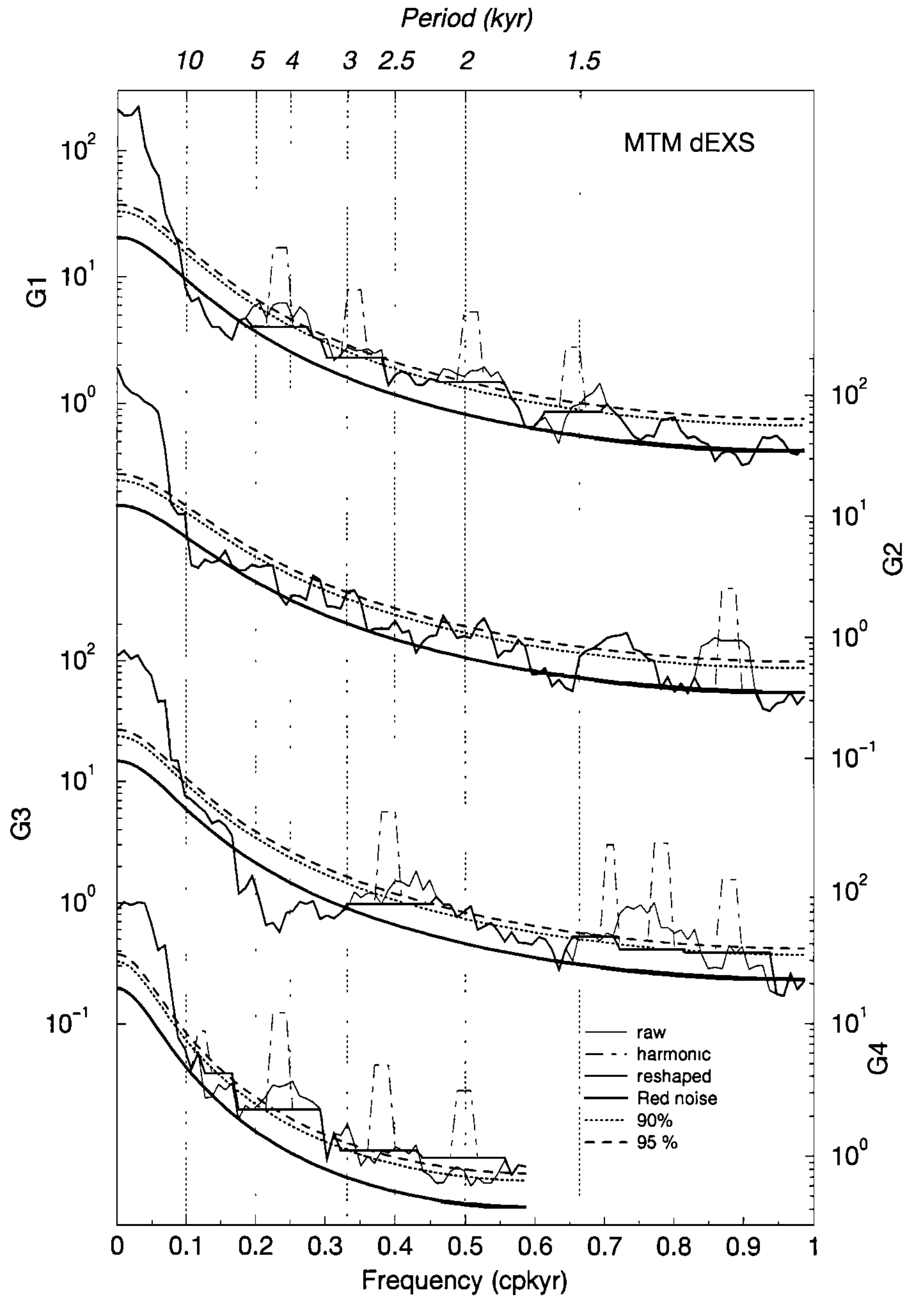

Figure 4. MTM spectral analyses of the four glacial d records (G1–4 from top to bottom, respectively). The MTM parameters are a $NW = 4$ bandwidth and $K = 7$ tapers. The legends are the same as for Figure 3.

and planktonic foraminifera were analyzed in high resolution [*Shackleton et al.*, 2000]; in this core the benthic (deep ocean) $\delta^{18}O$ variations are similar to the Vostok deuterium variations, whereas the planktonic (surface ocean) $\delta^{18}O$ follows the GRIP $\delta^{18}O$ record. *Schulz et al.* [1999] make the important point that this 1.5 kyr feature has a modulated amplitude throughout the last ice age and is prominent during its last phase (i.e. marine isotopic stage 3), when ice volume was higher. In the absence of detailed Northern Hemispheric data during G2–4, the correlation between this pseudo cyclic feature and large (and unstable) ice sheets has to be assumed. Moreover, since there are no long and high-resolution data sets from the southern oceans, the attribution of this period range found in the Vostok δD to the Dansgaard Oeschger events that take place in Greenland is also speculated here. *Ganopolski and Rahmstorf* [2001] present a long simulation of the CLIMBER2 model in which they simulated 1.5 kyr periodic DO/HEs in the North Atlantic and show that they had an impact on

Antarctic temperature, albeit with a low amplitude and opposite phase from what is seen in Greenland. Their result hence supports our hypothesis that the $\approx$ 1.5 cycle in the Vostok data is a shadow of the DOs of the Northern Hemisphere.

Interestingly, the deuterium excess d does not yield such spectral features. Excess d is connected to a surface source signal of the water vapor at Vostok located mainly in the southern Indian Ocean [*Delaygue et al.*, 2000], and with only $\approx$ 30% of moisture from the Atlantic and Pacific oceans. Estimates of surface temperature variations at subtropical latitudes in the Atlantic and the Pacific are around 3° to 5°C [*Sachs and Lehmann*, 1999; *Hendy and Kennett*, 2000] and around 3°C in the southern Indian Ocean [*Salvignac*, 1998]. If such surface variations were to be felt in the subtropical Indian Ocean, they would translate into deuterium excess variations of $\approx$ 3 per mil, which is larger than the fast peak-to-peak amplitude (Figure 2) and hence *detectable*. Thus we infer that the high latitude $\approx$ 5–10 and $\approx$ 1.5 kyr oscillatory signals do not propagate through the surface Indian ocean or the atmosphere from the North to the South because of their absence in the Vostok d record which should have contained them. However, the quasi-cyclic variations imprinted in the d record suggest that the midlatitude source regions of the Vostok ice reflect local oscillations that are independent from the D-O/HE, except possibly from the second part of the last glacial period. A simple tentative explanation for this spectral difference is that the southern Indian Ocean is at the "end" of the THC conveyor belt and hence would mitigate surface and deep ocean signals of different phases. On the other hand, the result of *Mazaud et al.* [2000] suggests that the surface anomalies induced by the few HE iceberg discharges were sufficiently strong to have a greater impact than their counterparts in early G1 and G2–4 and hence did have a global impact.

4. Conclusions

In this paper we investigated the spectral properties of two isotopic records from the full Vostok ice core: the deuterium and the deuterium excess records. The deuterium content is a proxy for local temperature variations, and the deuterium excess reflects changes in the source of the water vapor that precipitates at Vostok. We could thus assume that they are independent.

The spectral analyses of both records separated the low-frequency variability associated to the insolation forcing through the presence of orbital frequencies [*Petit et al.*, 1999]. Given that the extended glaciological chronology (EGT4) of Vostok is independent from orbital tuning (except for two control points at 110 kyr B.P. and 390 kyr B.P. [*Petit et al.*, 1999], which does have an influence on a 100 kyr cycle), this result comforts the classical orbital theory of paleoclimates [*Hays et al.*, 1976; *Crowley and North*, 1991]. The parallel between the deuterium record and the sea level change record (from the *Bassinot et al.* [1994] record) is also striking along each glacial period.

We extracted the four ice ages imprinted in the records. Since the last ice age has been well documented in the Vostok and other records throughout the globe, it was natural to compare the properties of the preceding ones. The four δD glacial records yield the conspicuous 5–8 kyr periodicity, and millenial variability in the 1.5–1.8 kyr range is also present in three of the ice ages (G1–3). This shows that this feature is not only general among paleorecords during the last ice age [*Yiou et al.*, 1994; *Mayewski et al.*, 1997; *Yiou et al.*, 1997], but it is also a characteristic feature of the previous ice ages. The deuterium excess d glacial records do not show those periodicities, and we are hence tempted to exclude that d follows the rapid glacial events connected to iceberg discharges in the northern oceans. Thus we can infer that in general, a glacial signal due to an iceberg discharge into the North Atlantic mainly propagates to the South through the deep ocean circulation and the upwelling zones of the southern oceans, as suggested by the coupled model simulation of *Ganopolski and Rahmstorf* [2001]. The last ice age (G1), especially during MIS 3 (between 60 kyr and 20 kyr B.P.) yields the peculiarity of showing a d record that varies in correlation with Heinrich events [*Mazaud et al.*, 2000]. This is not in contradiction with our main conclusion but rather refines it: climatic variability during MIS 3 is largely associated with HEs [*Bond et al.*, 1993; *Broecker*, 1994] which come from the Laurentide ice sheet. On the other hand, the early G1 does not have traces of Laurentide iceberg discharges but, possibly, of Scandinavian or Greenland ice sheets, and the global ice volume is lower. Thus we interpret the correlation of d events with isotopic anomalies in the GRIP ice core by the penetration of cold and fresh water from the Laurentide ice sheet into midlatitudes, while other ice sheet discharges do not flow that much into the South. Reconstructing the history of each ice sheet is hence essential to verify this conjecture.

We note that this result supports the genericity of oscillating ice sheet/ocean circulation mechanisms [*Ghil and Le Treut*, 1981; *MacAyeal*, 1992; *Paillard and Labeyrie*, 1994; *Verbitzky and Saltzman*, 1995]. The caveat of this deduction is that the deuterium excess reflects conditions at the moisture source, and this source can move with time, so the relevant information is smeared over a wide geographical area [*Vimeux et al.*, 1999].

Therefore we need more high-resolution records of deep and surface marine conditions, especially in the subtropical Indian Ocean, to constrain the spatial variability during the last ice age and be able to assess the "seesaw" scenario, which might have many exceptions. Moreover, other deep ice cores covering several climate cycles will help to document the genericity of the glacial features found at Vostok. In particular, we have shown that the Vostok isotopic data are just a piece of the paleocean circulation puzzle.

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