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# A 420,000 year deuterium excess record from East Antarctica: Information on past changes in the origin of precipitation at Vostok

F. Vimeux,<sup>1</sup> V. Masson,<sup>1</sup> G. Delaygue,<sup>1,2</sup> J. Jouzel,<sup>1</sup> J. R. Petit,<sup>3</sup> and M. Stievenard<sup>1</sup>

**Abstract.** Here we present and analyze the complete Vostok ice cores deuterium excess record which spans the last four climatic cycles, back to ~420,000 years B.P. To extract paleoclimate information from this record, we use isotopic modeling showing that changes in deuterium excess ( $d = \delta D - 8\delta^{18}O$ ) of Vostok precipitation reflect changes in the average temperature of oceanic moisture sources. Over the last 250,000 years the deuterium excess is strongly anticorrelated with changes in Earth's obliquity. This reflects changes in the relative contribution of low and high latitudes to the Vostok precipitation, resulting from changes in the latitudinal annual mean insolation gradient governed by the obliquity. However, this modulation by obliquity is not observed prior to 250,000 years B.P. We attribute this difference to the ice flow, the deeper ice under Vostok station having accumulated in a location upstream Vostok, receiving precipitation from different oceanic origins. Despite this difference between the earlier and the later portions of the record, the deuterium excess changes during all the glacial inception are similar in amplitude and timing relative to the deuterium decrease. The glacial inceptions are characterized by high deuterium excess, indicating the significant role of the tropics in supplying moisture to the already cold poles.

## 1. Introduction

The Vostok icecores studies have provided a wealth of information about climatic and other environmental changes over the past 420,000 years [Petit *et al.*, 1999], including changes in the atmospheric concentration of CO<sub>2</sub> and CH<sub>4</sub>, atmospheric chemistry, condensation temperature (derived from the isotopic composition of precipitation). Here we focus specifically on changes in southern ocean surface conditions using combined measurement of both water stable isotopes ( $\delta D$  and  $\delta^{18}O$ ). The deuterium excess ( $d$ ) in precipitation has been defined by Dansgaard [1964] from the Meteoric Water Line [Craig, 1961] as follows:

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

Both simple [Merlivat and Jouzel, 1979; Johnsen *et al.*, 1989] and comprehensive isotopic models [Armengaud *et al.*, 1998; Delaygue, 2000] exhibit a clear positive correlation between the temperature of the evaporating ocean surface and the deuterium excess of vapor in the overlying air. This correlation results from the dependency of the kinetic fractionation processes during evaporation on oceanic and meteorological moisture source characteristics (mainly the sea surface temperature (SST) and, to a lesser degree, the relative humidity of the air just above the sea surface  $h$ ).

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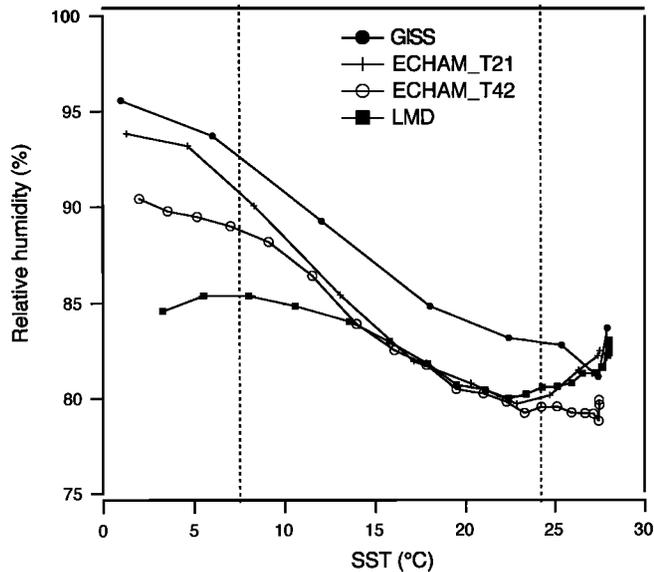
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The models also show that this source-region information is partly preserved along the poleward air mass trajectory despite the additional kinetic fractionations associated with droplet reevaporation and snow formation [Jouzel and Merlivat, 1984]. For example, a multiple linear regression analysis performed with a Rayleigh-type model reflects the dependency of Vostok deuterium excess ( $d$ , in ‰) on spatial changes in moisture source temperature ( $\Delta T_{\text{source}}$ , in Celsius degree, °C) and moisture source relative humidity ( $h$ , in %), as follows :

$$\Delta d = 1.2 \Delta T_{\text{source}} - 0.15 \Delta h. \quad (2)$$

The dependency of the deuterium excess at Vostok on the SST simulated by the GISS atmospheric general circulation model (1‰/°C) is in close agreement with our Rayleigh-type model result. To interpret past fluctuations of deuterium excess in terms of SST alone (no independent measure of past changes in relative humidity is available), we have explored the relationship between present-day SST and relative humidity simulated by three different general circulations models (GISS, LMD and ECHAM) [Vimeux *et al.*, 2001]. For all of these, spatial covariation of SST and relative humidity over the Southern Hemisphere ocean surface is linear (Figure 1) with a common slope of -0.4‰/°C for SST in the range 7°C to 24°C ( $\sigma = \pm 0.04\%$ /°C). Note that this SST range clearly includes the major oceanic contributions to Vostok precipitation, which are estimated to be, on average, ~11°C [Delaygue *et al.*, 2000]. Simulations of last glacial maximum climate (not shown here) show that this SST-relative humidity relationship is preserved even in past climate extremes. Indeed, the relative humidity changes between modern and last glacial maximum climates are estimated to be minor [Bush *et al.*, 1999]. Therefore our approach here is to interpret Vostok deuterium excess variations as depending on



**Figure 1.** Variation of the relative humidity as a function of the moisture source temperature simulated with three atmospheric general circulation models: GISS, LMD, and ECHAM (two different resolutions have been used for the latter (G. Hoffmann, personal communication, 2000)).

fluctuations of the oceanic moisture source surface temperature only, by combining equation (2) with the established correlation of the relative humidity and SST to yield a combined coefficient  $\Delta d/\Delta T_{\text{source}}$  of 1.3‰/°C.

We present and discuss the entire deuterium excess profile spanning the last 420,000 years, greatly extending the 150,000 year record obtained by *Vimeux et al.* [1999]. We will not discuss here the deuterium excess variations in the deepest part of the ice core (below 3310 m), which have been used to identify the existence of refrozen Vostok lake water below 3539 m [*Jouzel et al.*, 1999].

## 2. Results

In the first part of this section we describe the data, characterize the relationship between deuterium excess and  $\delta D$ , and examine the spectral properties of the deuterium excess profile. We identify a clear difference in deuterium excess variability before and after 250,000 years B.P.

In the second part of this section we examine the extent to which changes in ocean isotopic composition and site temperature may have affected the deuterium excess content (variations and/or amplitude). These effects are quantified with both Rayleigh type model and the GISS general circulation model simulations. Results from the two modeling approaches agree closely.

### 2.1. Data

The dated Vostok icecores deuterium excess profile is shown in Figure 2 along with  $\delta D$  and  $\delta^{18}O$  isotopic variations down to 3350 m. Below 3310 m, Vostok climate records are disturbed due to the ice flow [*Petit et al.*, 1999], and we therefore limit our discussion to the upper 3310 m of the ice core which extends to 423,000 years B.P. according to the glaciological timescale GT4 [*Petit et al.*, 1999].

Over each climate cycle the deuterium excess generally decreases from high values at the glacial inceptions to low values in the latter half of the glacial periods. The corresponding range of deuterium excess values increases with time from 6‰ (between 12‰ and 18‰) during the first two cycles and 10‰ during the two most recent cycles (between 10‰ and 20‰). The standard deviation varies from 1.4 to 1.9 ‰ between the oldest and the youngest climate cycles.

Examination of the phase relationship between  $\delta D$  and deuterium excess reinforces the striking difference between glacial and interglacial periods, first identified by *Vimeux et al.* [1999] (Figure 3).  $d$  and  $\delta D$  values are negatively linearly correlated in warm periods (characterized by high  $\delta D$  values), whereas no correlations can be identified during glacial periods (despite the full range of deuterium excess values being present). The two major types of climatic transitions are also clearly distinct: Deglaciations have low deuterium excess values, whereas glacial inceptions have high deuterium excess values.

Spectral analysis of the full profile identifies significant periodicities at 18,000 years, 40,000 years and 100,000 years (see legend of Figure 4 for details). However, because of the uncertainties of the age scale, we have also conducted the spectral analysis using an alternative time scale obtained by orbital tuning [*Parrenin et al.*, this issue]. This significantly affects the power spectrum (amplitude and location) only for periodicities lower than  $\sim 30,000$  years as it has already been shown for analysis of deuterium alone [*Petit et al.*, 1999].

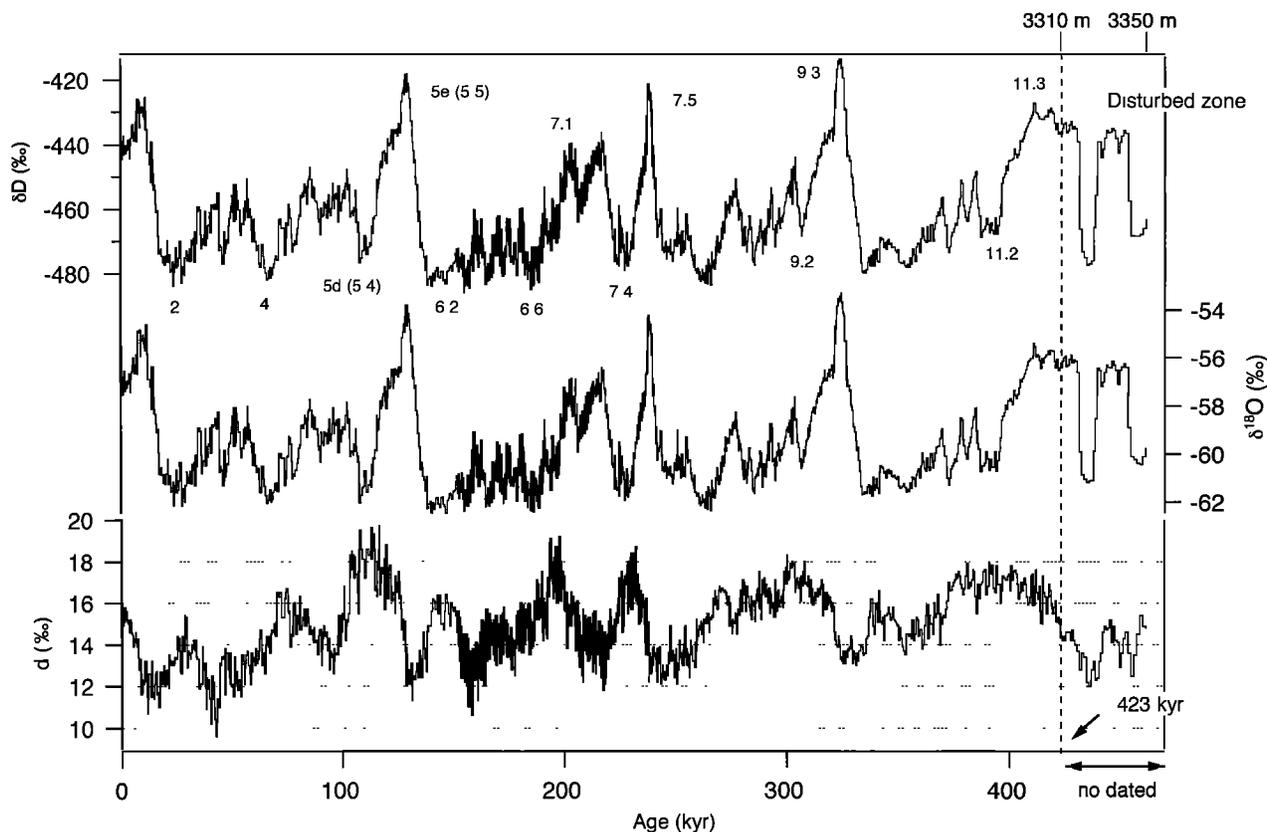
The spectral properties of the deuterium excess fluctuations differ between the last 250,000 years and the oldest part of the record. Indeed, the last 250,000 years are largely modulated by a single significant periodicity at 40,000 years (obliquity period) (Figure 4). Applying a Gaussian filter to extract variations of the deuterium excess in the obliquity band (Figure 5) clearly shows the strong anticorrelation with obliquity in the past 250,000 years and the weakening of the 40,000 year modulation before this time.

### 2.2. Influence of the Ocean Isotopic Composition Variation on the Deuterium Excess Profile

The oceanic isotopic composition has varied over time due to changes of ice sheet volume: measurements performed on benthic foraminifera in ocean sediment cores indicate an increase of the oceanic  $\delta^{18}O$  for the Last Glacial Maximum compared to the Holocene optimum [*Bassinot et al.*, 1994]. Assuming that the ocean deuterium excess is zero, the deuterium excess of the evaporated water vapor will depend on the oceanic  $\delta^{18}O$ . Here we calculate the variation of deuterium excess  $\Delta d_v$  in the initial vapor due to a change of oceanic  $\Delta \delta^{18}O_{\text{ocean}}$  based on the global evaporation model of *Merlivat and Jouzel* [1979]:

$$\Delta d_v = -8\Delta \delta^{18}O_{\text{ocean}} \left\{ \frac{1}{\alpha_O} \left( \frac{1-k_O}{1-k_O h} \right) - \frac{1}{\alpha_D} \left( \frac{1-k_D}{1-k_D h} \right) \right\}, \quad (3)$$

with  $\alpha_O$  and  $\alpha_D$  the equilibrium fractionation factors [*Majoube*, 1971],  $k_O$  and  $k_D$  the kinetic fractionation factors during evaporation from the ocean [*Merlivat et Jouzel*, 1979],  $h$  the relative humidity and  $\Delta \delta D_{\text{ocean}} = 8 \Delta \delta^{18}O_{\text{ocean}}$ . Without direct measurements of the glacial ocean deuterium (which



**Figure 2.** Times series of  $\delta D$ ,  $\delta^{18}O$  and deuterium excess. These records combine data available down to 2083m [Vimeux *et al.*, 1999] and new measurements performed along two deep cores : 4G from 2083m to 2755m and 5G down to 3350m with 1m depth resolution. Data are presented at 1m depth resolution excepting the last climatic cycle, which is presented at a 5m depth resolution. The temporal resolutions are always smaller than 500 years. Deuterium excess experimental accuracy is  $\pm 0.7\text{‰}$  ( $\pm 0.5\text{‰}$  for  $\delta D$  and  $\pm 0.05\text{‰}$  for  $\delta^{18}O$ ) excepting from 1413m to 2083m at  $\pm 1.3\text{‰}$ . Down to 3310m we used the glaciological timescale GT4 [Petit *et al.*, 1999], the accuracy of which is estimated to be always better than  $\pm 15$  kyr (kiloyears) all over the profile. GT4 provides an age of 423 kyr at the depth of 3310m [Petit *et al.*, 1999].

could be achieved with pore waters), we have assumed a zero deuterium excess. Rough estimates, based on the dilution of ice sheets, lead to an oceanic deuterium excess enrichment weaker than  $0.5\text{‰}$ , consistent with our uncertainty and the weak Vostok glacial-interglacial deuterium excess fluctuation.

According to equation (3), at  $20^\circ\text{C}$  with a humidity of 80%, a change of  $-1.2\text{‰}$  of the oceanic  $\delta^{18}O$  corresponds to a change in the initial vapor deuterium excess of  $+0.6\text{‰}$ . This imprint on the evaporated moisture is amplified along the air mass fractionation trajectory to Antarctica [Delaygue, 2000]. We calculate, based on a Rayleigh model, the variation of the deuterium excess  $\Delta d_p$  in the precipitation along the air mass trajectory due to a change of oceanic  $\Delta\delta^{18}O_{\text{ocean}}$  as

$$\Delta d_p = d_p - d_{p_0} = -8\Delta\delta^{18}O_{\text{ocean}} \left( \delta^{18}O_{p_0} - \delta D_{p_0} \right). \quad (4)$$

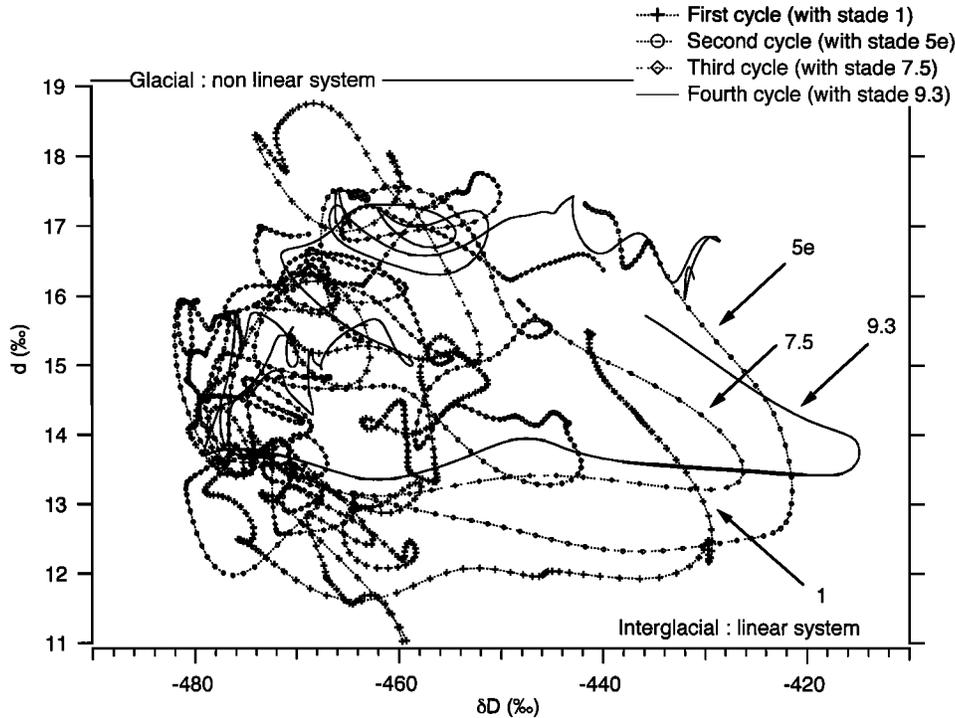
This indicates that the progressive change in the deuterium excess in precipitation is strongly controlled by the isotopic fractionations of D and  $^{18}O$  during air mass transport and that the magnitude of the signal increases with the total fractionation. The sensitivity of deuterium excess to a change

of the oceanic isotopic composition on the deuterium excess is thus related to the distance to the source (see Figure 6).

For Vostok a Rayleigh-type model indicates that a global variation of oceanic  $\delta^{18}O$  of  $-1.2\text{‰}$  induces a deuterium excess change of  $\sim +3.3\text{‰}$  in precipitation. The same change estimated from the GISS atmospheric general circulation model is  $+3.5\text{‰}$  for Vostok area (Figure 6), which agrees closely with the simpler model result.

The choice of  $+1.2\text{‰}$  for the glacial-interglacial variation of the isotopic content of the ocean is somewhat arbitrary with respect to the various available oceanic  $\delta^{18}O$  estimates, ranging from  $1.0\text{‰}$  to  $1.6\text{‰}$  [Schrag *et al.*, 1996; Dwyer *et al.*, 1995]. Such differences may arise from spatial and temporal isotopic variations existing between each ocean basin and each glacial-interglacial transition [Dwyer *et al.*, 1995; Lea *et al.*, 2000; Shackleton, 2000]. However, this  $1.2\text{‰}$  variation stands well within the range of mean estimates and corresponds to the global anomaly used in isotopic general circulation model simulations which compare favorably to the Rayleigh model results.

To remove effects of the oceanic isotopic composition, we therefore define a corrected deuterium excess ( $d_{\text{corr}}$ ) which



**Figure 3.** Deuterium excess versus  $\delta D$  after smoothing with a 4,500 year filter. Four interglacial periods are indicated with marine stages: 1, 5e, 7.5, and 9.3.

better represents source meteorological variations, such as

$$\Delta d_{corr} = \Delta d + \frac{3.3}{1.2} \Delta \delta^{18}O_{ocean} \quad (5)$$

Here we have assumed the deuterium excess versus ocean isotopic content relationship to be linear, which is probably accurate to first order. Given the imperfect nature of the isotopics models, a more complex relationship is not justifiable. Moreover, simulations with the GISS general circulation model using present-day climate show a linear relationship between deuterium excess and oceanic oxygen 18 changes.

Using the four cycle record of oceanic  $\delta^{18}O$  variations adapted from *Bassinot et al.* [1994], we compute a corrected deuterium excess profile shown in Figure 7.

The seawater isotopic correction does not modify the long-term variations but significantly imprints the amplitudes. The largest deuterium excess corrections (+2-3‰) occur during glacial-interglacial transitions, when seawater  $\delta^{18}O$  variations are largest. The most prominent effect of this correction is a reduction of the linear trend through each climatic cycle; in fact, this trend disappears from each of the climate cycles except the most recent one.

### 2.3. Influence of the Site Temperature on the Deuterium Excess Profile

A component of the deuterium excess depends on the site temperature through the variation of the slope  $\delta D/\delta^{18}O$  with the local temperature, reflecting the dependency of the ratio of the equilibrium fractionation coefficients to temperature. The slope decreases as temperature decreases, causing a deuterium

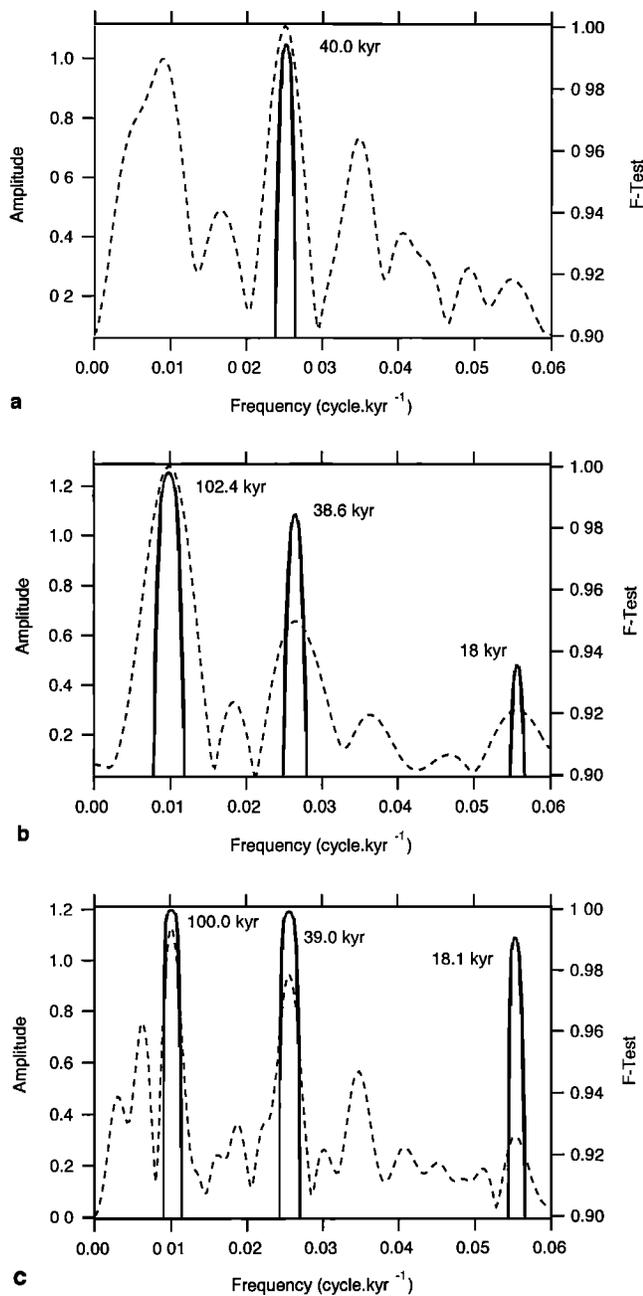
excess increase with colder temperature, independently of any moisture source fluctuations.

We expect the site temperature correction to be small, given that  $\delta D/\delta^{18}O$  slope for the full Vostok profile is 7.94 ( $\pm 0.02$ ). This supports the use of the definition of the deuterium excess as a good representation of the variation of the moisture source only. Moreover, the specific moisture source signature in the deuterium excess is clearly supported by a principal component analysis performed on the two isotopes which provides, as a second component, a combination similar to the deuterium excess profile, with a ratio of 8.03 between the two components defining the new computed signal.

Although we expect this site-temperature effect to be small, we attempt to correct for it to make our reconstructions as accurate as possible. A multiple linear regression is performed with a Rayleigh type model to calculate the sensitivity of Vostok deuterium excess to both source and site temperatures. The dependency of the deuterium excess to site temperature is found to be  $-0.5\text{‰}/^\circ\text{C}$ , approximately 3 times weaker than the source temperature impact ( $+1.3\text{‰}/^\circ\text{C}$ , see section 1). As in the previous section, we define a corrected deuterium excess from the local temperature variations, assuming that the latter are small enough to make a linear relationship valid (an assumption that is not true over the complete range of Antarctic temperatures, *Petit et al.* [1991]):

$$\Delta d_{corr} = \Delta d + \frac{0.5}{7.1} \Delta \delta D \text{ with } \Delta \delta D = 7.1 \Delta T_{site} \quad (6)$$

The spatial isotope-temperature slope 7.1, which is also determined by Rayleigh-type model [*Vimeux et al.*, 2001], is



**Figure 4.** Harmonic analysis of the deuterium excess (a) between 0 and 250,000 years; (b) between 250,000 and 420,000 years; and (c) over the last 420,000 years. Raw data are interpolated at 0.5 kyr intervals. The analysis used the multitaper method (MTM); the bandwidth parameter is 4, and the number of tapers is 6. The statistical test (solid line) validates the amplitude (dashed line) and the location of each peak. Calculations have been performed with the AnalyseSeries software [Paillard *et al.*, 1996].

at the high end of the range of the observed slopes varying between 5 and 7‰/°C [Lorius and Merlivat, 1977; Dahe *et al.*, 1994; Jouzel *et al.*, 1994]. The assumption that the spatial slope is similar to the temporal slope is demonstrably wrong in Greenland [Cuffey *et al.*, 1995]. However, at Vostok, the use of the spatial isotope/temperature slope as a surrogate for

the temporal slope is supported by recent independent methods, suggesting an uncertainty weaker than 20% [Caillon *et al.*, this issue; Parrenin *et al.*, this issue].

As expected, the corrected record (Figure 7) only shows a weak impact of the site temperature: the largest observed shift occurs during the glacial-interglacial periods and is approximately  $\sim -1\text{‰}$ .

Note that the sign of this correction is opposite to that for the oceanic correction. Thus the corrected deuterium excess profile for both ocean isotopic composition and site temperature does not differ from the initial measured profile by more than  $\sim +1\text{--}2\text{‰}$ , the largest corrections occurring during the glacial maxima (Figure 7). The overall decreasing trend within each climatic cycle is preserved after the corrections but is somewhat reduced in magnitude.

An important conclusion from this analysis is that much of the deuterium excess variation measured on Vostok ice cannot be explained by changes in ocean isotopic composition or site temperature and therefore results from moisture source temperature variations, which are now discussed.

### 3. Discussion

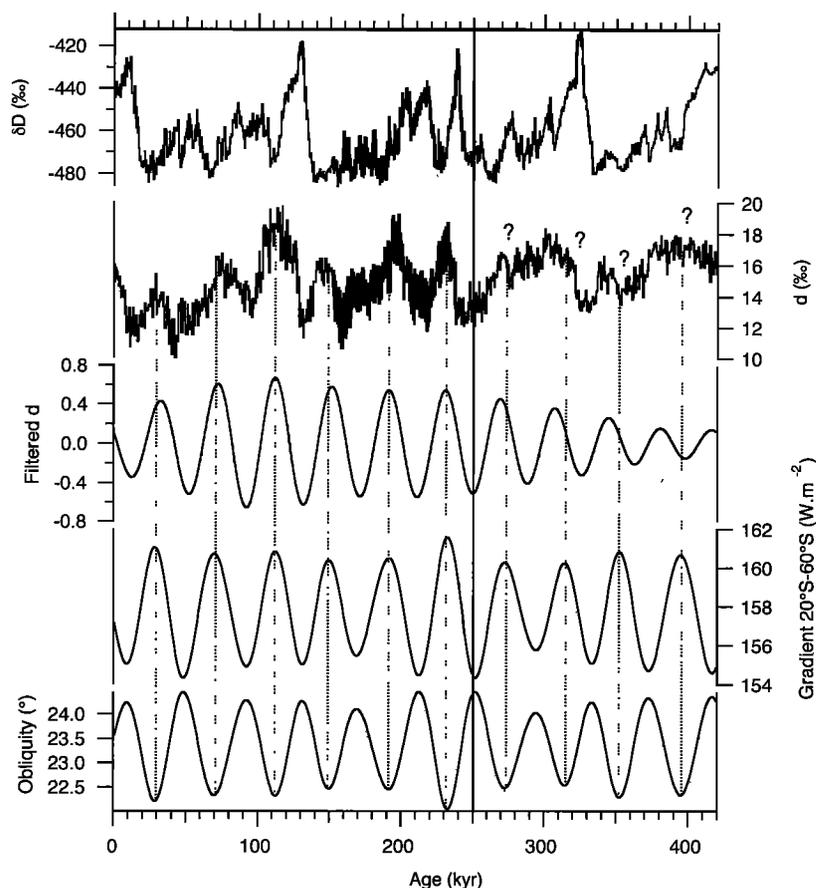
To discuss the possible mechanisms controlling the dominant moisture source temperature variations reconstructed with the deuterium excess record, it is necessary to consider the older and younger parts of the record separately. The younger part shows a large influence of obliquity variations while the older part, more complex, is uncorrelated with the obliquity (Figure 5). Also of interest are the periods of highest deuterium excess values and their relation to low-latitude SST changes.

#### 3.1. The Most Recent 250,000 Years

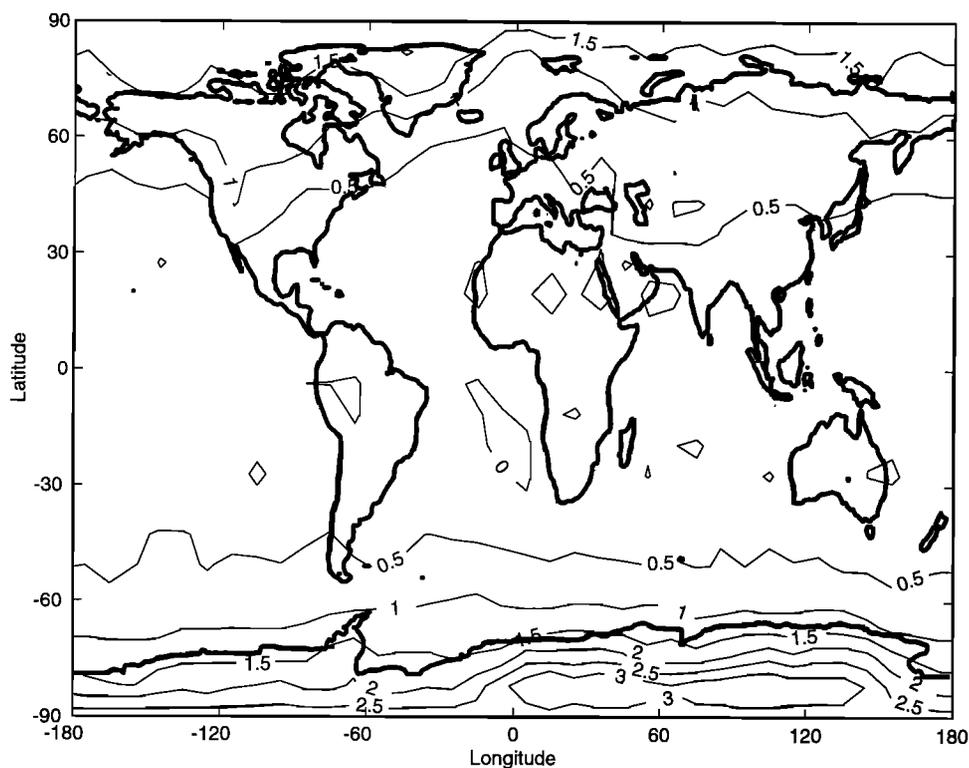
Here we mainly focus on the 40,000 years period modulation of the deuterium excess. As for the most recent climatic cycle [Vimeux *et al.*, 1999], the deuterium excess throughout the last 250,000 years is dominantly modulated by the obliquity periodicity and the variations of the deuterium excess are still strongly anticorrelated with the obliquity changes (Figure 5), basically controlling the variations of the mean annual insolation.

During times of low obliquity, the annual mean insolation at high latitudes is low, whereas the annual mean insolation at low latitudes (north of  $\sim 45^{\circ}\text{S}$ ) is high. As a result, the latitudinal insolation gradient between  $20^{\circ}\text{S}$  and  $60^{\circ}\text{S}$ , for example, is maximized at these times. Two climatic impacts of such an orbital configuration (low obliquity) may explain the corresponding low Vostok deuterium excess values. First, the maximum low-latitude insolation can strengthen evaporation of low latitude. Second, the maximum insolation gradient can increase latitudinal atmospheric moisture transport, enhancing the contribution of remote oceanic moisture sources and reducing the contribution of local, cooler, oceanic moisture sources.

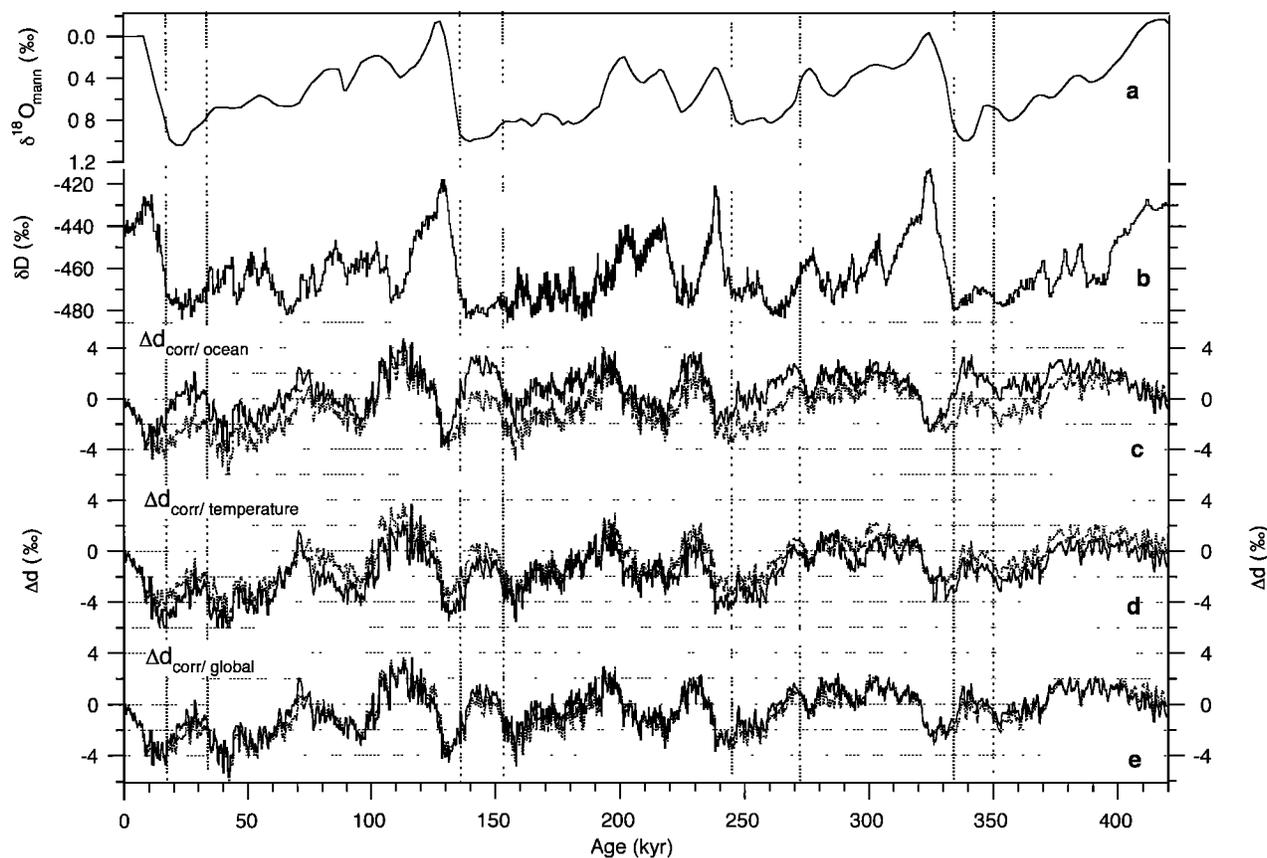
We thus interpret the anticorrelation between the obliquity and the deuterium excess in terms of the relative contribution of low and high latitudes to the precipitation at Vostok. This interpretation ignores the potentially complex influence of the insolation gradient on oceanic circulation. As with the atmospheric transport, it is probable that the latitudinal ocean heat transport is enhanced when the obliquity is low.



**Figure 5.** Deuterium and deuterium excess along with (a) the Gaussian-filtered deuterium excess in the obliquity band ( $0.025 \pm 0.005 \text{ kyr}^{-1}$ ), (b) the difference between the mean annual insolation at  $20^\circ\text{S}$  and  $60^\circ\text{S}$ , and (c) the obliquity variations.



**Figure 6.** Variations of the annual deuterium excess in precipitation (in ‰) due to a global oceanic oxygen 18 depletion of  $1.2 \text{ ‰}$  ( $9.6 \text{ ‰}$  for the deuterium), as simulated by the GISS general circulation model for a modern climate.



**Figure 7.** (a) seawater  $\delta^{18}\text{O}$  adapted from *Bassinot et al.* [1994]; (b) Vostok  $\delta\text{D}$  profile; (c) deuterium excess (dotted curve) and deuterium excess corrected to account for the oceanic variations of  $\delta^{18}\text{O}$  (solid curve); (d) deuterium excess (dotted curve) and deuterium excess corrected to account for the local temperature (solid curve); (e) deuterium excess (dotted curve) and deuterium excess corrected to account for both ocean isotopic composition and site temperature (solid curve). Deuterium excess records are deviations from their modern values and have been sampled at 200 year temporal resolution.

However, an increase of high-latitude precipitation driven by stronger low-latitude moisture supply could oppose this effect if deep water formation is reduced by surface water freshening. A reduction of deep water formation would in turn reduce the equator-pole transfer and cool the high latitudes [*Bryan, 1986; Manabe and Stouffer, 1995*]. This system is further complicated by the NADW (North Atlantic Deep Water) flux into the southern ocean which has a significant impact on the sea surface salinity and thus on the deep circulation [*Wang et al., 1999*].

To conclude, the suggestion of *Vimeux et al.* [1999] that Vostok deuterium excess variations are driven by relative contributions of moisture from the low- and high-latitude oceans appears valid for the last 250,000 years. We expect the same mechanism to operate in the Northern Hemisphere due to the symmetry of the obliquity forcing. Finally, the linear decrease of the obliquity-controlled deuterium excess maxima through a climatic cycle is not explained by the obliquity variations. In section 3.2, we therefore address the high deuterium excess values during interglacials and glacial inceptions and compare the deuterium excess during these periods with available low-latitude SST records.

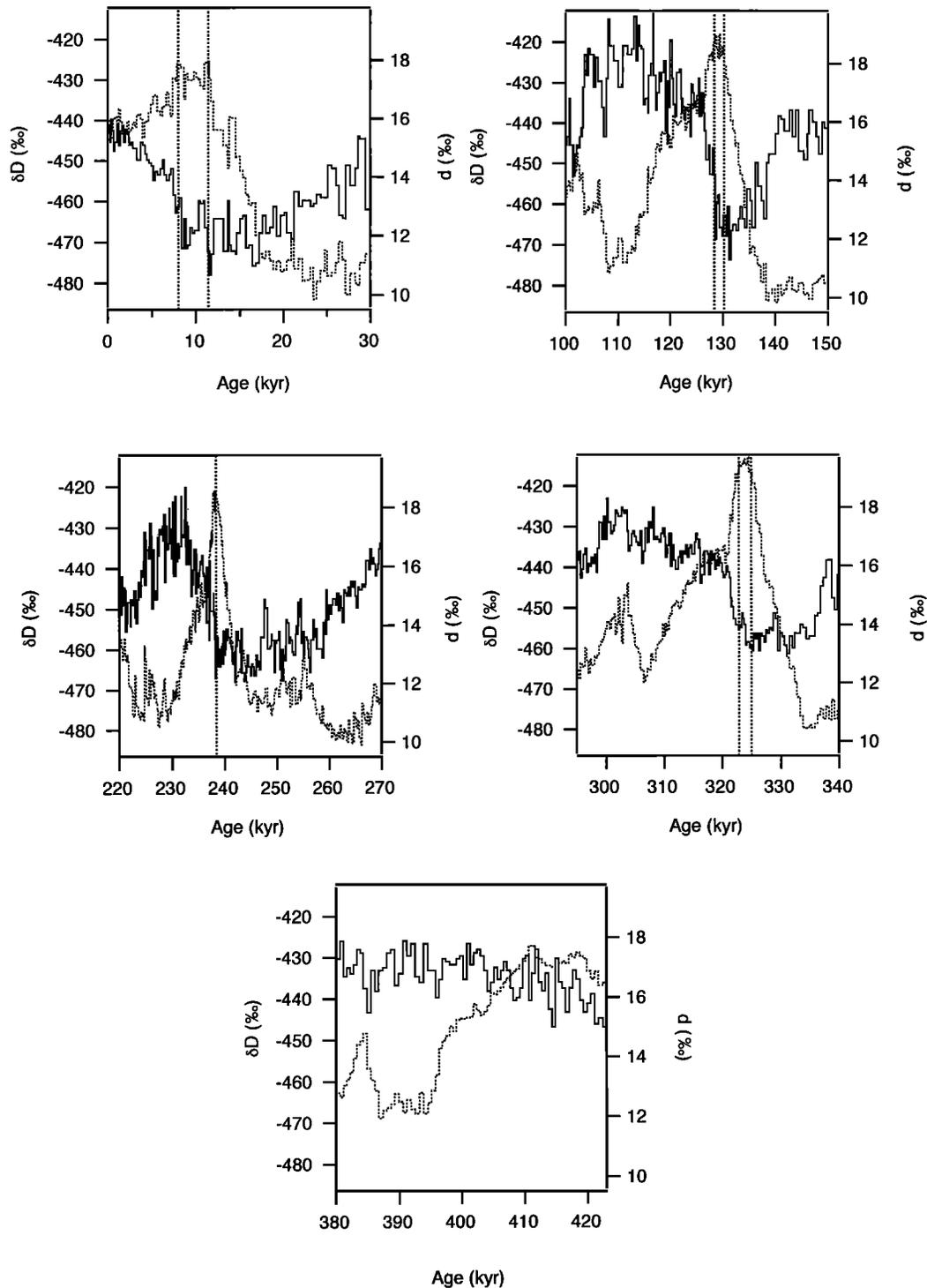
### 3.2. Interglacial Periods and Glacial Inceptions

Our complete Vostok data set allows us to examine all of the interglacial periods and glacial onsets in the past 420,000

years. A remarkable constant relationship between deuterium and deuterium excess can be observed during these periods (Figure 8).

The deuterium excess starts to increase during the warmest period of the interglacial periods and attains a maximum over the cold stage that immediately follows. This maximum is only slightly affected (less than  $-1\text{‰}$ ) by the large decrease of the site temperature (see section 2.3). The amplitude of the deuterium excess variation associated with the glacial onsets increases over time from  $\sim 2\text{‰}$  during the 11.3-11.2 transition to  $\sim 8\text{‰}$  during the 5e-5d transition (long-term deuterium excess changes; see section 3.3). In all cases the glacial inceptions occur when the obliquity is low, and the relative contribution of the tropics to Vostok precipitation is maximized. Moreover, the low concentrations of marine sodium and dust in Vostok ice [*Petit et al., 1999*] during glacial inceptions suggest that the local circumpolar-Antarctic atmospheric circulation is weak, which may reduce the contribution of high-latitude ocean sources and further enhance the contribution from the low-latitude oceans.

The most recent glacial onset (5e-5d) has the highest deuterium excess levels in the entire Vostok record. *Vimeux et al.* [1999] have shown that in addition to the role of the insolation gradient, SSTs at low latitudes are maintained at interglacial values, whereas the high latitude ocean cools. This combination explains the particularly high deuterium excess values of stage 5d.



**Figure 8.** Vostok glacial inception deuterium (dotted curve) and deuterium excess (solid curve).

During the penultimate glacial cycle, the deuterium excess maxima are very high, both at the glacial onset (7.5-7.4 transition) and within the glacial (7.1-6.6), suggesting warm low-latitude SST during both the glacial inception and the full glacial climate. Indeed, SST reconstructions indicate that low-latitude SST are remarkably high and stable during the first two thirds of this climatic cycle [E. Bard, personal communication, 1999; *Schneider et al.*, 1996]. The SST decrease only slightly at stage 6.2, while the deuterium excess

maximum is approximately 1‰ lower than at the two previous maxima.

Prior to 250,000 years B.P., as the anticorrelation with obliquity is reduced, it is not possible to discuss the relative amplitude of the different deuterium excess peaks. Nonetheless, as with the more recent cycles, the highest deuterium excess values occur during glacial onsets and the deuterium excess decreases through the glacial. For all four climate cycles the decreasing deuterium excess trends

probably reflect the long-term change of low-latitude SST [Schneider *et al.*, 1996; Salvignac 1998] as progressive cooling occurs after the rapid glacial onset at high latitudes.

Thus the deuterium excess suggests that at glacial inception the low-latitude SST remain at their interglacial level for some time after the high latitudes cool abruptly. This is probably important for maintaining evaporation and supplying moisture to grow continental ice caps in the Northern Hemisphere.

### 3.3. Prior to 250, 000 Years B.P.

Before ~250,000 years B.P. the correlation with the latitudinal insolation gradient is absent, although the obliquity periodicity is still detectable by the spectral analysis (Figure 4). The uncertainty of the timescale is 10,000 to 15,000 years in the interval between 250,000 years and 420,000 years B.P., and this could partly explain the absence of correlation. Here we discuss other possible explanations for such change in deuterium excess variations, which occurs without any recognizable changes of deuterium behavior.

**3.3.1. Climatic interpretation.** A large change in the moisture source meteorological conditions could sufficiently alter the deuterium excess fluctuations and probably also the response of the ocean to variations of the latitudinal insolation gradient. However, no significant changes at 250,000 years are revealed by SST reconstructions from different ocean basins B.P. [Schneider *et al.*, 1995, 1996; Salvignac *et al.*, 1998; E. Bard, personal communication, 1999]. Thus it is unlikely that the deuterium excess variability change reflects a global oceanic change.

**3.3.2. Diffusion interpretation.** Diffusion of isotopes in the firn could alter the deuterium excess record. This possibility has not been fully explored. However, the study carried out by Denux [1996] on Vostok deuterium has shown that 1000 year isotopic cycles are preserved through the entire 420,000 year record. Diffusion cannot therefore be responsible for weakening the 40,000 year variation.

**3.3.3. Glaciological interpretation.** The ice below Vostok station originates from surface deposition sites along the flow line up-glacier of Vostok, toward Ridge B (~300 km distant [Ritz, 1992]). Thus isotopes measured on the deepest part of the core reflect the composition of precipitation that has fallen farther inland, perhaps in regions being supplied by different oceanic sources than those for Vostok itself. In GT4 timescale an age of 250,000 years corresponds to a depth of 2820 m, for which ice flow models attribute a geographic origin approximately 230 km from Vostok. Surface snow isotopic compositions differ east and west from Vostok, as indicated by different isotope-temperature covariations [Dahe *et al.*, 1994]. Moreover, the isotopic compositions of recent snow at Dome B and Vostok cannot fit on the same distillation line [Jouzel *et al.*, 1996]. These two information suggest that air mass transport to Dome B and to Vostok occurs along different trajectories, possibly originating from different moisture source regions. Currently, there is now no surface deuterium excess data in this region, but future traverses may provide this information. Finally, the accumulation rate is 50% larger at Dome B than at Vostok, confirming that these locations are meteorologically distinct. Other parameters measured in Vostok ice support the idea that deep ice at Vostok was deposited in a different accumulation regime. First, the covariation of marine sodium flux with deuterium is different before and after 250,000 years (M.

Legrand, personal communication, 1999) and such a difference is most easily explained by a difference in the accumulation rate. Second, the glaciological and orbital approaches to date the Vostok core do not agree prior to 250,000 years. According to Parrenin *et al.* [this issue], the only way to reconcile both timescales is to assume a step-like accumulation change between Vostok and Ridge B at the spatial location corresponding to 250,000 year old ice beneath Vostok. The absence of deuterium changes is consistent with this interpretation, provided that climatic trends at Vostok and Ridge B are similar.  $^{10}\text{Be}$  profile, potentially containing information on past accumulation, will provide a further constraint on this interpretation.

The last possibility (that spatial changes in meteorology cause a depth gradient in Vostok ice) seems the most plausible explanation for the change in deuterium excess at approximately 250,000 years B.P. This may explain the decreasing amplitude of the deuterium excess extrema over the entire profile: deep Vostok ice may have initially fallen at a more central Antarctic location, where the contributions of the different ocean basins are more homogeneous and the Indian Ocean moisture contribution less dominant (major contributor according to GISS simulation) [Delaygue *et al.*, 2000].

Implicitly, this raises the question of how each oceanic basin responds to a common obliquity-driven latitudinal insolation change. It is possible that in the Indian Ocean there is a more linear response to insolation, in contrast with the Atlantic which has a large interhemispheric oceanic heat transport. To further explore this question, it would be necessary to compare Vostok deuterium excess history with deuterium excess records obtained at other locations (in the Atlantic sector, at Dome Fuji, and in the Indian-Pacific sector, at EPICA-Dome C).

## 4. Conclusion

In this article we have considerably extended the 150,000 year record analyzed by Vimeux *et al.* [1999] and have confirmed for the last 250,000 years the interpretation of the deuterium excess in terms of the relative contribution of low and high latitudes to Vostok precipitation.

Further, we have presented an original interpretation of the deuterium excess that accounts for several parameters affecting the deuterium excess variations: (1) we account for changes in relative humidity by establishing its covariation with SST and (2) based on modeling studies, we evaluate the influence of both ocean isotopic composition and site temperature on deuterium excess. The combined correction indicates a 1°-2°C smaller moisture source temperature variation during terminations than would be estimated from the uncorrected data.

The lack of correlation with obliquity prior to 250,000 years B.P. is likely due to the ice flow implying a remote origin for the deep ice drilled at Vostok station. This interpretation is supported by the few available isotopic surface snow isotopic data, suggesting different oceanic influences for precipitation recorded in the deepest part of the Vostok core. Obtaining new surface isotopic data in this region will help constrain the spatial change in moisture origin upflow of Vostok. Our interpretation is further supported by analyses of other Vostok parameters (marine

sodium, timescale construction), suggesting a change in the accumulation regime upstream Vostok possibly related to a different ocean origin of the air masses.

A primary result of our deuterium excess analyses for each of the last four glacial inceptions is that warm tropics may have been an important source of moisture to new and growing ice caps during those periods. Recent modeling of the coupled ocean-atmosphere system at 115,000 years in the Northern Hemisphere suggests a similar scenario for the North than as for the South during glacial inception: low latitudes, still warm, supplying moisture to high latitudes which become progressively colder as the thermohaline circulation weakens due to the freshwater supply [Khodri et al., 2001].

Spatial [Vimeux et al., 2001] and temporal deuterium excess variations are now better characterized in East Antarctica, even if our interpretation need to be qualified in the future to incorporate insights from new deuterium excess records in this region (EPICA Dome C), in the Atlantic sector (Dome F, EPICA Dronning Maud Land) and at coastal locations (Taylor Dome, Law Dome), or from new reconstructions of SST.

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