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Air content paleo record in the Vostok ice core (Antarctica): A mixed record of climatic and glaciological parameters

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Abstract. Under present-day climatic conditions the air content of ice shows a high sensitivity to the atmospheric pressure and hence to the elevation at the surface of the ice sheet. This observation has been used to infer past ice sheet thickness variations of Antarctica and Greenland. A high-resolution air content profile (more than 1000 measurements) covering approximately the last 200,000 years was obtained along the 2546-m long Vostok ice core. Three analytical techniques were used, leading to consistent results which show large amplitude and rapid air content variations. The Vostok results support thicker/thinner ice in the central part of East Antarctica during warm/cold periods. However, constraints imposed by ice sheet dynamics suggest that the Vostok air content signal cannot be interpreted only in terms of ice sheet thickness variations. Apart from ice thickness changes, the two other potential sources of air content variations are atmospheric pressure and ice porous volume at the air isolation level. Several atmospheric general circulation models have been applied to the last glacial maximum. They show atmospheric pressure changes which can only explain part of the air content variations in the Vostok ice core. On the other hand, the ice porous volume at the depth of air isolation undergoes fairly well-quantified thermal variations, but they are too small to play a dominant role in the Vostok signal. On the basis of new data concerning the present day ice porous volume variations we suggest that a wind influence on ice porous volume at the air isolation level could be a source for the unexplained air content variations at Vostok. Equivalent contributions from elevation, air pressure, and nonthermal porous volume changes could explain the air content drop during the penultimate deglaciation. Wind speed changes by about 7 m s^{-1} could be the source of the large and rapid air content variations observed during glacial stages.

1. Introduction

The upper first layer of the ice sheet (generally the first 50-110 m, depending on the site) results mainly from the packing and sintering of the snow grains deposited at the surface. This layer, called firn, is characterized by an open porosity decreasing with depth. When all the pores are closed off, the material is called ice (or bubbly ice). During the firn-ice transition, the air inside the pores becomes progressively isolated from the atmosphere prevailing at the surface of the ice sheet and is no longer free to reach pressure equilibrium with the atmosphere below a certain depth. The air content in ice V is then determined by the air pressure P_i and the temperature T_i, as well as the volume of the pores $\mathcal{V}_i$ under conditions prevailing at the time the pores become isolated from the atmosphere in terms of air pressure. As atmospheric pressure and altitude are strongly linked by the hydrostatic equation, air content depends on the surface elevation of the ice sheet. Under present-day conditions, $\mathcal{V}_i$ appears to be generally well correlated with temperature, with lower values of $\mathcal{V}_i$ measured at colder sites [*Miller*, 1978; *Raynaud and Lebel*, 1979; *Higashi et al.*, 1983; *Martinerie et al.*, 1992]. The mean $\mathcal{V}_i$ decrease is about 23% between -20° and -57°C.

In fact, the stage of air isolation in the firn is directly determined by the properties of snow at the surface and by the characteristics of the firn metamorphism. This implies that parameters other than temperature may play a role on $\mathcal{V}_i$. Therefore the conditions at the ice sheet surface, such as wind strength or radiation, can strongly affect the snow characteristics and create stratification of the ice sediments (wind or radiation crusts, summer melting layers for the warmest sites, etc.), that can be detected in depth in the firn or ice.

Air content profiles versus depth (generally scarce) previously obtained along several ice cores were interpreted in terms of changes in elevation of the ice origin site and, more generally, changes in ice thickness during the past were deduced [*Budd and Morgan*, 1977; *Raynaud et al.*, 1979; *Raynaud and Whillans*, 1981, 1982; *Herron and Langway*, 1987; *Kameda et al.*, 1990]. Most of these records reach the last ice age. The interpretation was based on inferring T_i from the isotopic records (considered a proxy for temperature) and using the $\mathcal{V}_i$-T_i relationships inferred from present-day conditions.

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We present here the high-resolution air content profile (more than 1000 measurements) that we obtained along the 2546-m long ice core drilled at Vostok station (78°30'S, 106°50'E, 3488-m altitude). We first discuss the experimental part and the possible artifacts caused by the quality of ice cores and processes occurring in depth. We then use a parameterization of $\mathcal{V}_i$ as a function of T_i to interpret the record in terms of pressure changes attributed to surface elevation or atmospheric pressure variations. The results show that only a part of the V changes observed can be attributed to the possible pressure change having occurred during the past. We finally consider the influence of wind velocity on surface density of snow ρ_s and on $\mathcal{V}_i$. This last investigation is implemented on the basis of a new data set obtained from nine boreholes drilled along the Mirny-Vostok route. The data suggest that changes in wind strength at the surface of the ice sheet is a candidate for explaining a large part of the air content variations along the Vostok ice core.

2. Measurements and Results

Most of the measurements were performed in the 800-2546-m depth range because the ice retrieved above 800 m (in the bubble compression zone) has many fractures, which implies important gas losses. Three different analytical methods were used to measure the air content along two deep Vostok ice cores (3Γ and 4Γ, Figures 1 and 2), which were retrieved 75 m apart. Both cores cover the last climatic cycle. All series of measurements are listed in Table 1. The different analytical methods are indicated by letters A, B, and C in the series designation. All these techniques involve a melting of the sample, therefore all the gas trapped in ice (even the air trapped as air hydrate) is extracted from the ice.

The most accurate of the three analytical methods is the vacuum volumetric technique (A), which is based on gas extraction by melting/refreezing under vacuum and air volume measurement in the burette of a Toepler pump [*Raynaud et al.*, 1982]. This technique has recently been proved to be absolute within ±1.5%, and its reproducibility is higher than ±0.7% (mean value ±0.35%) [*Martinerie*, 1990; *Martinerie et al.*, 1992]. Three series of results (3Γ-A1, 3Γ-A2, and 4Γ-A) were obtained with this method. The first series of measurements (3Γ-A1) was performed before the absolute calibration of the system, and a defect in the Toepler pump occurred during most of the determinations for this profile. Although the results were validated by careful comparison with other series (3Γ-A2 and 3Γ-A) [*Martinerie*, 1990], their accuracy is lower.

The experimental series 3Γ-B was carried out in parallel with methane concentration measurements [*Chappellaz et al.*, 1990]. The experimental procedure of the vacuum chromatographic method (B) consists of extracting the air by melting/refreezing and chromatographic measurement of the air peak [*Chappellaz*, 1990]. As the temperature in the vessel which contains the sample was not measured, obtained values are relative. Nevertheless, 19 ice core sections have been analyzed with both A and B methods in order to estimate vessel temperature and correct the results obtained with method B on the basis of absolute method A. The corrected B values are used here and the relative precision of the B results is better than 5%.

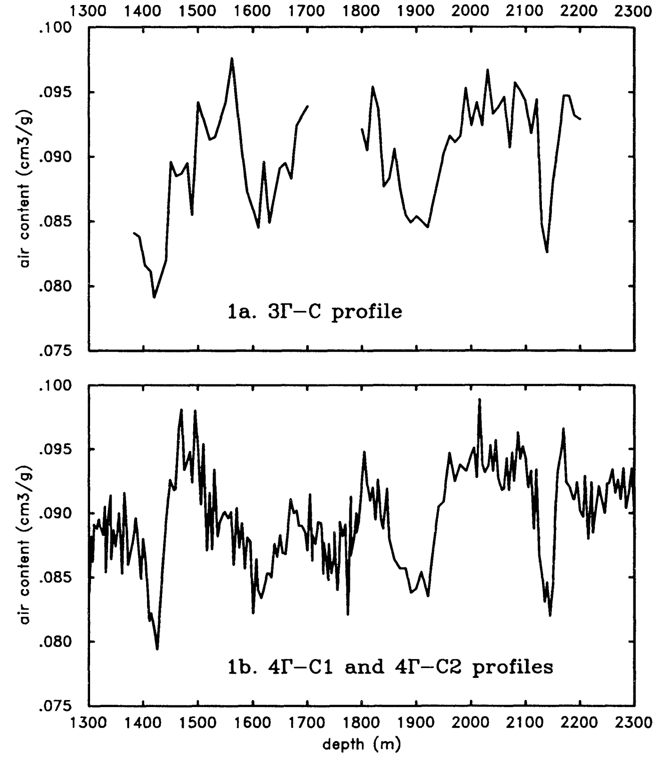

Figure 1. Comparison of the air content profiles obtained with the C method ("liquid" volumetric) on the two Vostok ice cores (3Γ and 4Γ). The discrepancies between the two holes can be explained by experimental uncertainties and differences in sampling except in one case: at 1560 m depth, but the peak which appears on the 3Γ profile for this depth is based on only one point.

High-resolution profiles 3Γ-C, 4Γ-C1, 4Γ-C2 were obtained on the field at Vostok station with a method (C) based on gas extraction by ice melting under liquid and air volume measurement in a burette [*Lipenkov et al.*, 1993]. This technique is derived from the ones described by *Arnold-Alyabyev* [1930] and *Langway* [1958], and salt-saturated water was used as a liquid. The main problem with melting under liquid is to estimate the volume of air that remains dissolved in the meltwater. The use of three temperature gauges placed on the system allowed to better estimate the amount of air dissolved, using the known solubility of air in salt-saturated water. These results were controlled by oxygen concentration measurements. The calculated absolute error of the C method is ±3.5-4%, and its mean experimental reproducibility was found to be ±0.5%. Twelve sections of the 4Γ ice core were analyzed for intercomparison between A and C methods and the following linear regression was obtained: $V^C = 0.79\ V^A + 0.016$ (the C data in Figure 2 are adjusted using this regression for intercomparison). This regression is confirmed by the intercomparison made on the 3Γ core: values measured with the two methods on 16 depth levels separated by less than 5 m lead to a very similar regression, namely, $V^C = 0.78\ V^A + 0.017$. The low values of the slope imply that the use of the C method leads to some smoothing of the V variations. Nevertheless, it should be noted that results of the two methods differ within the range of their errors.

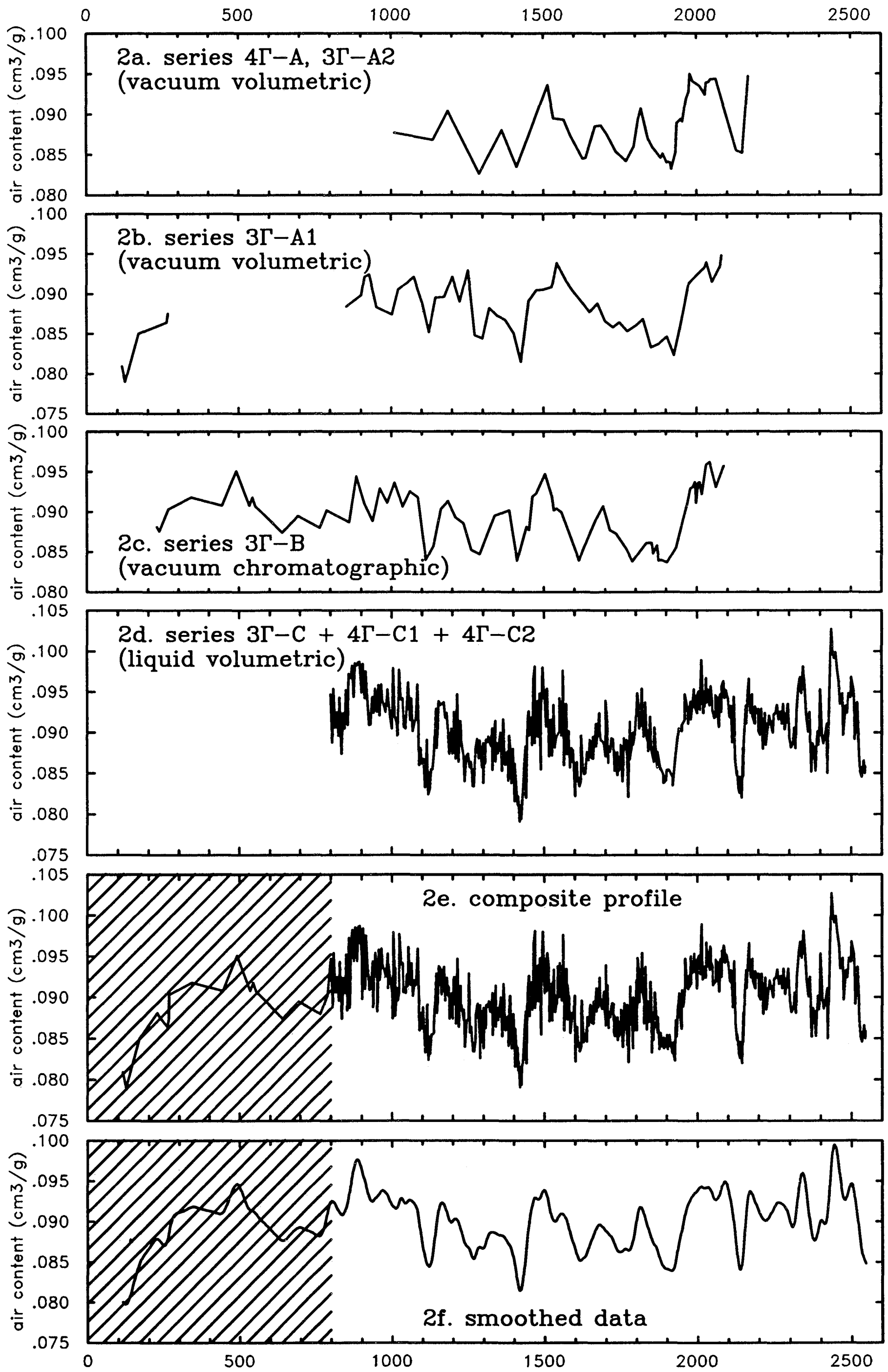

Figure 2. Comparison of the air content profiles obtained with the three analytical techniques and composite profile. (a) Results obtained after the absolute calibration of the vacuum volumetric method, (4Γ-A and 3Γ-A2 are plotted separately from those obtained before). (b) Same as (a) but for 4Γ-A1. (c) and (d) represent the data obtained with the B and C techniques, respectively. (e) All results plotted together and (f) smoothed with a spline function. Shaded part of the curves represents the low-reliability data due to ice core fracturation.

A good depth agreement between the 3Γ and 4Γ ice cores was observed by comparing their water isotope profiles [*Jouzel et al.*, 1992, 1993], as well as by the presence of volcanic dust layers at similar depths in the ice electrical conductivity records of the two ice cores (J.-R. Petit, personal communication, 1993). Although a discrepancy in depth could have been expected on account of different inclinations of the drill holes and existence of several deviations made during the 3Γ drilling, the above results indicate that the differences between the two holes do not exceed 5 m. With

Table 1. Experimental Series of Air Content Measurements in the Vostok Ice Core

Series	Borehole	Range of Depth, m	Number of Depth Levels	Total Number of Measurements	Method	Laboratory
3Γ-A1	3Γ	114-2082	54	178	A, vacuum volumetric	LGGE
3Γ-A2	3Γ	1011-2064	35	111	A, vacuum volumetric	LGGE
3Γ-B	3Γ	228-2089	75	109	B, vacuum chromatographic	LGGE
3Γ-C	3Γ	1300-2201	82	142	C, liquid volumetric	Vostok
4Γ-A	4Γ	1810-2170	12	24	A, vacuum volumetric	LGGE
4Γ-C1	4Γ	800-2546	176	370	C, liquid volumetric	Vostok
4Γ-C2	4Γ	806-1846 2005-2544	158	318	C, liquid volumetric	Vostok

3Γ and 4Γ are the two drill holes, and the different analytical methods are designated by letters A,B,C (see text). Experiments were carried out either at Laboratoire de Glaciologie et Géophysique de l'environnement (LGGE), Grenoble or on the field (Vostok).

the exception of one depth level, our highest resolution results also indicate a good agreement between the 3Γ and 4Γ ice cores (Figure 1). The profiles obtained with the three methods are compared in Figure 2. The results obtained with methods B and C were relative and therefore corrected to fit the results from method A. However, the correction was based on a limited number of common levels and did not affect significantly the amplitude of the signal in the case of method B. Furthermore, method A was calibrated "absolutely" using five cells with calibrated volumes. The data for the upper part of the ice cores are scarce because of the ice fractures. Below 800 m, when taking into account the different sampling and experimental uncertainties, all data sets show the same major *V* variations. Therefore it seems reasonable to combine all the results in order to get a profile with high depth resolution. The resultant profile, shown in Figure 2e, includes 591 values of air content obtained from 1256 measurements (on average about two samples were measured for each depth). As depth resolution increases, the natural short-term *V* variability becomes visible (Figures 2d and 2e). This fact, as well as experimental errors, can explain the high-frequency V variability on the composite profile. This "noise", which includes short-term V variations, is removed in Figure 2f using a spline smoothing and will not be discussed in this paper.

In the next sections we will assume that our experimental results reflect the air content in ice at the time of the air isolation from the atmosphere. Several arguments are in favor of such an assumption.

1. During ice core drilling, fractures or cracks can be formed. Our ice samples were carefully selected outside of visible fractures. Moreover, the fractures in the Vostok core were observed generally to contain kerosene used as drilling fluid. Kerosene is very easy to detect by its smell and a white coloration or iridescence at the surface of the melted ice after the experiment. Kerosene was never detected in our samples taken below an 800-m depth.

2. The relaxation of deep ice cores during storage time, which leads to the transformation of the clathrates into cavities containing the air molecules, can be suspected to induce gas losses. All the 4Γ, as well as the 3Γ-C results, were obtained on unrelaxed ice samples (these samples were stored at -50°C), whereas other profiles were obtained from ice samples containing numerous relaxation cavities in the part of the core where clathrates were initially present. Figure 2 shows that the same air content variations are detected both on unrelaxed and relaxed ice.

3. The air content values in Figure 2 could be too low on account of gas losses from air inclusions near the surface of the ice samples during their preparation. Such gas losses were estimated on ice core sections from the 3Γ-A2 and 4Γ-A profiles by comparison of results from samples with two different shapes cut on the same horizontal slice of ice [*Martinerie et al.*, 1990]. Their average magnitude is 2.7%. Gas losses of that magnitude are produced by rather small cavities (or clathrate crystals) with mean heights of about 0.3 mm [*Martinerie*, 1990]. Such estimates of gas losses are not available for all the analyzed ice core sections, therefore the results are not corrected for such effect, and a 2.7% amplitude gas loss might modulate the amplitude of the air content variations depicted but do not question their existence.

4. Finally, a good conservation with depth of the initial air content signal in the ice is supported by the agreement found for the glacial-interglacial changes of CO_2 and CH_4 concentrations recorded in different types of ice (with and without

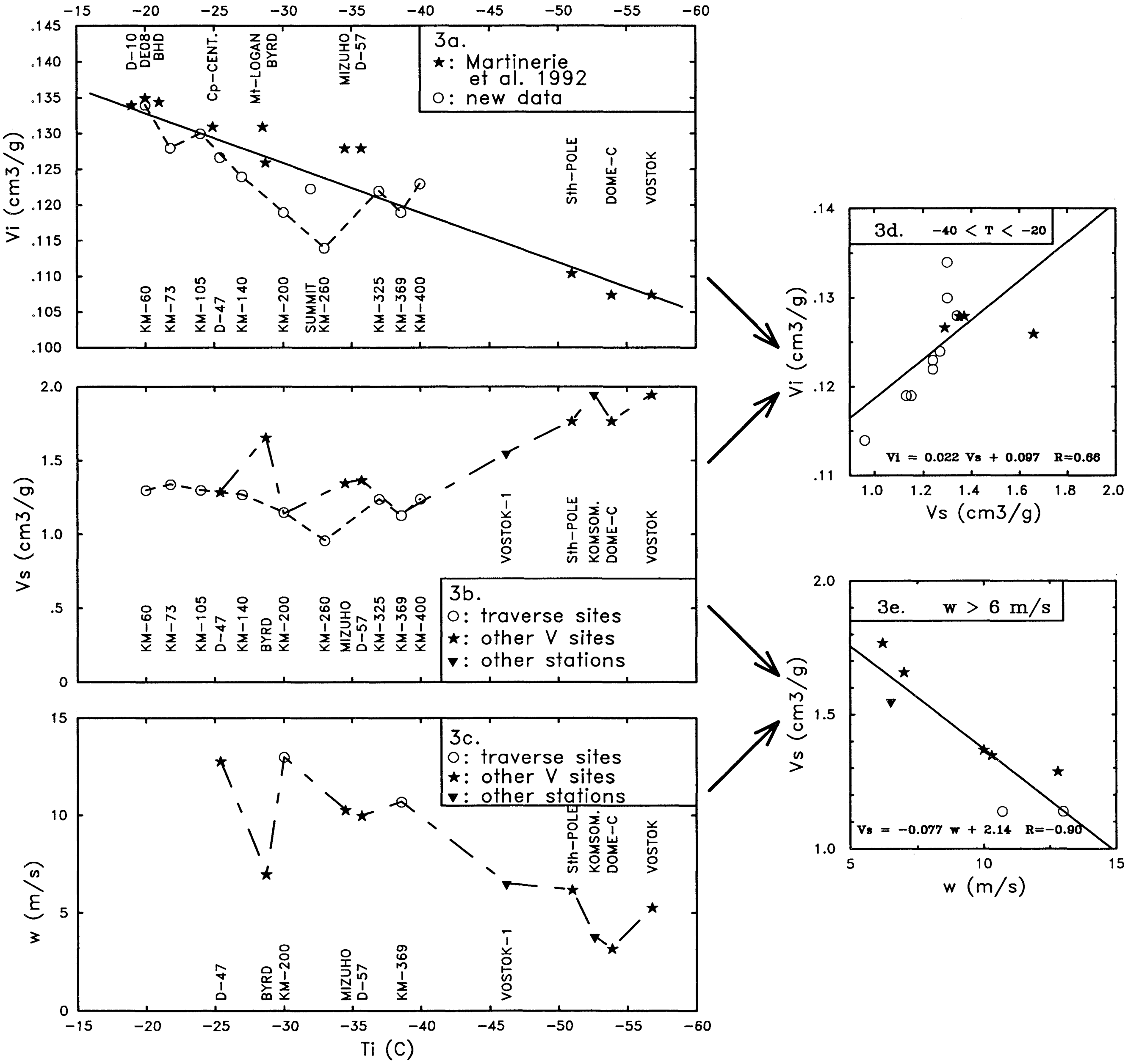

Figure 3. Present-day spatial variations of $\mathcal{V}_i$ compared with available data for surface snow porosity and wind speed. All the stations are in Antarctica except Camp Century and Summit (Greenland), as well as Mount Logan (Canada). (a) $\mathcal{V}_i$ versus temperature. The continuous line is the linear regression obtained from the whole data set. The dashed line emphasizes the results obtained along the Mirny-Vostok traverse. (b) $\mathcal{V}_s$ versus temperature, the long/short dashed line shows the sites for which wind data are available. (c) Wind speed versus temperature (d) $\mathcal{V}_i$ versus $\mathcal{V}_s$, The continuous line is the regression used to infer the $\partial\mathcal{V}_i/\partial\mathcal{V}_s$ gradient, and the circles and stars are the same as in (c). (e) $\mathcal{V}_s$ versus wind. The continuous line is the regression used to infer the $\partial\mathcal{V}_i/\partial w$ gradient, and the circles, stars, and triangles are the sames as in (b) and (c).

air hydrates, different temperatures, snow accumulations, ice structures, etc.) [*Raynaud et al.*, 1993].

The major conclusion of the comparison of the different series of measurements is that reliable large-amplitude V variations (of the order of 10%) are observed with three different analytical techniques and on the two ice cores. Therefore the consistency between the various profiles tends to exclude the possibility of artifacts linked with experimental errors or ice core quality variations.

3. Transforming Air Content Values Into Atmospheric Pressure

The first step in the interpretation of air content data is to derive a parameter of direct climatic interest: the air pressure P_i in the bubbles when they become isolated from the atmosphere.

P_i can be expressed as

$$P_i = P_0 \frac{T_i}{T_0} \frac{V}{\mathcal{V}_i} \tag{1}$$

where V is the air content of ice ($\mathrm{cm^3\,g^{-1}}$) reduced to standard temperature T_0 and pressure P_0 [see *Martinerie et al.*, 1992]. T_i is the temperature of the air, and $\mathcal{V}_i$ is the pore volume of the ice when the air becomes isolated from the atmosphere. From the firn densification model described by *Barnola et al.* [1991] the close-off depth at Vostok did not change by more than 40 m over the last climatic cycle. This corresponds to about 3.5 mbar in terms of pressure variations. Therefore the P_i signal is essentially an atmospheric pressure signal.

The main uncertainty when using (1) for reconstructing the atmospheric pressure is the parameterization of $\mathcal{V}_i$. The study of the present-day geographic variations of the air content shows that $\mathcal{V}_i$ is temperature dependent [*Miller*, 1978; *Raynaud and Lebel*, 1979; *Higashi et al.*, 1983; *Martinerie et al.*, 1992]. A possible wind dependence of $\mathcal{V}_i$ was also suggested by *Martinerie et al.* [1992], while the data showed no dependence on snow accumulation. Important additional data from the Mirny-Vostok axis further support a wind influence on $\mathcal{V}_i$. This is the object of the first subsection of this paragraph. On the other hand, the very low snow accumulations recorded at Vostok imply that the transformation of snow into ice can take between ~2500 and 6000 years (i.e., time intervals that are comparable to the time scale of large climatic changes). The problems linked with the V to P_i transformation in transient climatic conditions will be discussed in a second subsection.

Discussion of the Parameterization of $\mathcal{V}_i$

Eleven new ice cores were analyzed with experimental method A for their present-day air content, doubling the number of data points available for the $\mathcal{V}_i$ parameterization: 9 cores from the axis between Mirny and Vostok (East Antarctica) (V. Y. Lipenkov, manuscript in preparation), the D-47 (Adelie Land, Antarctica), and the Summit (Greenland) ice cores [*J.-P. Vandervaere*, 1991]. In this section the important conclusions for interpreting the air content record at Vostok are presented. The complete analysis of the new information will be published elsewhere. Figures 3a, 3b, and 3c show the available results of ice porous volume at the air isolation level, together with available data of surface snow porous volume and wind versus temperature. Most of the new $\mathcal{V}_i$ values in Figure 3a are lower than the values obtained previously. This trend is less clear when looking at the air content versus elevation or pressure. Absolute calibrations of the experiment have been carried out during the new measurements, therefore the lower $\mathcal{V}_i$ values for these sites should not be due to an experimental artifact. Some of the new sites exhibit especially low values of surface snow porous volume, which may influence $\mathcal{V}_i$, as explained below.

The $\mathcal{V}_i$-T_i regression line calculated with the 22-points data set (including new and previous results)

$$\mathcal{V}_i(\mathrm{cm^3 g^{-1}}) = 6.95\ 10^{-4}\ \mathrm{T_i(K)} - 0.043 \tag{2}$$

(correlation coefficient: 0.90) is close to the one calculated with the previous 11 sites [*Martinerie et al.*, 1992] plotted as stars in Figure 3a. On the other hand, the previous data set suggested a lower $\mathcal{V}_i$-T_i slope when considering only the warmer sites ($T_i \in$ [-15, -36]). This is not any more true with the 22-points data set. Our knowledge of the $\mathcal{V}_i$ temperature dependence relies only on an empirical approach, but no quantitative theoretical explanation is available. Therefore we do not know whether the empirical relationship reflects only a direct temperature influence or also the signature of other parameters correlated to temperature. Finally, we note that the $\mathcal{V}_i$-T_i relationship is not documented in the temperature range [-41, -50]°C and below -57°C (the present day close-off temperature at Vostok).

In fact, a large fraction of the $\mathcal{V}_i$ variability is not correlated to temperature (noise around the regression line in Figure 3a). Therefore the next step is to consider whether nonthermal $\mathcal{V}_i$ changes can be correlated to a climatic parameter. Such a study is limited by data availability. Figures 3b and 3c indicate a correlation between porous volume of surface snow $\mathcal{V}_s$ and mean annual wind speed w. It may reflect the snow packing by wind at the surface of the ice sheet. We should, nevertheless, mention the uncertainties (measurements at different heights above the ground, with different types of anemometers) existing when comparing wind data from different sites. Surface snow porous volumes $\mathcal{V}_s$ are deduced from snow density data: ρ_s ($\mathcal{V}_s = 1/\rho_s - 1/\rho_{ice}$, with ρ_{ice}: pure ice density). $\mathcal{V}_s$ can also be subject to large temporal variability as a function of weather conditions and time elapsed since the last snowfall. However, a survey of fresh snow density over several years was performed by the Russian Antarctic expeditions involving hundreds of measurements obtained at various sites with the same experimental technique [*Averyanov*, 1990]. A correlation between ρ_s and wind was observed for wind speeds higher than 6 $\mathrm{m\ s^{-1}}$ [*Kotlyakov*, 1961]. Mean wind speeds higher than 6 $\mathrm{m\ s^{-1}}$ are observed outside of the East Antarctic plateau (i.e., for sites with temperatures ranging between -20 and -40°C). In this temperature range, wind speed looks independent from temperature (Figure 3c). Therefore we will assume that the $\mathcal{V}_s$-w slope from Figure 3e ($w > 6\ \mathrm{m\ s^{-1}}$) reflects the pure wind effect on $\mathcal{V}_s$: $\partial\mathcal{V}_s/\partial w = -7.7\ 10^{-2}\ (\mathrm{cm^3\ g^{-1}})/(\mathrm{m\ s^{-1}})$.

In the warm temperature range ([-20, -40]°C) a correlation is observed (Figure 3d) between $\mathcal{V}_i$ and $\mathcal{V}_s$. Although weak ($r^2 = 0.66$), this $\mathcal{V}_i$-$\mathcal{V}_s$ correlation could explain part of the nonthermal $\mathcal{V}_i$ variations (see Figures 3a and 3b). From Figure 3d we estimate the $\mathcal{V}_i$-$\mathcal{V}_s$ gradient as: $\partial\mathcal{V}_i/\partial\mathcal{V}_s = 2.2\ 10^{-2}$ $(\mathrm{cm^3\ g^{-1}})/(\mathrm{cm^3\ g^{-1}})$. By multiplying $\partial V_i/\partial\mathcal{V}_s$ and $\partial\mathcal{V}_s/\partial w$ gradients, we obtain the following magnitude for the wind influence on $\mathcal{V}_i$: $\partial\mathcal{V}_i/\partial w = -1.7\ 10^{-3}\ (\mathrm{cm^3\ g^{-1}})/(\mathrm{m\ s^{-1}})$.

The $\mathcal{V}_i$-$\mathcal{V}_s$ correlation observed for T ∈ [-20, -40]°C cannot be directly extended to the coldest sites (Figure 3b). It may reflect different types of dominant precipitation: in the relatively warm sites, precipitation originates from orographic lifting and consequent adiabatic cooling, whereas in the Antarctic plateau, clear sky precipitations due to radiative cooling dominate today [*Bromwich*, 1988]. The above analysis is therefore not directly applicable to the coldest sites. However, as a sensitivity test, the impact of a gradient $\partial\mathcal{V}_i/\partial w = -1.7\ 10^{-3}\ (\mathrm{cm^3\ g^{-1}})/(\mathrm{m\ s^{-1}})$ on the air content paleo record measured on the Vostok core will be examined in section 4. Such a use of the $\mathcal{V}_i$-w gradient for interpreting the Vostok paleo record can be valid only if, in some periods of the past, wind speeds at Vostok were higher than 6 m s^{-1}, and if we assume that the gradient $\partial\mathcal{V}_i/\partial\mathcal{V}_s$ = 2.2 10^{-2} (cm^3 g^{-1})/($cm^3 g^{-1}$) is also valid on the Antarctic plateau.

Finally, a direct attempt of multiple correlation between $\mathcal{V}_i$, T_i and wind was performed for the whole temperature range ($T_i \in$ [-15, -60]°C). For the nine sites where those three data are available, we get

$$\mathcal{V}_i = 7.13\ 10^{-4}\ T_i - 1.84\ 10^{-4}\ w + 0.1488 \qquad (3)$$

with a correlation coefficient of 0.90. The Fisher test (which specifies that for three variables and nine samples the correlation coefficient has to be higher than 0.75) is satisfied, but the $\mathcal{V}_i$ wind slope is smaller than the previous one by a factor of ten (such a small slope would have a negligible impact on $\mathcal{V}_i$). Therefore a high $\mathcal{V}_i$ wind gradient is obtained only if a nonlinearity occurs between warm sites and cold sites. Other possible sources of $\mathcal{V}_i$ variations were also examined [*Martinerie et al.*, 1992]. The comparison of $\mathcal{V}_i$ results from three couples of sites with similar temperatures but snow accumulation rates varying by at least a factor of two suggests that $\mathcal{V}_i$ is independent from snow accumulation rate. A sealing effect of summer snow layers by winter snow layers was identified as the source of the air content seasonal variations at high snow accumulation sites. But this is not relevant for the Vostok site, where the accumulation is very low. Other heterogeneities in the firn, such as wind crusts, are potential sources for a sealing effect, however no significant V variations above and below such crusts were observed. Important depth hoar formation, another source of heterogeneity in firn, is known to occur in the central Antarctic plateau. Numerous air content measurements were performed on the south pole and dome C cores, that showed smaller short-term variability than in high-accumulation areas, where seasonal variations are observed. However, at the time scale of a few months to one year, the air content variability at dome C or south pole still reaches about 8% [*Martinerie*, 1990]. This suggests that heterogeneities in firn are not negligible even in these low-accumulation regions. The variability of closed porosity and total porosity of the firn in the close-off zone at Vostok is even higher (J.-M. Barnola, personal communication, 1993).

To summarize, several empirical studies show thermal $\mathcal{V}_i$ variations with consistent slopes. A sealing effect is also observed on $\mathcal{V}_i$ but only at a single high-accumulation site, and with negligible effect on the mean annual V value. On the other hand, our data suggest no effect of accumulation on $\mathcal{V}_i$. Finally, on the basis of new data along the Mirny-Vostok traverse, we suggest a wind speed influence on $\mathcal{V}_i$ that could explain $\mathcal{V}_i$ changes of the order of 10%.

The Conversion of V Into P_i for Transient Climatic Conditions

Using the Vostok isotopic temperature [*Jouzel et al.*, 1987, 1993] and V records for estimating T_i and $\mathcal{V}_i$, different assumptions can be made to calculate a P_i profile for transient climatic conditions. The temperature T_i used in (1) is the temperature at the bottom of the firn, when the air becomes trapped in ice. As the firn densification process takes several thousand years in the Vostok area, if the surface temperature change is slowly transmitted to the bottom of the firn, T_i can differ significantly from the surface temperature T_s inferred from the isotopic record. As a sensitivity test, the results obtained with two extreme assumptions were compared. A T_s perturbation was considered to be transmitted instantaneously through the firn in a first case and at the speed of the snow burying in a second case. The amplitude of the P_i variations changed by less than 10 mbar in the case of glacial-interglacial change, which is small compared to their total amplitude shown in Figure 4. In this paper, T_i is evaluated by assuming an "instantaneous" transmission of T_s changes through the firn (i.e., fast transmission compared to the time scale of the firn densification).

The temperature to be used in the $\mathcal{V}_i$ parameterization can be either controlled by thermal conditions during the densification process (if the $\mathcal{V}_i$ temperature dependence originates from a phenomenon which occurs during the snow densification) or by the temperature at the time of snow deposition (if the $\mathcal{V}_i$ temperature dependence originates from initial properties of snow, as $\mathcal{V}_s$). The induced differences in the P_i signal are again smaller than 10 mbar. In the discussion below, the temperature at the time of snow deposition is used for the $\mathcal{V}_i$ parameterization.

The effect of choosing different ice or gas datings was also considered and led to negligible impacts on the P_i signal [*Martinerie*, 1990]. Therefore the most sensitive parameter in the calculation of P_i is the $\mathcal{V}_i$ parameterization.

4. Discussion of the Calculated Pressure Signal

Figure 4 shows the isotopic temperature record together with the smoothed air content and P_i profiles versus age. The ice dating was derived from *Jouzel et al.* [1993]. This new dating is based on modeling of ice sheet dynamics and takes into account a snow accumulation rate increase upstream from the Vostok station. The comparison with previous datings and with oceanic sediment records is discussed by *Jouzel et al.* [1993]. The calculation described by *Barnola et al.* [1991] was used for determining the ice-gas age difference, taking into account the new ice dating and close-off densities deduced from (2). Equation (2) was first used for the $\mathcal{V}_i$ parameterization (i.e., taking only into account the thermal influence on $\mathcal{V}_i$). Several pressure changes by about 100 mbar in a few thousand years are observed. Most of these P_i variations are not correlated with temperature. The following parameters may, a priori, contribute to the P_i changes shown in Figure 4: variability in the volume of air lost at the surface of the sample when cutting it, changes in the elevation of the ice formation site, changes in atmospheric pressure fields over Antarctica, and changes in the ice porous volume at the air isolation depth other than those taken into account by (2).

Part of the V and P_i variations could arise from differences in the amount of air lost at the surface of the ice sample during its preparation. The evaluation of the air lost is

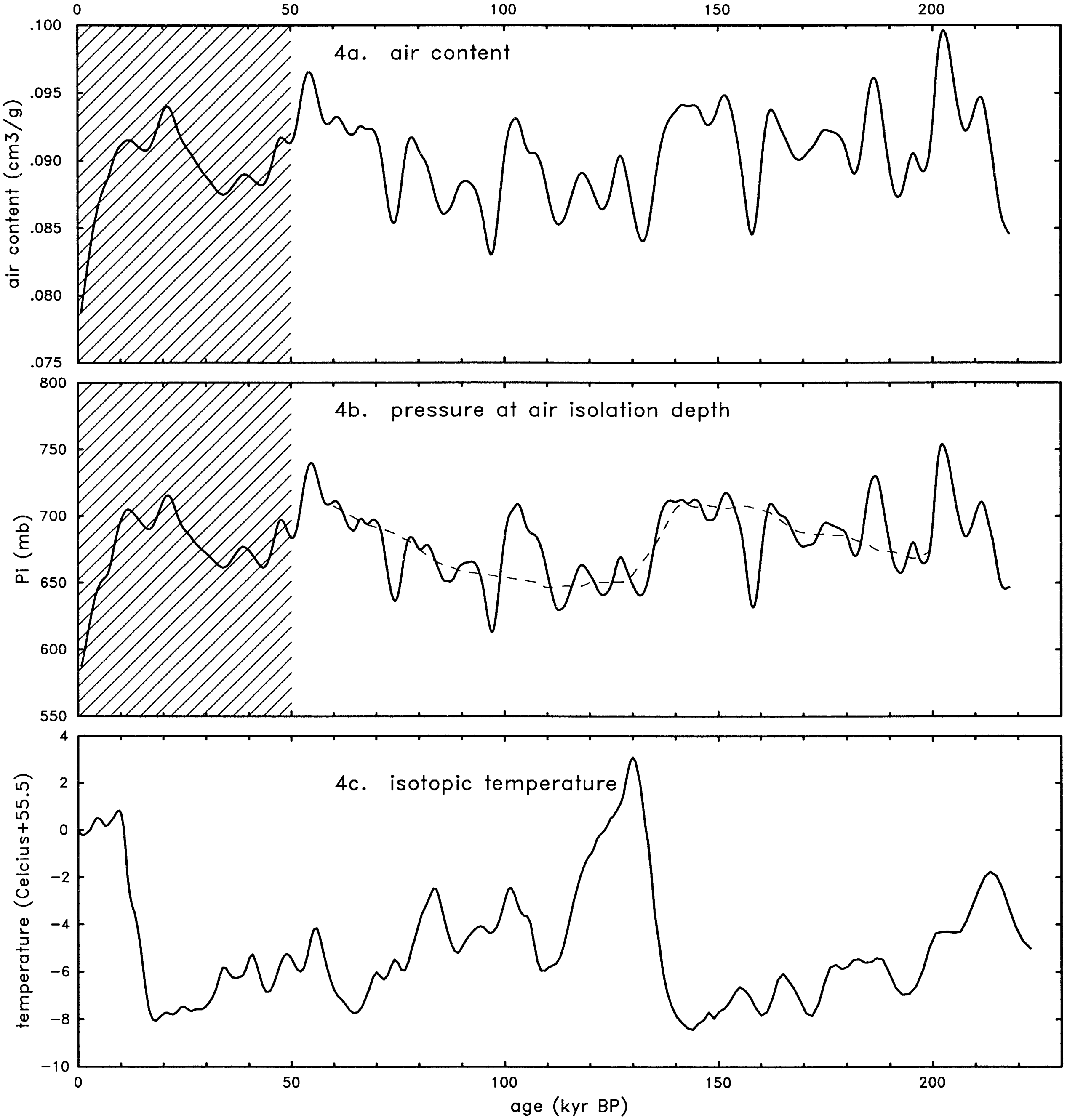

Figure 4. Air content (a), pressure at the depth of air isolation (b), and isotopic temperature (c) versus age in kilo years B. P. The shaded part of the curves represents the low-reliability data due to ice core fracturation. The present-day value of the air pressure at the depth air isolation for the Vostok site is 632 mbar. The dashed line in (b) suggests the long-term trend of P_i changes (see text).

discussed in section 2. The results are not precise enough to allow for a core by core comparison, but based on mean data in the 126-134.5 kyr B.P. range (8 core sections) and in the 141-154 kyr B.P. range (7 core sections), the correction appears significantly smaller at the end of the penultimate glacial period than during the following interglacial stage [*Martinerie*, 1990]. Thus the air lost during sample preparation could explain about 5 mbar of the pressure decrease during this climatic transition, compared to a net change of 70 mbar. The available data are too scarce to allow for similar estimates on other parts of the record. The correction is too small to question the existence of the major air content variations, but it could modulate their amplitude.

Ice Flow and Ice Thickness Variations in the Vostok Region

The calculated pressure varies between about 750 and 600 mbar for the time period considered (50-220 kyr B.P.). As a reference the present-day value for P_i is 632 mbar. Atmospheric pressure and elevation are strongly linked by the hydrostatic equation. A 100-mbar pressure change corresponds to a 1000- to 1250-m elevation change (taking into account a range of 8-10 mbar/100 m for the pressure-elevation gradient). This is very large compared to predictions of ice origin and ice thickness changes in the Vostok area based on ice dynamics modeling [*Huybrechts*, 1990; *Ritz*, 1992]. It is also important to note that the P_i decreases are generally as quick as the P_i increases, although ice flow modeling explains more easily a rapid and large amplitude ice thinning (in response to boundary condition changes) than an equivalent ice thickening in this low-accumulation area. It seems reasonable to assume that the "rapid" and symmetric variations in P_i observed for ice older than about 50 kyr (i.e., for the part of the record corresponding to ice of good quality) around 74.5, 97, 158, 186.5, and 202 kyr B.P. are not due to ice elevation changes. The remaining trend (except between 100 and 110 kyr B.P.), as suggested by the dashed line in Figure 4b, is in agreement with an ice sheet thicker during the interglacial period than during the two glacial periods in the Vostok area and a progressive thinning during the glacial periods reaching a maximum at their end with full glacial conditions. Such behavior suggests that changes in accumulation rate play a major role in controlling the ice thickness in the central part of East Antarctica.

A rough estimate of the effect of the origin of the ice due to ice flow (in the absence of ice sheet surface elevation change) can be obtained by multiplying the ice speed at the surface (2 m yr^{-1} [*Hamley*, 1985]) by the age of the ice and the ice surface slope at Vostok (about 1x10^{-3} m/m [*Ritz*, 1992]). It leads to a slow surface elevation increase of the ice origin site, the elevation increase being 360 m for the ice 180,000 years old. The use of a two dimensional ice flow model, taking into account the flow line divergence, allows for a better estimate of this effect and leads to a smaller value: about 100 m (C. Ritz, personal communication, 1993).

The effect of accumulation rate $\dot{b}$ changes on ice thickness H variations can be estimated using a simplified form of the continuity equation [*Ritz*, 1989]

$$\partial H/\partial t = \dot{b} - \langle \dot{b} \rangle \qquad (4)$$

where $\langle \dot{b} \rangle$ is the mean accumulation rate over a climatic cycle. Here we use (4) with different accumulation rate profiles: the snow accumulation rates deduced from the Vostok core isotopic temperatures [*Lorius et al.*, 1985], those obtained from ^{10}Be measurements [*Yiou et al.*, 1985; *Raisbeck et al.*, 1987], and those consistent with the recent dating given by *Jouzel et al.* [1993] which takes into account the present-day accumulation increase upslope from the Vostok station. The calculations lead to maximum elevation changes during the last climatic cycle ranging from 150 to 250 m. In any case, the elevation changes thus inferred are slower than the observed P_i variations and can explain only a minor part of them. Other effects, such as isostatic adjustment or the impact of sea level changes on ice flow are difficult to evaluate precisely.

Two different ice flow models were used to infer the past ice surface elevation changes at Vostok over the last climatic cycle. Several simulations were performed with a bidimensional model [*Ritz*, 1992] to test the sensitivity of different parameters such as geothermal flux, ice rheology, and snow accumulation. The surface elevation variations obtained are slow and are less than 150 m. A calculation with a three dimensional ice flow model of the whole Antarctic continent [*Huybrechts*, 1990] also leads to small and slow ice thickness changes in the Vostok region. It shows a maximum predicted elevation change of about 300 m around 120 kyr B.P. and lasting about 20 kyr. The difference between the results of the two models is essentially due to the fact that, in the three dimensional model, the sea level variations produce ice flow perturbations up to the central Antarctic plateau. Both ice sheet models produce much smaller and slower elevation variations than those suggested by the P_i signal that can reach up to 90 mbar in 4000 years (see Figure 4b, around 150-160 kyr B.P.). Although there are large uncertainties when modeling ice sheet evolutions, it should be emphasized that the speed of change of ice surface elevation as deduced from air content would be about an order of magnitude higher than model predictions.

Therefore the Vostok air content signal should reflect, for a large part, effects other than ice surface elevation change. Other candidates for explaining the P_i signal are atmospheric pressure changes and nonthermal $\mathcal{V}_i$ variations.

Atmospheric Pressure Changes

The glacial-interglacial change in mean sea level pressure, related to Earth surface topography and atmospheric mass changes, would be less than 3 mbar [*Mélières et al.*, 1991]. An atmospheric pressure decrease at Vostok elevation under colder conditions could be related to an air mass transfer toward low-altitude regions (colder air is more dense). The amplitude of such a hydrostatic effect is estimated to reach 10-25 mbar, taking into account a surface temperature change of about 10°C and different temperature-elevation gradients [*Martinerie*, 1990]. Finally, changes in more global atmospheric dynamics can also lead to pressure changes. An increase of the meridional temperature gradient during glacial periods would induce a reinforcement of the Antarctic anticyclone and would then tend to compensate for the hydrostatic effect.

Several general circulation models (GCM) simulate the climate of the last glacial maximum (LGM). Only a few references provide atmospheric pressure results for the southern hemisphere [*Gates*, 1976a,b; *Manabe and Hahn*, 1977; *Kutzbach and Guetter*, 1986; *Rind*, 1987; *Joussaume*, 1989]. The results obtained over Antarctica are different: the change in pressure brought back to sea level varies between -6 and +20 mbar for the LGM compared to today. The differences are probably partly linked with the very different temperature fields simulated by the four models over and around Antarctica. In summary, large-scale patterns of atmospheric pressure changes deduced from GCM simulations could explain up to 20 mbar of the P_i glacial-interglacial variations but not the whole signal.

Nonthermal $\mathcal{V}_i$ Changes

As mentioned above in this paper, the conversion of air content into pressure at the depth of air isolation uses a parameterization of the $\mathcal{V}_i$ dependence upon temperature. However, a large fraction of the $\mathcal{V}_i$ variability is not correlated to temperature (see Figure 3 and section 3). The largest deviation from the $\mathcal{V}_i$ temperature regression is the 11.6% $\mathcal{V}_i$ increase found between km-260 and Mizuho, while the $\mathcal{V}_i$-T_i

relationship would predict a 0.8% decrease. This 12.4% nonthermal $\mathcal{V}_i$ change is of the same order of magnitude as the large air content variations observed along the Vostok ice core (Figure 4a). Therefore, nonthermal $\mathcal{V}_i$ variations can potentially explain a large part of the V variability found in the Vostok paleo record.

Although the existing results are still too scarce to conclude definitely, the present wind-surface snow porous volume-$\mathcal{V}_i$ spatial correlations suggest significant temporal variations of $\mathcal{V}_i$ associated with wind activity changes. At present, the dominant wind on the Antarctic plateau is inversion wind (see, for example, *Schwerdtfeger* [1984]). The inversion wind w_I has been expressed as

$$w_I = \frac{g}{f}\,\frac{T_{inv}-T_s}{T}\,p \qquad (5)$$

[*Dalrymple et al.*, 1966] where g is gravity, f is the Coriolis parameter, T_{inv}-T_s is the temperature difference between the top of the inversion layer and the surface, $\bar{T}$ is the mean temperature of the inversion layer, and p is the slope of the ice sheet surface. From *Jouzel and Merlivat* [1984], T_{inv} and T_s are related by:

$$T_{\mathrm{inv}} = 0.67\ T_s + 88.9 \qquad (6)$$

Using (5) and (6), with $p = 1\mathrm{x}10^{-3}$ as an estimate of the ice sheet slope in the Vostok area [*Ritz*, 1992], the inversion wind increase for a surface temperature drop by 10°C is about 1.2 m s^{-1}. With the slope of the $\mathcal{V}_i$-w relationship estimated in section 3 ($\partial\mathcal{V}_i/\partial w$ = -1.7 10^{-3} $(\mathrm{cm}^3\mathrm{g}^{-1})/(\mathrm{m\ s}^{-1})$), such a change in the inversion wind intensity would lead to a $\mathcal{V}_i$ decrease close to 2%. This is small compared to the amplitude of V variations depicted in Figure 4a. On the other hand, most of the air content changes are not correlated to temperature. However, (5) shows that inversion wind is also directly dependent on the ice sheet slope. More generally, *Parish and Bromwich* [1987] emphasize the strong link between ice topography and the surface wind regime over the whole Antarctic continent. Another potential source of wind speed changes in the past is the possible occurrence of more frequent weather perturbations. Nowadays, such events are very seldom over the Antarctic plateau. However, *Dalrymple* [1966] reports a frontal passage at Vostok in winter associated with a wind speed reaching 25 m s^{-1}. Using the previous $\partial\mathcal{V}_i/\partial w$ slope, a wind speed increase by 7 m s^{-1} could be the source of the largest negative peaks in air content observed during glacial periods.

Other potential sources of $\mathcal{V}_i$ variations are changes of the porous volume of surface snow not related to wind and the heterogeneities in firn which could induce a sealing effect (wind or radiative crusts, depth hoar, etc.). If we take into account the $\mathcal{V}_i$-$\mathcal{V}_s$ gradient derived in section 3 ($\partial V_i/\partial\mathcal{V}_s$ = $2.2\mathrm{x}10^{-2}$), a reduction of surface snow porous volume by 0.6 cm^3 g^{-1} could account for the largest air content negative peaks. Such a $\mathcal{V}_s$ change is smaller than the present-day geographic variations of $\mathcal{V}_s$. It corresponds to a close-off density variation of about 0.01 g cm^{-3}. Note that such a close-off density change would change the age of the air trapped in the ice by about 150 years, using the snow densification model described by *Barnola et al.* [1991]. This is small compared to the other uncertainties linked with the age determination. Concerning the sealing effect by heterogeneities in the firn, the measured air content profiles (Figure 2) reveal gradual changes in air content, while we expect that a sealing effect would produce more abrupt changes.

Further indications on the causes of air content variations related to nonthermal $\mathcal{V}_i$ changes could be provided by correlations with other paleo signals. Marine sodium [*De Angelis et al.*, 1987] and dust [*Petit et al.*, 1990] records in Vostok ice core have been partly interpreted in terms of changes in the strength of meridian circulation. The only correlation between these records and the air content signal is observed around 160 kyr B.P. (when the same ice dating is used), where a dust peak and a negative pressure peak appear simultaneously. Nevertheless, the absence of correlation over the whole profile suggests no meridian circulation influence on the V record, but long-range meridian circulation and local wind in the Vostok region are not necessarily linked. The nitrogen isotopic composition (δ^{15}N) of the air trapped in ice cores results from gravitational separation during the firn densification. Therefore the δ^{15}N record in the Vostok ice core [*Sowers et al.*, 1992] could reflect some close-off depth variations. Close-off depth variations might be correlated to air content variations that would originate from close-off density variations. However, no clear correlation is seen between the δ^{15}N and V signals. It may be due to the fact that the δ^{15}N fractionation does not occur over the whole depth range of the firn but in the part of the firn column where only gas molecular diffusion takes place [*Sowers et al.*, 1992].

5. Conclusion

A unique high-resolution air content profile obtained from two Vostok deep ice cores reveals high-amplitude and short-term variations that question the traditional interpretation of air content signals in terms of ice surface elevation changes and thermal variations of porous volume at the depth of air isolation. Repeated large amplitude and very rapid ice thinning and thickening can hardly be considered in the central part of East Antarctica and would contradict the available ice sheet modeling results.

During the penultimate deglaciation (around 135 kyr B.P.), a 70-mbar pressure drop is observed. Five mbar should be subtracted from that number on account of differences in the amount of air lost during sample preparation. Atmospheric pressure directly influences the air content in ice, and atmospheric general circulation model simulations for both glacial and interglacial conditions indicate that up to 20 mbar [*Gates*, 1976*a*] can originate from an atmospheric pressure decrease. Ice sheet modeling results from *Huybrechts* [1990] suggest that the ice surface elevation in the Vostok region was 200 m higher during the penultimate interglacial than in the previous glacial maximum, which corresponds to a pressure decrease by about 20 mbar. The remaining 25 mbar could result from nonthermal $\mathcal{V}_i$ variations.

Present-day spatial variations of the ice porous volume at the depth of air isolation reveal important non-thermal $\mathcal{V}_i$ variations and suggest a porous volume-wind speed correlation. $\mathcal{V}_i$ changes of similar amplitude could explain the large pressure variations (about 100 mbar) observed during glacial periods, for which we have no indications of large ice surface elevation or atmospheric pressure changes. Using the $\mathcal{V}_i$ wind gradient suggested by the present-day spatial variations of $\mathcal{V}_i$, wind speed changes by about 7 m s^{-1} could explain the air content variations during glacial stages.

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