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Air content along the Greenland Ice Core Project core: A record of surface climatic parameters and elevation in central Greenland

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Abstract. We present here measurements of the air content of the ice, V, performed along the Greenland Ice Core Project (GRIP) ice core. The main features of the long-term trends are (1) a decrease of 13% between the last glacial maximum (LGM) and the earliest part of the Holocene, and (2) an increase of 8% during the Holocene. The results are discussed in terms of changes in atmospheric pressure, surface elevation and porosity at close-off. The V record contains a significant signal of past changes of surface elevation in qualitative agreement with ice sheet modeling simulations. It suggests a thickening of central Greenland during the transition from the LGM to the early Holocene, and a significant thinning through the Holocene period. It also stresses the large influence on past V variations of changes in ice porosity, which are not explained by the present-day spatial relationship with temperature and may reflect changes in other surface climatic parameters (like precipitation seasonality or wind stress). The potential role of temporal variations of atmospheric pressure patterns is also evaluated. Air content results in the GRIP ice older than 110 ka indicate values approximately in the same range as those observed during the last 40,000 years, with generally higher air content corresponding to isotopically warmer ice.

1. Introduction

The largest sintering process taking place on the Earth's surface occurs in the first 50–120 m below surface (mbs) of the melting-free areas of the polar ice sheets. At the end of this process (transformation of firn into ice), atmospheric air becomes trapped in the ice in the form of air bubbles.

The air content V thus enclosed in the ice depends on the atmospheric pressure and temperature prevailing at the ice formation site as well as on the ice porosity when the air bubbles close off. V measurements are generally performed on ice samples enclosing air that has been trapped in the ice as thousands of air bubbles during the enclosure process. The results, expressed in cubic centimeters STP per gram of ice, are related to pressure, temperature, and pore volume at close-off by [*Martinerie et al.*, 1992]

$$V = V_c \frac{P_c}{T_c} \frac{T_0}{P_0} \qquad (1)$$

where

V_c pore volume at close-off, in cubic centimeters per gram of ice;
P_c mean atmospheric pressure at the elevation of the close-off depth interval;
T_c firn temperature prevailing at the same depth interval;
P_0 standard pressure (1013 mbar);
T_0 standard temperature (273°K).

V measurements performed on ice recently formed at a large number of sites covering a wide range of atmospheric pressure, temperature, and snow accumulation rate conditions, lead to the following trends and conclusions [*Martinerie et al.*, 1992, 1994]:

1. The site mean V value decreases very significantly with the mean atmospheric pressure and hence with increasing site elevation.
2. The mean V_c value generally decreases with the site temperature at close-off. The best linear fit is obtained from [*Martinerie et al.*, 1994]

$$V_c = (6.95 \times 10^{-4}\, T_c) - 0.043 \qquad (2)$$

(correlation coefficient = 0.90). The significant variability around the regression line indicates that part of the V_c changes are not correlated with the close-off temperature. *Martinerie et al.* [1994] suggest that the snow packing by wind at the surface of the ice sheet may have an influence on the porosity at close-off and that V_c may also be correlated with wind speed.
3. At a given site, short-term V variations are observed. Their amplitudes can reach up to about 20% of V. They essentially reflect a seasonal type of V_c variability that has been associated either with the seasonal variations of the surface snow temperature [*Raynaud and Lebel*, 1979; *Raynaud and Whillans*, 1982] or with the fact that the high-density winter layers close their bubbles at shallower depth and thus prematurely isolate the summer layers from the free atmosphere [*Martinerie et al.*, 1992].

Because of the pressure dependence, V changes observed along several Antarctic and Greenland ice cores were interpreted in terms of past changes in the elevation of the ice formation site [*Budd and Morgan*, 1977; *Raynaud and Lebel*, 1979; *Raynaud et al.*, 1979; *Raynaud and Whillans*, 1981, 1982; *Herron and Langway*, 1987; *Kameda et al.*, 1990]. By correcting for the ice advection due to upslope origin, we may have thus access to past changes in ice thickness. On the other hand,

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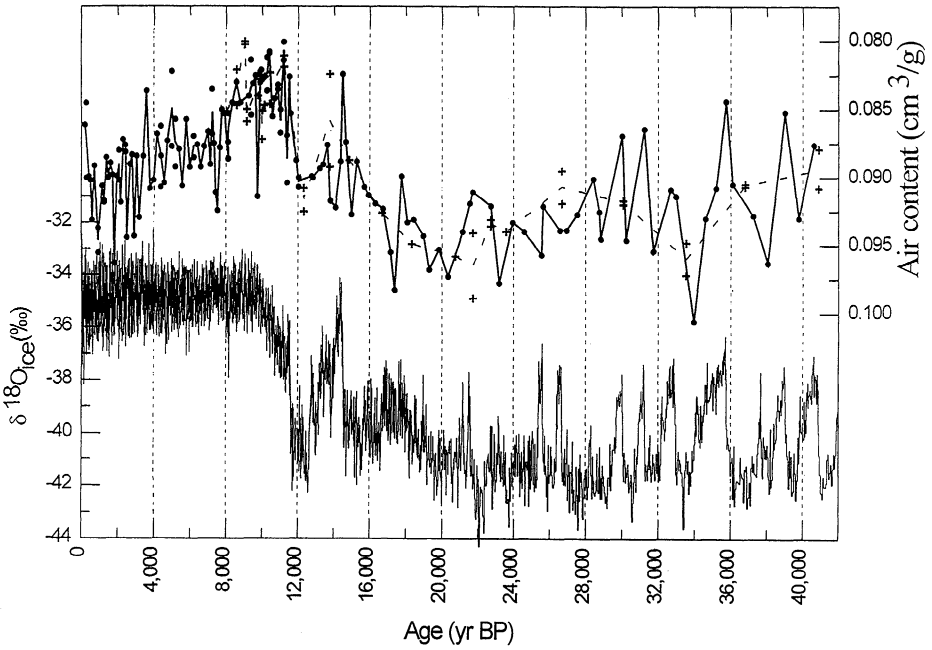

Figure 1. Record of GRIP air content (V) record versus age for the last 40,000 years. Results were obtained by methods A (dots and solid line) and B (crosses and dotted line) discussed in the text. The lines run through the averages at each depth level. The climatic ice isotopic record (reproduced with permission from *Nature* [*Dansgaard et al.*, 1993]; copyright Macmillan Magazines Limited) is also plotted for comparison. The two records can be directly compared, since the age difference between the trapped air and the ice has been taken into account. The ice chronology is from *Johnsen et al.* [1995].

more recent results obtained along the Vostok Antarctic core [*Martinerie et al.*, 1994] indicate that the interpretation of the V profile in terms of altitude is not straightforward: (1) past changes in atmospheric pressure fields over the ice sheets are still poorly constrained by current global circulation model results, and (2) a significant fraction of the geographic variations of V_c is not correlated with the close-off temperature (for instance, a wind influence on the pore volume in the firn may explain V_c changes of the order of 10%).

We present in this paper the air content results obtained along the Greenland Ice Core Project (GRIP) ice core for three periods: the Holocene, the last ice age–Holocene transition, and the Eemian ice. The results are discussed in terms of ice flow, atmospheric pressure, and porosity changes. They are also compared with different ice flow modeling experiments that have been performed for the Summit region in Greenland.

2. GRIP V Measurements and Results

The GRIP core provides new data for understanding the influence of the different parameters on past changes in ice air content. Measurements of V are obtained after extracting the air by melting and refreezing the ice under vacuum, and chromatographic measurement of the air peak (method A [*Chappellaz*, 1990]) or accurate air pressure and temperature measurements in a calibrated volume (method B [*Lipenkov et al.*, 1995]). This latter technique has a proven accuracy within ±0.6% and average precision of ±0.5% [*Lipenkov et al.*, 1995]. Measurements obtained with method A are a by-product of methane measurements [*Chappellaz et al.*, this issue]. The method provides reliable relative measurements with a precision within ±5%; nevertheless, because the gas temperature after extraction is not known, it was initially calibrated versus another accurate method used previously for measuring the Vostok V profile [*Martinerie et al.*, 1994]. For the present work, the chromatographic measurements of the air content have been performed with a new extraction line allowing simultaneous extraction of 7 samples under very similar temperature conditions. This improvement leads a priori to an enhanced reproducibility of the measurements. The results obtained by techniques A and B and presented in this paper are in good agreement (Figure 1).

GRIP V results cover two wide depth intervals. The first interval corresponds to the last 40,000 years and indicates long-term trends on which higher frequency variations are superimposed. The high-frequency variations show amplitudes generally less than 10% of the signal, and there are some more dramatic "events" (up to 15% of the signal).

The main features of the long-term V trend (Figure 1) are (1) a decrease of ~13% between the last glacial maximum (LGM) and the earliest part of the Holocene and (2) an increase of ~8% during the Holocene. The long-term trends are discussed in the two following sections in terms of changes in atmospheric pressure, elevation, and porosity at close-off. We should keep in mind that part of the observed V variations could arise from differences in the amount of air lost by cutting air bubbles or cavities when preparing the ice samples. Nevertheless, this effect is generally too small to question the existence of the major air content variations; it can at most modulate their amplitude. Thus the air lost during sample preparation could explain about 5 mbar of the deduced pressure decrease during a glacial-interglacial transition, as observed along the Vostok core [*Martinerie et al.*, 1994]. A few evaluations of air lost during ice sample preparation have also been performed in the case of the GRIP core. They indicate effects similar to those obtained at Vostok. In the discussion below we will assume that the uncertainity on the deduced pressure changes is about 5 mbar as a result of this air loss effect.

The second depth interval investigated includes Eemian ice (i.e., ice formed during the interglacial preceding the last ice age). We consider how V can provide information on the formation conditions for this ice whose stratigraphic continuity is currently under debate.

3. The Glacial to Holocene Transition

The air content decreases from about 0.095 $cm^3\ g^{-1}$ to about 0.083 $cm^3\ g^{-1}$ between the LGM and the Boreal period (early Holocene). It appears to be well in phase with the surface warming, as depicted by the ice isotopic record (Figure 1).

Interpreting this V change is not an easy task because the three parameters influencing V (pressure, temperature, and porosity at close-off) may all have changed contemporaneously during the shift from glacial to interglacial conditions. Our approach here is first to evaluate the best estimates for temperature, atmospheric pressure, and elevation changes and their influence on V. Then we discuss the change in porosity conditions necessary to account for the part of the glacial to interglacial V change which remains to be explained.

3.1. Sensitivity of V to Glacial-Interglacial Temperature, Atmospheric Pressure, and Surface Elevation Changes

The amplitude of the LGM to Holocene surface warming, as deduced from the GRIP and Greenland Ice Sheet Project 2 (GISP2) ice isotopic (δ) records by using the spatial relationship between temperature and δ observed today at the surface, has been recently questioned by the interpretation of the borehole temperature records [*Cuffey et al.*, 1995; *Johnsen et al.*, 1995]. These last records indicate that the mean surface temperature, at the time and place the snow was deposited, increased by about 20°C (or slightly more) from the LGM to early Holocene. This is about twice or more the estimate obtained from the spatial present-day δ-T relationship. By assuming that the current spatial V_c-T_c relationship (equation (2)) is also valid during the LGM and the transition to Holocene, we find that a 20°C (or 10°C) warming would lead to a slight V increase from 0.095 to 0.098 (or 0.0965) $cm^3\ g^{-1}$, a trend opposite to that observed between the LGM and the early Holocene.

On the other hand, part of the V change observed could be due to higher atmospheric pressures at constant elevation during the glacial maximum. A comparison has been recently undertaken between the glacial-interglacial differences in atmospheric pressure at the surface of the polar ice sheets, as obtained from certain general circulation models participating in the Paleoclimate Modeling Intercomparison Project (PMIP) [*Joussaume and Taylor*, 1995]. The results suggest again an opposite effect: the simulated atmospheric pressure for the LGM in the GRIP site area, is about 15 mbar lower than present-day pressure (G. Krinner et al., manuscript in preparation, 1997). Nevertheless, we should keep in mind that these experiments are not properly designed for simulating the climate over the ice sheets and that the simulations do not cover the early Holocene. Therefore the results mentioned above should be considered with caution.

Finally, as will be discussed in section 5, modeling of past changes in ice flow pattern and ice thickness indicates a 120- to 250-m increase of surface elevation in this region of Greenland during the LGM-Holocene transition. Simulations of atmospheric general circulation models for glacial conditions suggest similar pressure-elevation gradients as for the present-day situation (G. Krinner et al., manuscript in preparation, 1997). If a range of 9.5–15 mbar per 100 m for this gradient (see section 4) is used, the 120- to 250-m increase in elevation would correspond to a pressure drop between 11.5 and 37.5 mbar. Such a pressure decrease (at constant V_c and T_c) would produce a V decrease of 1.7–5.7%. If we take into account a 15-mbar increase of atmospheric pressure at constant elevation, as suggested by general circulation models, then the net pressure change (including changes in elevation and atmospheric patterns) between the LGM and early Holocene will range from +3.5 to −22.5 mbar. Such pressure range would correspond to a maximum V decrease of 3.5%.

Thus according to our present knowledge, both long-term changes in surface temperature and atmospheric pressure between LGM and early Holocene are not candidates to explain even part of the observed V increase. We have then to turn toward the influence of a glacial-interglacial change in surface elevation, which would explain up to a 6% V decrease. This is less than half of the observed 12.6% V drop.

3.2. Implications on Close-Off Porosity

We should, then, consider the possibilities of V_c changes which cannot be explained by the spatial V_c-T_c linear relationship (equation (2)). Although not yet quantitatively explained, this linear relationship is most likely due to the firn densification processes, which are essentially dependent on temperature and snow accumulation rate, and to the fact that temperature and accumulation rate are strongly related. On the other hand, possible causes for the large noise observed under present-day conditions have been discussed [*Martinerie et al.*, 1992, 1994]. It appears that the densification processes at close-off could also be influenced by the snow characteristics found in the firn upper layers, which in turn depend on several atmospheric parameters. For instance, part of the V_c variability could reflect the effect of the snow packing by the wind at the surface of the ice sheet, and V_c seems to decrease with increasing wind speed w, especially for $w \geq 6\ m\ s^{-1}$ [*Martinerie et al.*, 1994]. Also, important seasonal variations of V (up to 25% of the yearly V minimum) are observed at several ice core sites [*Raynaud and Lebel*, 1979; *Raynaud and Whillans*, 1982; *Martinerie et al.*, 1992], which reflect the seasonal variability in snow densities (the porosity of the summer layers is larger than that of the winter layers [*Schwander and Stauffer*, 1984]). Furthermore, as was mentioned in section 1, the winter layers at Summit (Greenland) can close at shallower depth than the summer ones and prematurely isolate the summer layers found just below [*Martinerie et al.*, 1992]. Such seasonal processes would lead to an enhanced porosity at close-off of the summer layers. During the climatic shift from LGM to early Holocene conditions, the wind stress at the surface of the ice sheet may have changed, but it would have had to increase very significantly to explain more than half of the observed V decrease during this period. This is not supported by the results of the PMIP comparison mentioned above (see section 3.1), which indicate only low or moderate wind speeds and no very significant changes between the LGM and today simulations (G. Krinner et al., manuscript in preparation, 1997). On the other hand, we can expect that any changes in the winter to summer precipitation ratio during the glacial to Holocene transition may have influenced the porosity at close-off. An increase in this ratio (increasing winter precipitations relative to summer ones) during the deglaciation would lead to a decrease of V_c and hence of V. We note that such a change in precipitation seasonality (increasing winter to summer ratio during warming) would also affect the ice isotopic paleothermometry and lead, as from borehole temperature profiles, to a larger glacial-interglacial temperature change than that deduced using the spatial δ–surface temperature relationship.

In summary, there are mechanisms able to account at least qualitatively for a significant decrease of V_c between the LGM and early Holocene. This decrease combined with an increase in elevation of the ice formation site is currently the most plausible explanation for the V decrease observed during the glacial-interglacial warming.

4. The Holocene Record

We first note that the mean V value measured on the GRIP ice for the last millennia is 0.090–0.091 $cm^3\ g^{-1}$. This is in good agreement with the V range (0.092–0.093 $cm^3\ g^{-1}$) deduced from equations (1) and (2) for present-day conditions (at the GRIP site: P_c = 660–670 mb; T_c = 241.5°K), and the mean V value of 0.091 $cm^3\ g^{-1}$ [*Vandervaere*, 1991] measured on air trapped under recent conditions at approximately 160 m depth in the EUROCORE ice core, another core drilled at the same site as GRIP.

The mean V values (Figure 1) increase from about 0.083 $cm^3\ g^{-1}$ 10 kyr ago to about 0.090–0.091 $cm^3\ g^{-1}$ during the last millennia. This contrasts with the ice isotopic record ($\delta^{18}O$ curve in Figure 1), which indicates no similar surface temperature trend over the Holocene period. Because the Holocene period experienced climatic conditions fairly similar to those prevailing today (in contrast with the glacial conditions), we will first assume that the mean porosity at close-off during the Holocene depends mainly on temperature as today. Then, from equations (1) and (2), the smooth V increase should reflect an increase of about 50 mbar of the atmospheric pressure prevailing at the ice formation site between the ice formed 10 kyr ago and today. Such pressure change could be due to a decrease in elevation of the ice formation site and/or an increase in atmospheric surface pressure over the interior of Greenland.

The pressure-elevation gradient ($\partial P/\partial Z$) in the GRIP area, even today, is not well known. The hydrostatic equation leads to $\partial P/\partial Z$ = 9.5 mbar/100 m. On the other hand the 1993 pressure data of four automatic weather stations (AWS) located in the GRIP area (at elevations of 3185, 3205, 3105, and 3100 m) reveal mean annual gradients in the range 11 to 15 mbar per 100 m (data from University of Wisconsin). Taking into account a range of 9.5–15 mbar per 100 m, the 50-mbar increase, if only due to an elevation effect, would correspond to a lowering of the ice formation site by ~530–330 m. Ice sheet modeling simulations also predict a lowering, but one ranging only between 220 and 10 m (see Table 1 and section 5). We note at this stage that the present location of the GRIP site being on the ice divide, a lowering of the close-off elevation necessarily implies a change in the geometry of this part of the ice sheet.

On the other hand, the atmospheric surface pressure may have increased in the interior of Greenland during the Holocene, indepedently of any surface elevation change. However, on the basis of an estimate of only about 15 mbar of atmospheric surface pressure changes in the GRIP site area linked with the drastic transition from glacial to interglacial climatic conditions (see section 3), we can assume that any long-term variation in mean atmospheric pressure at constant elevation during the Holocene (a period with much more stable climatic conditions) would have been small compared with the global 50-mbar pressure change derived from V data.

Finally the assumption, that V_c was dependent only on T_c during all the period covering the Holocene, as it is today, may be wrong. As was explained above, other parameters can affect V_c. For instance, a decrease of the mean wind strength, or more likely a moderate decrease in the winter to summer precipitation ratio, between the early Holocene and today may have contributed, together with the surface lowering, to the observed increase in air content.

In conclusion, the Holocene air content record suggests strongly that various climate parameters may have changed significantly over central Greenland between the Boreal period (early Holocene) and today. Because of the surface lowering, the apparently constant isotopic temperature may in fact reflect an isotopic cooling at constant elevation, and the winter to summer precipitation ratio may have been reduced in relation to the cooling trend.

5. Comparison With Ice Sheet Modeling

The air content data suggest that the elevation of the ice formation site found in depth at the GRIP site increased during the glacial-Holocene climatic transition and then decreased during the Holocene period, but with present-day elevation still higher than that during the glacial period. Straightforward qualitative explanations include (1) the fast thickening of the central part of the Greenland ice sheet in response to the increase in accumulation rate during the transition; (2) the retreat of the margins, due to sea level rise and to ablation rate increase, which could cause a wave of thinning propagating upward and eventually a change in the divide position on which the GRIP site is located today; and (3) the response of ice flow to temperature changes and to changes in location of soft Wisconsin ice within the ice sheet. The climatic warming should lead to a thinning during the Holocene, while the change in ice stiffness should induce a thickening. Both processes have a delayed effect because only the deeper part of the ice sheet is really involved in ice flow, and either temperature change or stiffness transition needs time to reach these depths.

Two types of models have been used to quantify these different mechanisms: (1) models based on a succession of steady state profiles as snapshots of Greenland at different times [*Anandakrisnan et al.*, 1994; *Cuffey et al.*, 1995; *Johnsen et al.*, 1995], and (2) three-dimensional (3-D) thermomechanical models [*Letréguilly et al.*, 1991; *Huybrechts et al.*, 1991; *Fabre et al.*, 1995; *Greve and Hutter*, 1995; *Ritz et al.*, 1997]. Most of these models are compared by *Ritz et al.* [1997], and the results concerning surface elevation changes are summarized in Table 1.

In the first type of models the change in margin position is prescribed and has an important effect on the ice divide elevation and position (see, for instance, the results of *Cuffey et al.* [this issue] in Table 1). The 3-D thermomechanical models have a rather different approach because the position of the margin is not prescribed but computed interactively as a function of ice flow, ablation rates, and sea level.

Table 1. Changes in Surface Elevation in the Summit Area as Deduced From Different Ice Flow Modeling Experiment

	Surface Elevation Difference		
Model Reference	LGM-Present	Boreal-Present	LGM-Boreal
Anandakrishnan et al. [1994]*	−50	+200	−250
Cuffey et al. [this issue]*			
ΔL = 50 km	−210	+10	−220
ΔL = 100 km	−100	+40	−140
ΔL = 200 km	+90	+220	−130
Johnsen et al. [1995]*	+70	+190	−120
Letréguilly et al. [1991]†	−150	+30	−180
Fabre et al. [1995]† (thickness differences)	−200	+40	−240
Ritz et al. [1997]†	−210	+15	−225

Cuffey et al. and Johnsen et al. assume a large glacial-interglacial temperature change as deduced from borehole temperature profiles. ΔL is the amplitude of margin migration.

*Ice sheet profiles obtained with prescribed position of margin.

†Three-dimensional thermodynamical models with margin position computed interactively.

An interesting point is that the 3-D models simulate the margin position retreat between the Boreal period and today with an amplitude of 100–200 km. This amplitude range is the same as the one prescribed in the steady state profiles [*Anandakrishnan et al.*, 1994; *Cuffey et al.*, 1995; *Johnsen et al.*, 1995]. However, in the 3-D simulations the ice divide lowering between the Boreal and Present periods is only 20 to 30 m, indicating that the margin retreat does not affect the central part of Greenland.

Explanations of the discrepancy between the two types of models could be either that in the steady state profiles the role of ablation rate on both the margin migration and the profile of the ice sheet is not well accounted for, or that the grid of the 3-D models (20–40 km) is too large to correctly simulate the margins. Finally, we must note that in all the 3-D simulations the climatic forcing has been derived from isotopic signal with such coefficients that the temperature change from glacial to interglacial is about 10°C. As was mentioned in section 3.1, recent interpretations of the borehole temperature profiles at both GRIP [*Johnsen et al.*, 1995] and GISP [*Cuffey et al.*, 1995] show that the amplitude of temperature change must have been much larger (20°C). If we used such large changes in a 3-D model, we could expect a larger thinning during the Holocene and preliminary experiments indicate a 100-m decrease. A change in the location of soft glacial ice should also result in an enhanced thinning.

In conclusion, the model results are generally in good agreement with the GRIP air content record in terms of trends and phasing. They currently provide the most reliable range for past ice thickness changes and thus constrain the part of the V variations to be attributed to surface elevation changes.

6. Air Content in the "Eemian" Ice

We performed 67 V measurements on ice found between 2780 and 2910 mbs. This depth interval corresponds to ice found below the 110 ka horizon, and most likely includes Eemian ice, although the stratigraphic order of the layers found at these depths is seriously questioned [see *Chappellaz et al.*, this issue]. Our V data should provide additional information concerning the conditions under which this ice was formed.

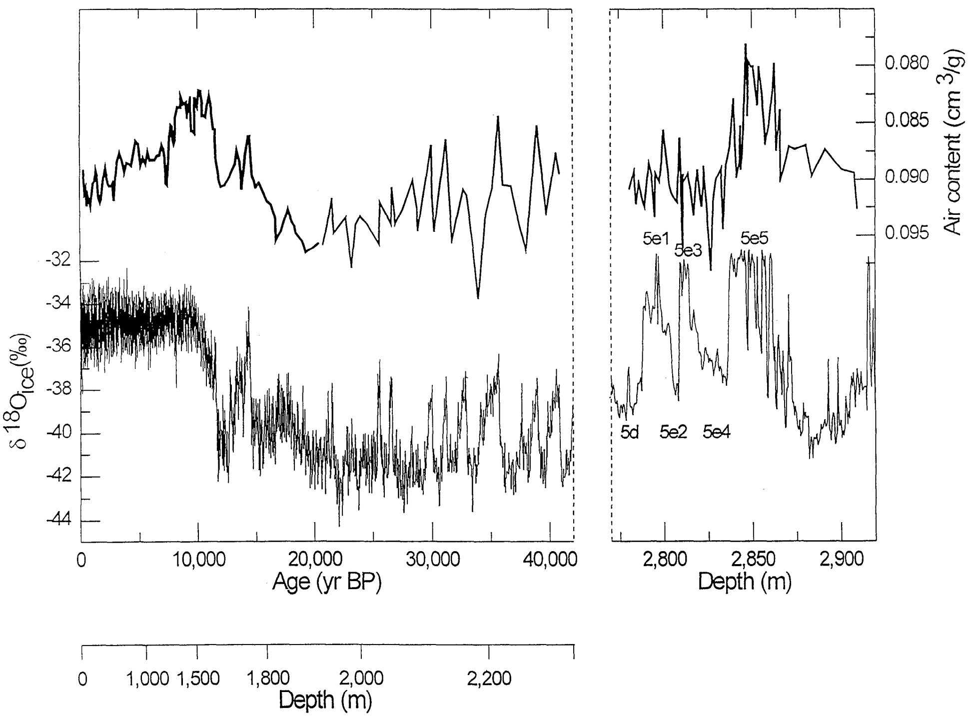

Figure 2. (top) GRIP V record corresponding to the two depth intervals: 122–2280 m and 2780–2910 m. In the 0–20 kyr period the V data are represented by a running average over three consecutive depth levels. (bottom) Climatic ice isotopic profile (reproduced with permission from *Nature* [*Dansgaard et al.*, 1993]; copyright Macmillan Magazines Limited), shown for comparison.

The results indicate V values approximately in the same range as the values found during the last 40,000 years (Figure 2) with generally, but not systematically, lower air content corresponding to isotopically warmer ice. Low V values between about 2840 and 2862 m are slightly lower than during the early Holocene. They may consequently correspond to surface conditions close to those prevailing during an interglacial period. Most of the remaining V values in the interval 2780–2910 mbs are similar to the air content of the last glacial period (between about 20 and 40 ka) or of the most recent part of the Holocene.

As was pointed out above, the chronological identification of the ice layers corresponding to these different depth intervals is difficult. Initially, the ice found between 2790 and 2860 m [*GRIP Project Members*, 1993] was thought to correspond to the last interglacial period (corresponding to the marine isotope stage 5e) and the ice isotopic record has been interpreted in terms of climate instability during this period with the identification of different substages: 5e1 to 5e5 (see Figure 2). *Chappellaz et al.* [this issue] use CH_4 and $\delta^{18}O$ of O_2 records from Antarctic and Greenland ice as a clue for stratigraphic disturbances in this part of the GRIP core. They suggest that the GRIP ice found in stages 5e1 and 5e3 and the shallowest part of 5e5 would be in fact from the same time period, corresponding to the middle of the marine isotope stage (MIS) 5e. The cold periods of the GRIP "Eem", noted 5e2 and 5e4, most probably correspond to MIS-5d, or possibly MIS-7, according to their analysis. Our V results are not in contradiction with this interpretation of the GRIP stratigraphy. Indeed, the corresponding periods indicate similar air content. However, the existence of high-frequency V variations (as shown for instance by the GRIP Holocene record (Figure 1)) does not allow us to use the air content as a stratigraphic tool like CH_4 or $\delta^{18}O$ of O_2.

7. Conclusions

Part of the trend observed along the GRIP air content record reflects and confirms the fast thickening of the central part of the Greenland ice sheet in response to the increase in accumulation rate during the LGM to Holocene transition, as well as the subsequent thinning between the early Holocene and present as a response to the glacial-interglacial warming of the ice margin retreat, ablation rate increase, and ice flow.

In the case of the LGM to Holocene transition, less than half of the V decrease can be explained by the ice sheet thickening. A change of the mean close-off porosity reflecting an increase in the winter to summer precipitation ratio appears to be a serious candidate for explaining most of the rest of the V decrease. Such a change in precipitation seasonality would also affect the ice isotopic paleothermometry and lead to a glacial-interglacial warming larger than the one deduced by using the current spatial δ–surface temperature relationship.

The Holocene air content record suggests strongly that various climate parameters may have changed significantly over central Greenland between the Boreal period (early Holocene) and today. Because of the lowering of the surface, the apparently constant isotopic temperature may in fact reflect an isotopic cooling at constant elevation, and the winter to summer precipitation ratio may have been reduced in relation with the cooling trend.

Finally, we did also measure air content in the GRIP ice older than 110 ka. The results indicate V values approximately in the same range as for the last 40,000 years with, generally, higher air content corresponding to isotopically warmer ice.

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