

Factors controlling nitrate in ice cores: Evidence from the Dome C deep ice core

Regine Röthlisberger, Manuel A. Hutterli,¹ and Stefan Sommer

Climate and Environmental Physics, University of Bern, Bern, Switzerland

Eric W. Wolff and Robert Mulvaney

British Antarctic Survey, Natural Environment Research Council, Cambridge, England

Abstract. In order to estimate past changes in atmospheric NO_x concentration, nitrate, an oxidation product of NO_x , has often been measured in polar ice cores. In the frame of the European Project for Ice Coring in Antarctica (EPICA), a high-resolution nitrate record was obtained by continuous flow analysis (CFA) of a new deep ice core drilled at Dome C. This record allows a detailed comparison of nitrate with other chemical trace substances in polar snow under different climatic regimes. Previous studies showed that it would be difficult to make firm conclusions about atmospheric NO_x concentrations based on ice core nitrate without a better understanding of the factors controlling NO_3^- deposition and preservation. At Dome C, initially high nitrate concentrations (over 500 ppb) decrease within the top meter to steady low values around 15 ppb that are maintained throughout the Holocene ice. Much higher concentrations (averaging 53 ppb) are found in ice from the Last Glacial Maximum (LGM). Combining this information with data from previous sampling elsewhere in Antarctica, it seems that under climatic conditions of the Holocene, temperature and accumulation rate are the key factors determining the NO_3^- concentration in the ice. Furthermore, ice layers with high acidity show a depletion of NO_3^- , but higher concentrations are found before and after the acidity layer, indicating that NO_3^- has been redistributed after deposition. Under glacial conditions, where NO_3^- shows a higher concentration level and also a larger variability, non-sea-salt calcium seems to act as a stabilizer, preventing volatilization of NO_3^- from the surface snow layers.

1. Introduction

Considering the importance of NO_x (NO and NO_2) for tropospheric chemistry and taking advantage of NO_x being a precursor of NO_3^- , attempts have been made to reconstruct past atmospheric NO_x by NO_3^- measurements in polar ice cores. Polar ice sheets are well-established archives of paleoclimatic information. While some species measured in ice cores can be used to infer directly past atmospheric composition, it is more difficult to draw conclusions for those particulate and reactive gas species where depositional and postdepositional processes overlay the changes in the atmosphere (e.g., HNO_3).

Although NO_3^- data from polar ice cores already exist, it remains difficult to interpret them [Wolff, 1995]. Some features in the NO_3^- records can be explained, for example, the clear increase since 1940 seen in Greenland ice cores, which is attributed to NO_x emissions from industrialized countries. Others, such as the difference in Greenland and Antarctic NO_3^- records, are only vaguely understood.

Many sources for NO_x and therefore NO_3^- have been discussed [Legrand and Kirchner, 1990; Wolff, 1995]. Meteorite impacts, supernovae, and solar modulation (sunspot cycle, solar proton events) seem to have a minor impact on NO_3^- in Antarctica. NO_x production in the stratosphere and tropospheric lightning are considered to be the main sources [Wagenbach *et al.*, 1998]. However, recent studies of atmospheric NO_y (NO_x , HNO_3 , N_2O_5 , particulate and organic nitrates) concentrations showed considerable amounts of organic nitrate [Jones *et al.*, 1999; Dibb *et al.*, 1998], which further complicates the interpretation of ice core NO_3^- data.

¹Now at Department of Hydrology and Water Resources, University of Arizona, Tucson.

Before past changes in atmospheric chemistry can be derived from NO_3^- records, the preservation of NO_3^- in ice cores has to be examined. Recent studies have shown that depositional and postdepositional processes have a strong influence on NO_3^- concentrations preserved in snow [Neubauer and Heumann, 1988a; Wolff, 1995; Mulvaney et al., 1998]. Substantial postdepositional losses have been reported from low-accumulation sites [Wagnon et al., 1999; Legrand et al., 1996]. Also, an influence of high sulfuric acid (H_2SO_4) concentrations, originating from volcanic eruptions, has been found in both Antarctic and Greenland ice cores [Laj et al., 1993; Legrand and Kirchner, 1990; Wolff, 1995], leading either to less formation of NO_x (a precursor of NO_3^-) in the atmosphere or to a displacement of NO_3^- after deposition in the ice. On the other hand, an irreversible deposition of NO_3^- related to high levels of continental dust has been suggested for ice of the Last Glacial Maximum (LGM) [Legrand et al., 1999]. However, no detailed study with high-resolution data has been done so far.

Deposition and preservation mechanisms of NO_3^- in snow can be analyzed through direct studies of the atmosphere and of the air-snow transfer [Mulvaney et al., 1998; Dibb et al., 1998; Munger et al., 1999] combined with transfer models. However, studies of the way in which NO_3^- in ice cores changes under different conditions can also give clues about the processes involved.

Here we present high-resolution data from Dome C (75°06'S, 123°24'E, 3233 m above sea level, -53.5°C mean annual temperature), a low-accumulation site (2.7 $\text{g cm}^{-2} \text{ yr}^{-1}$) on the East Antarctic plateau, that allow a more detailed study of the different mechanisms involved in NO_3^- deposition and conservation. The core was drilled in the frame of the European Project for Ice Coring in Antarctica (EPICA) during the 1997/1998 and 1998/1999 field seasons. Of the 786.4 m recovered, 585.2 m have been processed, and they cover approximately 30,000 years. The remaining 200 m of ice was too brittle to be processed yet and therefore has been left in a storage container at Dome C for later analyses.

2. Methods

The high resolution of the data is achieved by continuous flow analysis (CFA) [Röthlisberger et al., 2000]. Measurements were done in a processing line at Dome C during 1997/1998 and 1998/1999 field seasons. Along the whole core, subsections of $3.2 \times 3.4 \text{ cm}^2$ and 1.1 m length were melted slowly from one end, and the meltwater was continuously drained off into a heated laboratory for online analysis. NO_3^- was measured using an absorption spectrometry method developed by McCormack et al. [1994], based on reduction of NO_3^- to NO_2^- (nitrite) with copperized cadmium and subsequent diazotization with sulfanilamide and naphthylethylenediamine (NED) to form a colored complex. Thus the measured concentrations include both NO_3^- and NO_2^- .

However, owing to the low NO_2^- concentrations in polar snow [Legrand and De Angelis, 1995], the influence of NO_2^- is negligible. The resolution is approximately 1 cm with a detection limit of 1 ppb ($\mu\text{g/kg}$) and a linear range exceeding 1000 ppb, which is ample for Antarctic ice samples. The analytical procedure is described in more detail by Röthlisberger et al. [2000]. Owing to technical problems, no NO_3^- data are available in the depth interval from 123 to 320 m.

3. Results

The whole NO_3^- record obtained from the EPICA ice core is shown in Figure 1, together with non-sea-salt Ca^{2+} (nss- Ca^{2+}), calculated as $[\text{nss-Ca}^{2+}] = [\text{Ca}^{2+}] - 0.038[\text{Na}^+]$ using the seawater ratio of 0.038 [Bowen, 1979]. We used total Na^+ for this calculation, although some Na^+ is of crustal origin during the LGM. Thus nss- Ca^{2+} is slightly underestimated. Even so, over 90% of the total Ca^{2+} is nss- Ca^{2+} in the LGM, so that Ca^{2+} is considered to be a reliable tracer of continental dust during this period. As an indicator of climatic stages, deuterium data (J. Jouzel et al., A new 27 kyr high-resolution East Antarctic climate record, submitted to *Geophysical Research Letters*, 2000) are added to the plot. The isotope record shows the gradual increase in temperature from the last glacial maximum (LGM) toward the Holocene, while nss- Ca^{2+} shows a strong decrease from the LGM to the Holocene, opposite to the isotope record. The dating of the record is based on flow modeling and comparison of reference horizons with other well-dated records (J. Schwander et al., A tentative chronology of the EPICA Dome Concordia ice core, submitted to *Geophysical Research Letters*, 2000).

As seen in other ice cores of the East Antarctic plateau (e.g. Vostok [Legrand et al., 1988], Dome F [O. Watanabe et al., 1999]), the mean NO_3^- concentration was several times higher during the LGM than during the Holocene. However, this change in concentration does not necessarily reflect a corresponding change in atmospheric NO_3^- load, but rather a change in the depositional and postdepositional mechanisms. Present NO_3^- concentration in summer surface snow exceeds the highest concentrations seen in the LGM, but only a minor fraction is preserved. The high surface levels drop within the top 5 to 10 cm depth to values slightly above the mean Holocene concentrations and reach mean Holocene concentrations by a depth of approximately 50 cm (Figure 2). Possible processes for this substantial loss are volatilization of HNO_3 from the surface snow layer and photolytic decomposition [Neubauer and Heumann, 1988b; Honrath et al., 1999].

Another prominent feature of the high-resolution data is the high variability of the NO_3^- concentration and the coincidence of high NO_3^- peaks with high nss- Ca^{2+} peaks (Figure 3). This is observed clearly in ice of the LGM, when nss- Ca^{2+} concentrations and variability were high. Also in the Holocene and the transition, nss-

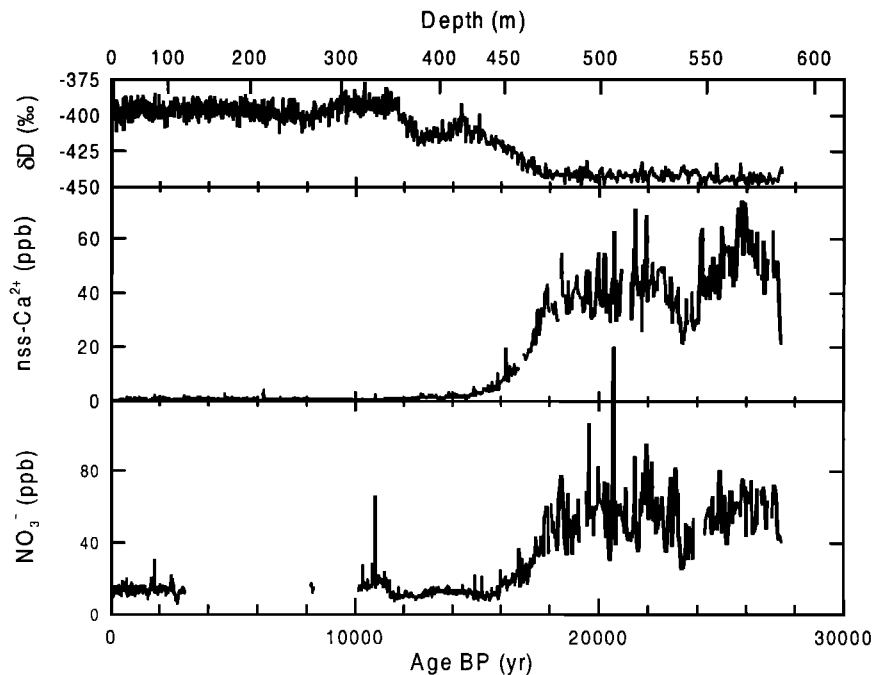


Figure 1. NO_3^- , nss-Ca^{2+} and δD record (bag averages) from Dome C. Owing to technical problems during 1997/1998 field season, no NO_3^- data are available from 123 to 320 m.

Ca^{2+} peaks coincide with NO_3^- , but due to the missing data from 123 to 320 m, only a few events have been recorded. A relation between nss-Ca^{2+} and NO_3^- has been suggested recently by *Legrand et al.* [1999], who proposed that nss-Ca^{2+} prevents NO_3^- from being lost. This hypothesis will be discussed with respect to the high-resolution data presented here.

4. Discussion

In order to investigate possible processes influencing NO_3^- concentrations in ice, the high-resolution NO_3^- record was considered in the light of the various parameters that may affect it, namely, accumulation rate, temperature, and the major impurities found in the ice [*Legrand and Mayewski, 1997*]. A possible effect of al-

titude on NO_3^- concentrations in Antarctic snow cannot be distinguished from the effects of accumulation rate and temperature. However, the relationship between NO_3^- and altitude [*Mulvaney and Wolff, 1994*] is weaker than that of NO_3^- versus temperature. Since there is also a simple physical mechanism for a temperature effect on nitrate concentrations, we treat it as a more important determinant, while accepting that altitude could also play a role.

Particular features that must be explained are the much higher concentrations in the LGM, the high vari-

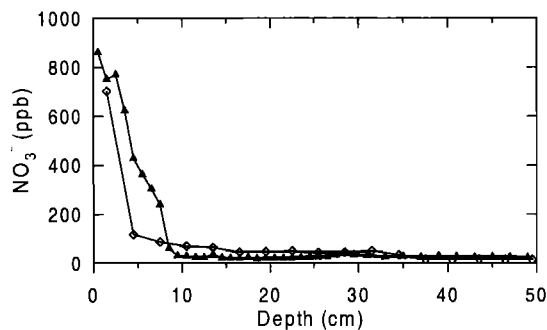


Figure 2. NO_3^- concentration profiles of the top 50 cm at Dome C. The squares and triangles correspond to two different pits, excavated and analyzed in January 1999.

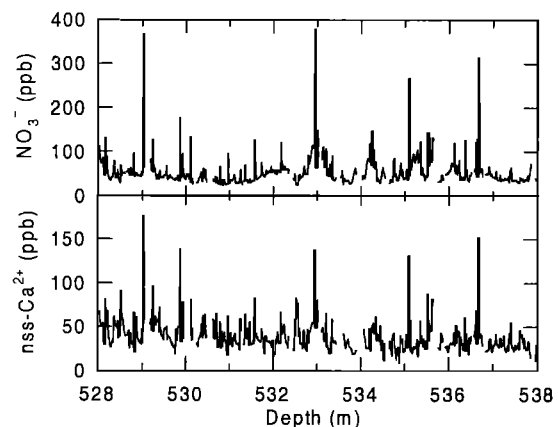


Figure 3. High-resolution NO_3^- and nss-Ca^{2+} data (one data point every 2 mm). According to a tentative timescale (*J. Schwander et al., A tentative chronology of the EPICA Dome Concordia ice core, submitted to Geophysical Research Letters, 2000*), this interval corresponds to almost 900 years at 23,000 years B.P.

Table 1. Nitrate Concentrations and Holocene Accumulation Rates for Different Antarctic Sites

Station	Holocene, ppb	LGM, ppb	Accumulation Rate, $\text{g cm}^{-2}\text{yr}^{-1}$	Reference
Dome C	15	53	2.7	this study
Dome C	19	39	3.4	[Legrand and Delmas, 1988]
Vostok	16	87	2.3	[Legrand et al., 1988]
Dome Fuji	20	80	2.8	[O. Watanabe et al., 1999]
Byrd	38	49	10	[Palais and Legrand, 1985]
Taylor Dome	51/25	19*	6.5	CCRC [†] (unpublished data, 1996)
South Pole	100		8.0	[Legrand and Kirchner, 1990]
Dronning Maud Land	82		7	BAS [‡] (unpublished data, 2000)
Dronning Maud Land	44		15.5	BAS [‡] (unpublished data, 1993)
Berkner Island	56		23	BAS [‡] (unpublished data, 1998)

Nitrate concentrations at Taylor Dome show major concentration changes from the early to the late Holocene, presumably due to considerable changes in accumulation rate. The values given are calculated for the period from 0 to 6000 years B.P. and 9000 to 11,500 years B.P., respectively.

*Concentrations during the LGM vary from 15 to 60 ppb. Data are available at <http://www.ngdc.noaa.gov/paleo/icecore/antarctica/antarctica.html>.

[†]Climate Change Research Center, University of New Hampshire

[‡]British Antarctic Survey, Cambridge, England

ability, and the difference between Dome C and other Antarctic sites.

4.1. Accumulation Rate

Under present-day conditions, NO_3^- concentrations in polar snow seem to be related to the accumulation rate. At low-accumulation sites such as Dome C, the typical NO_3^- profile of the top meter shows a sharp decrease with depth and stable concentrations with little variation thereafter (Figure 2) [Mayewski and Legrand, 1990]. Munger et al. [1999] hypothesized that changes in surface/volume ratio contributed to release of HNO_3 in deeper snow layers and subsequent uptake by the fine-grained snow at the surface. However, the concentration of fresh snow at Dome C is unknown, leaving the source of the abundant NO_3^- in surface snow unclear. The decrease in NO_3^- concentration in the upper snow layers is attributed to postdepositional concentration changes (uptake and release and/or photolytic decomposition). At sites with higher accumulation rates, the typical pit profile looks quite different [Legrand and Kirchner, 1990; Isaksson, 1994; Mulvaney et al., 1998]; the surface concentrations are lower than in the low-accumulation sites, but they decay less, so that generally higher mean concentrations and annual fluctuations are seen below the surface layer. In analogy to H_2O_2 , which shows a similar behavior, one would expect that less NO_3^- is lost with higher accumulation rates [Bales, 1995; McConnell et al., 1998].

If we apply this in a qualitative way to the Dome C record, the low accumulation rate of the LGM ($1.5 \text{ g cm}^{-2} \text{ yr}^{-1}$, (J. Schwander et al., A tentative chronology of the EPICA Dome Concordia ice core, submitted to *Geophysical Research Letters*, 2000)) should then lead

to lower NO_3^- concentrations during the LGM than in the Holocene ($2.7 \text{ g cm}^{-2} \text{ yr}^{-1}$), that is, to a completely different shape of the NO_3^- record. Although accumulation rate and presumably seasonality of precipitation are involved in the processes of NO_3^- deposition under present-day conditions, they cannot explain the high NO_3^- concentrations of the LGM. However, the large difference between Holocene and LGM concentration levels is seen at low-accumulation sites only (Table 1). It is not seen at Byrd Station with a much higher accumulation rate.

An interesting intermediate case is that of Taylor Dome. This site shows a strong decrease in concentrations between about 7 and 12 kyr, in line with a strong reported decrease in accumulation rate; in the early Holocene the NO_3^- concentration is as low as 10 ppb when the accumulation rate falls below about $3 \text{ g cm}^{-2} \text{ yr}^{-1}$ according to estimates based on ^{10}Be data [Steig et al., 2000]. It appears as if NO_3^- at Taylor Dome is not subject to major loss under present-day accumulation rates, but was so in the early Holocene. The values then increase back up in the late glacial period, but show much variability.

4.2. Temperature

Another factor which potentially influences NO_3^- concentration in snow is temperature. At colder temperatures the ice-air concentration ratio of HNO_3 is shifted toward higher snow concentrations at a given atmospheric concentration [Abbatt, 1997], that is, a tendency of higher uptake at lower temperatures. In addition, colder temperatures decrease the exchange of HNO_3 between ice and interstitial air, leading to a higher variability preserved in the ice. Figure 4 shows that tem-

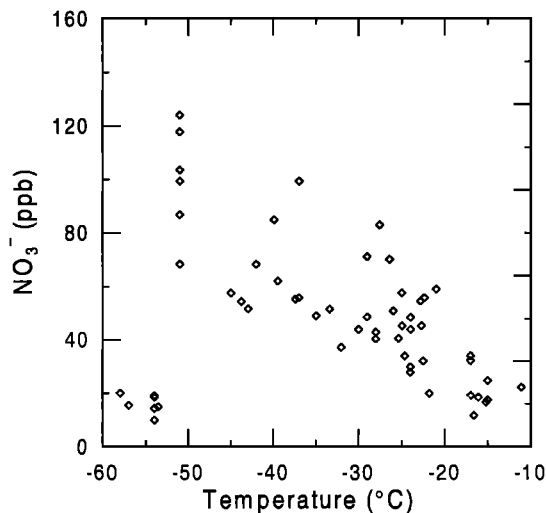


Figure 4. NO_3^- concentrations from different Antarctic sites versus present-day mean annual temperature. The data points at temperatures below -53°C correspond to low-accumulation sites such as Dome C, Dome F, and Vostok. Data are from *Mulvaney and Wolff* [1994], *O. Watanabe et al.* [1999], *K. Watanabe et al.* [1999], *Stenberg et al.* [1998], *Kreutz and Mayewski* [1999], and *Curran et al.* [1998], as well as British Antarctic Survey (unpublished data, 2000).

perature is a very strong indicator for NO_3^- concentrations in present-day Antarctic snow, as long as the accumulation rate is high enough to limit postdepositional losses. It seems as if, under present conditions, the effect of lowering the accumulation rate dominates the effect of lowering temperature at accumulation rates below $5\text{ g cm}^{-2}\text{ yr}^{-1}$.

Another reversibly deposited species, formaldehyde (HCHO), showed an elevated concentration level as well as high peaks during the last glacial period in the Greenland Ice Core Project (GRIP) ice core [*Fuhrer et al.*, 1993]. Transfer studies showed a strong temperature dependence of the HCHO concentration in ice, which probably accounted for a large part of the higher concentration level in the glacial period, but whether the high HCHO peaks in the glacial period are solely an effect of the colder temperatures remains still unclear [*Hutterli et al.*, 1999; *Hutterli*, 1999]. Analogous to HCHO, transfer studies for NO_3^- are required to estimate the importance of temperature on the high NO_3^- concentrations during the LGM (Figure 3). We could imagine that the lower temperatures of the last glacial were at least partially responsible for an enhanced uptake of NO_3^- , overcoming the effect of lower accumulation rate, and therefore leading to higher concentrations of NO_3^- in the ice. However, the detailed shape of the temperature changes seen at sites such as Vostok and Taylor Dome does not support this as the only factor, since NO_3^- changes significantly during the earlier parts of the glacial with only small temperature changes.

4.3. Impurities

In relation to NO_3^- , sea salt (mainly Na^+ and Cl^-) shows a different general shape (R. Röthlisberger et al., manuscript in preparation, 2000), as well as no correlation of the peaks. The only similarity between sea salt and NO_3^- is a substantial postdepositional loss of Cl^- and NO_3^- in surface snow at low-accumulation sites [*Wagnon et al.*, 1999; R. Röthlisberger et al., manuscript in preparation, 2000], although for Cl^- it is less pronounced. Thus sea salt seems to have no significant influence on NO_3^- in polar ice.

SO_4^{2-} , the only anion occurring in high concentration apart from Cl^- and NO_3^- , offers no obvious mechanism influencing the NO_3^- concentration either. The SO_4^{2-} and NO_3^- records have no similarities. Both the long-term trend and the high peaks are fairly different in shape and timing. On a large scale, the same also applies to acidity (inferred from the electrical conductivity measurements (ECM) and dielectric profiling (DEP) records). However, on a short scale, high acidity, which is usually related to H_2SO_4 peaks of volcanic origin, seems to coincide with low NO_3^- levels (Figure 5). The same has been reported for volcanic events recorded at other sites, for example, in the GRIP ice core [*Clausen et al.*, 1997]. Two hypotheses have been proposed to explain this phenomenon. Less NO_3^- production in the atmosphere after volcanic eruptions or the mobilization of NO_3^- in the snowpack after deposition could be the reason for the low NO_3^- concentration levels during vol-

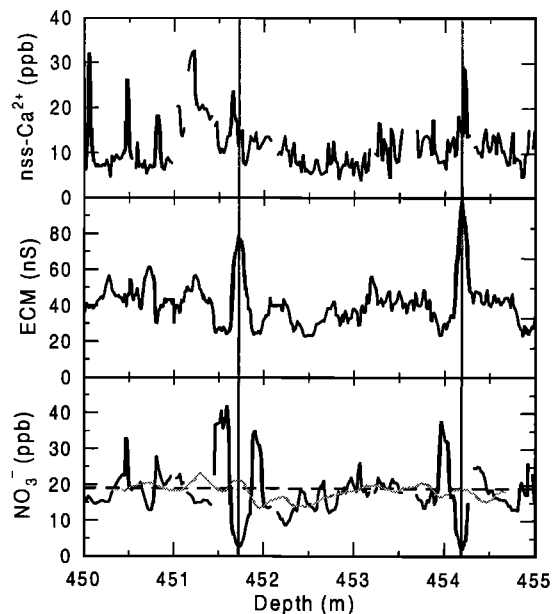


Figure 5. Example of the low NO_3^- concentrations in the presence of high acidity, indicated by the peaks in the electrical conductivity measurement (ECM) record. In the lower plot the dashed line indicates the mean concentration level and the shaded line the running mean over 62 cm.

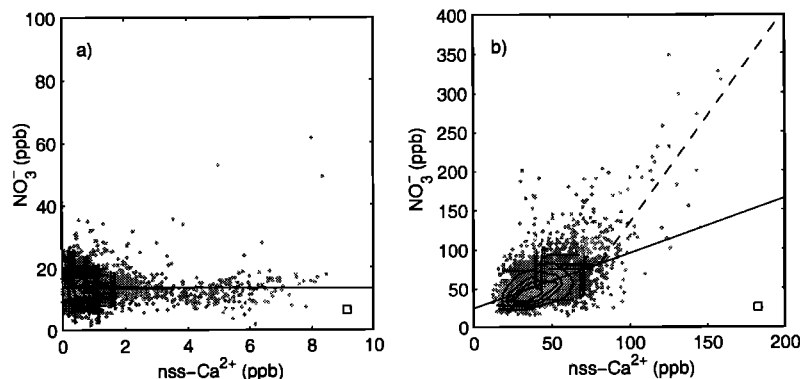


Figure 6. Plots of NO_3^- against nss-Ca^{2+} : (a) Holocene (0 to 310 m), (b) Last Glacial Maximum (LGM) (490 to 590 m). Each data point is a 2 cm average. A linear fit is shown for the Holocene. For the LGM, a linear fit for nss-Ca^{2+} ranging from 20 to 80 ppb (solid line) and one for nss-Ca^{2+} from 80 to 200 ppb (dashed line) are shown. To improve visibility of the data points, the data were gridded and contoured; grid size is indicated by the square in the lower right angle. For Holocene data, grid boxes are 0.25 ppb horizontally and 2.5 ppb vertically. Contours are 100, 200, and 300 points per box. For the LGM, grid boxes are 5 ppb horizontally and 10 ppb vertically. Contours are 25, 50, 75, and 100 points per box.

canic events. Volcanic eruptions with emission of large amounts of SO_2 have a large impact on atmospheric chemistry in reducing the concentration of oxidants. Assuming that the oxidation of NO_x is a major NO_3^- source, formation of NO_3^- would be reduced after volcanic eruptions [Yang *et al.*, 1996; Laj *et al.*, 1993]. However, other reactions that are enhanced by high SO_4^{2-} concentrations (conversion of N_2O_5 to HNO_3) might compensate or even overcompensate this [Wolff, 1995]. The second hypothesis considers processes occurring in the snowpack to be responsible for the effect observed. Wolff [1995] suggested that atmospheric NO_3^- concentration was not affected, but that during and/or after recrystallisation, NO_3^- was mobilized and pushed to the sides of the SO_4^{2-} peak, leaving a NO_3^- dip coincident with the H_2SO_4 peak and slightly increased NO_3^- concentrations on the shoulders of the H_2SO_4 peak. A similar effect is also seen for fluoride [De Angelis and Legrand, 1994]. The high-resolution NO_3^- data of the Dome C ice core reveal several events that support this hypothesis, while the first hypothesis seems less plausible due to the fact that NO_3^- levels are enhanced before and after the acidity peak (Figure 5).

Of the major impurities in polar ice, nss-Ca^{2+} (i.e., dust) is the only species that is remarkably similar to NO_3^- with respect to the general trends and the high spikes during the LGM (see Figures 1 and 3). Additionally, the trends in the two species are very similar in the earlier parts of the glacial recorded at Vostok, with both varying strongly together in periods when variability in other parameters was subdued. The nss-Ca^{2+} (or more generally dust) might lead to more efficient scavenging of NO_3^- and thus to more NO_3^- deposition or to a reaction of NO_3^- and dust particles, which prevents postdepositional NO_3^- losses. The lat-

ter seems more appropriate, since the high surface snow concentrations under present-day conditions imply efficient deposition even in the absence of nss-Ca^{2+} . However, it is not clear whether such reactions occur in the atmosphere or in the snowpack. If they happen in the atmosphere, one would expect to see a coincidence of nss-Ca^{2+} and NO_3^- peaks all over Antarctica, since nss-Ca^{2+} originates from quite far north and is rather well mixed in the Antarctic atmosphere. Furthermore, most NO_3^- sources are expected to lead to a fairly uniform concentration over Antarctica, giving a common basis for reaction of NO_3^- and dust for all Antarctic sites. Unfortunately, there are no high-resolution data from other sites going back into the LGM that would allow a comparison and support the assumption of atmospheric processes.

Recently, Legrand *et al.* [1999] established a relationship between nss-Ca^{2+} and NO_3^- in the Vostok ice core. Based on 54 samples of the last glacial period which contained more than 20 ppb nss-Ca^{2+} , they derived $[\text{NO}_3^-] = 4.0 \text{ ppb} + 1.542 [\text{nss-Ca}^{2+}]$ with $r^2 = 0.65$. If we apply the same criterion to our data (2 cm averages, 4117 data points), we obtain a different relationship ($[\text{NO}_3^-] = 12 \text{ ppb} + 1.0 [\text{nss-Ca}^{2+}]$) and also a weaker correlation ($r^2 = 0.37$).

Plots of NO_3^- versus nss-Ca^{2+} are presented in Figure 6. As discussed above, the climatic conditions may have a strong influence on the NO_3^- concentrations preserved in ice. Therefore we examine the relationship between nss-Ca^{2+} and NO_3^- for two different climatic regimes. Figure 6a shows 2 cm averages of the Holocene, Figure 6b shows 2 cm averages of the LGM. During the Holocene, there is no correlation between nss-Ca^{2+} and NO_3^- . Irrespective of the nss-Ca^{2+} concentration, NO_3^- concentrations are around 15 ppb. In the LGM

the slope of a linear relationship increased with higher thresholds of the nss-Ca^{2+} chosen. With nss-Ca^{2+} concentrations ranging from 20 to 80 ppb, we obtain a linear relationship with a slope of 0.7, which seems to fit the data reasonably well. However, with higher nss-Ca^{2+} concentrations, we obtain a slope of 2.7, which is close to the stoichiometric ratio of $\text{Ca}(\text{NO}_3)_2$.

5. Conclusions

To summarize, we found that under present-day conditions, which are characterized by low nss-Ca^{2+} (a few parts per billion) in Antarctic snow, accumulation rate and temperature control NO_3^- preservation. At sites with accumulation rates higher than $\sim 5 \text{ g cm}^{-2} \text{ yr}^{-1}$, mean NO_3^- concentrations are higher than at sites with low snow accumulation, although the nss-Ca^{2+} concentration is comparable to the one seen at Dome C (see Table 1). Given a sufficient accumulation rate preventing NO_3^- from being lost, colder temperatures lead to higher mean NO_3^- concentrations (Figure 4). While the detected vast loss of NO_3^- in the top meter of the snowpack at Dome C can be explained by volatilization and/or photochemical decomposition, the origin of the abundant NO_3^- in surface snow has still to be determined.

Snow layers with high acidity of volcanic origin lead to NO_3^- redistribution in the firn, occurring regardless of accumulation rate. The acid layer shows a depletion in NO_3^- and the layers above and below show an enhancement. The redistribution has to occur in the top few meters, since the effect is already seen at a depth of 12 m, where the Tambora eruptions are recorded in the Dome C ice core.

In the LGM, lower temperatures and the reaction of NO_3^- with nss-Ca^{2+} (or dust) reduce or prevent NO_3^- loss despite lower accumulation rates, leading to higher mean concentrations as well as higher variability. However, the reaction of NO_3^- with nss-Ca^{2+} seems to be more efficient at higher nss-Ca^{2+} levels. So far, it remains unclear whether this reaction takes place in the atmosphere or in the snow.

Although the factors favoring loss or retention of NO_3^- in polar ice have been identified, further studies are needed to quantify the contribution of each of them and the interplay of all of them. Only when the effect of all these processes can be determined and accounted for will it be possible for information on past NO_x concentrations to be extracted from ice core nitrate data.

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M. A. Hutterli, Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ 85721. (manuel@hwr.arizona.edu)

R. Mulvaney and E. W. Wolff, British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, England. (rmu@bas.ac.uk; ewwo@bas.ac.uk)

R. Röthlisberger and S. Sommer, Climate and Environmental Physics, Physics Institute, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland. (regine@climate.unibe.ch; sommer@climate.unibe.ch)

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