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Glacio-chemical study spanning the past 2 kyr on three ice cores from Dronning Maud Land, Antarctica
1. Annually resolved accumulation rates

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Abstract. For the first time, annually resolved accumulation rates have been determined in central Antarctica by means of counting seasonal signals of ammonium, calcium, and sodium. All records, obtained from three intermediate depth ice cores from Dronning Maud Land, East Antarctica, show rather constant accumulation rates throughout the last 9 centuries with mean values of 63, 61, and 44 mm H_2O yr^{-1} and a typical year-to-year variation of about 30%. For the last few decades, no trend was detected accounting for the high natural variability of all records. A significant weak intersite correlation is apparent only between two cores when the high-frequency part with periods less than 30 years is removed. By analyzing the records in the frequency domain, no persistent periods were found. This suggests that the snow accumulation in this area is mainly influenced by local deposition patterns and may be additionally masked by redistribution of snow due to wind. By comparing accumulation rates over the last 2 millennia a distinct change in the layer thickness in one of the three cores was found, which might be attributed either to an area upstream of the drilling site with lower accumulation rates, or to deposition processes influenced by surface undulations. The missing of a clear correlation between the accumulation rate histories at the three locations is also important for the interpretation of small, short time variations of past precipitation records obtained from deep ice cores.

1. Introduction

The European Project for Ice Coring in Antarctica (EPICA) plans to carry out two deep ice core drillings in Antarctica. While the first drilling, situated at Dome C, will provide data records over several climatic cycles, the second drilling aims to achieve high-resolution records of at least the last ice age. In order to link the latter ice core to respective Greenland records, it will be recovered from a region which is expected to be influenced by the Atlantic Ocean as well. Thus the drilling will take place somewhere in Dronning Maud Land (DML). An extensive reconnaissance of this little investigated area of East Antarctica will help to select a suitable drilling site. Since 1995/1996, several programs were performed to collect glacio-meteorological and geophysical data and to drill firn and ice cores [e.g., *Van den Broeke et al.*, 1999; *Oerter et al.*, 1999, 2000].

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One of the main feature of interest for site selection is the spatial and temporal variation of the snow accumulation rate. Its accurate knowledge allows the estimation of the depth-age relationship of an ice core. Furthermore, high-resolution accumulation histories provide important paleoclimatic information. Since ice cores are a unique archive for past accumulation rates, changes in atmospheric moisture transport may be derived from those records. This has been demonstrated impressively on a Western Greenland ice core, where the North Atlantic Oscillation has been reconstructed based on past accumulation rates [*Appenzeller et al.*, 1998].

Accumulation records deduced from Antarctic ice cores are already available from both coastal and inland sites. Owing to the low accumulation rate within Antarctica, most records were determined using a few single time horizons. While in earlier studies artificial radioactive horizons were used [*Jouzel et al.*, 1983; *Petit et al.*, 1982; *Pourchet et al.*, 1983], recent investigations could take advantage from well-known volcanic chronologies [e.g., *Isaksson et al.*, 1996; *Karlöf et al.*, 2000]. Only a few studies, carried out mainly in coastal high-accumulation areas, have so far achieved in annual resolution [e.g., *Morgan et al.*, 1991; *Thompson et al.*, 1994] and enabled an insight on the variability at shorter timescales. However, most of these records are limited in their duration and reach back only a few centuries. Recently, the spatial variability of annual accumulation rate records spanning several centuries has been investigated with two different ice cores from the South Pole area [*Van der Veen et al.*, 1999]. However, because these records are based on seasonal variations obtained from only one trace species, the dating uncertainty is higher compared to our data.

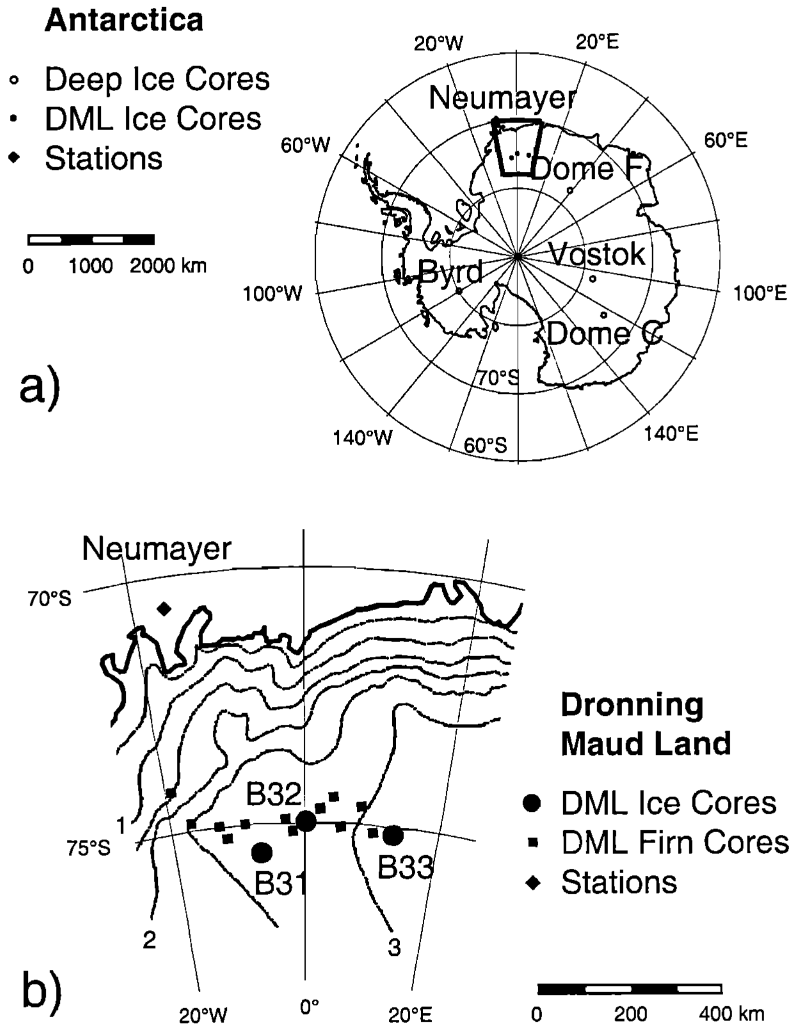

Figure 1. (a) Antarctica: Map showing locations of major deep ice core drillings and the Neumayer base as starting point for the Dronning Maud Land traverse. (b) Dronning Maud Land: Locations of the DML ice and firn cores. Elevation data [*Bamber*, 1994] is contoured at 0.5 km spacing. As Antarctic demarcation, the grounding line is shown.

Here we present analyses of ammonium, calcium, sodium, hydrogen peroxide, and the electrolytical conductivity performed on three ice cores, which were drilled in the frame of the DML site selection and reach depths up to 150 m. The measurements were done by a Continuous Flow Analysis (CFA) system [*Röthlisberger et al.*, 2000]. Thus an excellent depth resolution of less than 1 cm could be achieved. On the basis of the so obtained high-resolution data set we attempted to extract possible seasonal variability along with well-known volcanic chronology to accurately date the cores as well as to investigate the spatio-temporal variability of the accumulation rate. Results regarding these latter aims are included in present paper 1. Taking the advantage of the thus well-defined experimental area, in an accompanied work [*Sommer et al.*, this issue] the ion data are used to study the spatial and temporal variability of the ammonium, calcium, and sodium signals in seasonal resolution over the last 2 millennia.

2. Samples and Measuring Methods

The three ice cores used for this study were drilled during the austral summer 1997/1998 in the area of DML (see Figure 1). Along a 2000 km long traverse, starting at Neumayer, several shallow firn cores and three intermediate depth ice cores were drilled [*Oerter et al.*, 2000]. The deeper cores, which were used for this study, are located between approximately 75°S, 3°W (B31) and 75°S, 6°E (B33) in the area of DML (see Table 1). The distances between the drilling locations are 116 km (B31-B32) and 187 km (B32-B33), with a maximum elevation difference of 491 m.

The measurements reported in this study were carried out at Neumayer, several days after drilling. During this time all ice cores were packed in polyethylene bags and stored in a field laboratory room, approximately 6 m below the snow surface. Dielectric profiling (DEP) [*Wilhelms et al.*, 1998] and density measurements by gamma ray attenuation [*Gerland et al.*, 1999] as well as electrical conductivity measurements (ECM) were done before ice cores were cut for chemical analysis.

For the chemical in situ measurements a CFA system was used as described in more detail elsewhere [*Röthlisberger et al.* 2000]. A subcore cut by a band saw from the main core is melted continuously on a melt head. Contamination is avoided because only the inner part of the sample, which is

Table 1. Main Characteristics of the Three Drilling Sites at Dronning Maud Land

Core	Latitude	Longitude	Elevation, m asl	10-m Temperature °C	Depth, m	Maximum Age of Ice, year
B31	75° 34.9' S	3° 25.8' W	2669	-44.3	115.1	1536
B32	75° 00.1' S	0° 00.4' E	2882	-44.5	149.9	1885
B33	75° 10.0' S	6° 29.9' E	3160	-46.1	130.5	2142

not exposed to the surrounding atmosphere, is analyzed. Because of a slow melt rate of less than 3 cm min^{-1}, a very high depth resolution of 0.7 cm of ice could be obtained. Since most of the samples at DML consisted of firn, a specially designed firn melt head with narrow slits was used successfully to prevent additional dispersion by meltwater filling the porous firn [*Röthlisberger et al.*, 2000]. Because of logistic constraints, the number of measured species had to be limited to five compounds. We selected for various reasons ammonium, calcium, sodium, hydrogen peroxide, and the electrolytical conductivity. The chemical species were measured by continuously operated spectrometric methods with detection limits between 0.1 (NH_4^+, Ca^{2+} and H_2O_2) and 0.5 ppb (Na^+) and an accuracy of better than 10% [*Röthlisberger et al.*, 2000]. All measured values are concentrations relative to the blank, which was produced by a Millipore MilliQ system. The conductivity measurements were carried out by a commercially available conductometer. Slow drifts in the raw data of the conductivity records due to unstable measuring temperatures as well as unsteady bicarbonate enrichment in the meltwater were removed by using a high-pass filter with a cutoff frequency of about 80 years. Because of this, the signal to noise ratio of events lasting up to a few years could be noticeable improved without changing the relative signal height.

3. Dating Methods

Owing to the low accumulation rate in DML, it has not been clear whether seasonal signals could be resolved. Moreover, it is not obvious that every year's snow accumulation remained in place. Therefore the depth-age scale of the three ice cores is based on different dating techniques. On one hand, the identification of well-known historic volcanic layers may fix a timescale with individual time horizons. On the other hand, annual layer counting by a multiparameter record of trace species can exhibit the depth-age scale at a high resolution. In addition to these two main dating tools, a theoretical depth-age scale was used in the deeper part of the cores to get a robust timescale based on mean accumulation rates. Finally, a very good intersite correlation within the hydrogen peroxide records allowed an independent check of the dating quality.

3.1. Volcanic Horizons

Explosive volcanic eruptions inject large amounts of dust and gaseous materials into the atmosphere, often directly into the stratosphere. Aerosols, which are formed from these materials, are transported by the atmospheric circulation up to the polar ice sheets. Deposition of these aerosols results in snow layers with very high ionic concentrations, especially high SO_4^{2-} and H^+ concentrations. Common methods to detect these horizons are either direct chemical analysis, or ECM [*Hammer et al.*, 1980] and DEP measurements [*Moore et al.*, 1992] on the ice core. Since we measured the total ionic content of the meltwater by a conductivity cell as well as the major sea-salt ion Na^+ [*Sommer et al.*, this issue], for this study we applied a new detection criterion for volcanic horizons by reconstructing a so-called non-sea-salt (nss) conductivity.

Nearly all peaks in the electrolytical conductivity records are either due to high sea-salt concentrations or caused by volcanic horizons. In order to remove the sea-salt part from the electrolytical conductivity data set we subtracted its contribution by using the measured Na^+ content and its seawater ratio of major ions [*Bowen*, 1979] and the specific ionic conductivity at infinite dilution [*Lide*, 1998], adjusted for a measuring temperature of 18°C. This may be written as [nss conductivity] = [conductivity] − 0.0060 × [Na^+], where 0.0060 is the total ionic conductivity of seawater per 1 ppb of sodium, given in ($\mu S\ cm^{-1}\ ppb^{-1}$).

In Figure 2 the nss conductivity records from all three ice cores are shown. Several clearly visible peaks can be used as reference horizons in comparison with common volcanic chronologies from Antarctica [*Cole-Dai et al.*, 1997; *Delmas et al.*, 1992; *Langway et al.*, 1995]. Three well-known volcanoes were selected as fixed points: the two most prominent volcanoes Tambora, erupted 1815 AD in Indonesia and an unidentified volcanic event around 1259 AD. Several authors [*Delmas et al.*, 1992; *Langway et al.*, 1995] attributed the deposition horizons of these two volcanoes in Antarctica to the years 1816/1817 and 1259 AD. One of the highest peaks in this millennium occurred in the middle of the fifteenth century and served as a third fixed point. Although this distinct peak is seen in all Antarctic ice cores, there is no agreement in the absolute date of the horizon. Estimates ranging from 1450 [*Delmas et al.*, 1992] to 1464 AD [*Langway et al.*, 1994]. Following *Cole-Dai et al.* [1997], who dated this layer in a high accumulation core to the year 1455 and attributed it to the eruption of Kuwae in early 1453, we also fixed 1455 AD for the maximum concentration. This dating is confirmed by a Northern Hemisphere tree ring chronology of *Briffa et al.* [1998], who suggests Kuwae as trigger for several notable frost rings after 1453 AD. Apart from these three fixed points additional 16 smaller volcanic horizons could be identified within the last 9 centuries and were used to check the annual layer counting.

While the volcanic chronology for the last 900 years is thus well known, no accurate dating of volcanic snow layers in Antarctica, reaching back into the first millennium, is available so far. In all our three records we could find three distinct conductivity peaks between 500 and 700 AD (see Figure 3). These signals were also identified in the DEP and ECM records in the new drilled Dome C ice core and were dated there to the years 677, 575, and 544 AD (J. Schwander, personal communication, 2000). By using a weighted

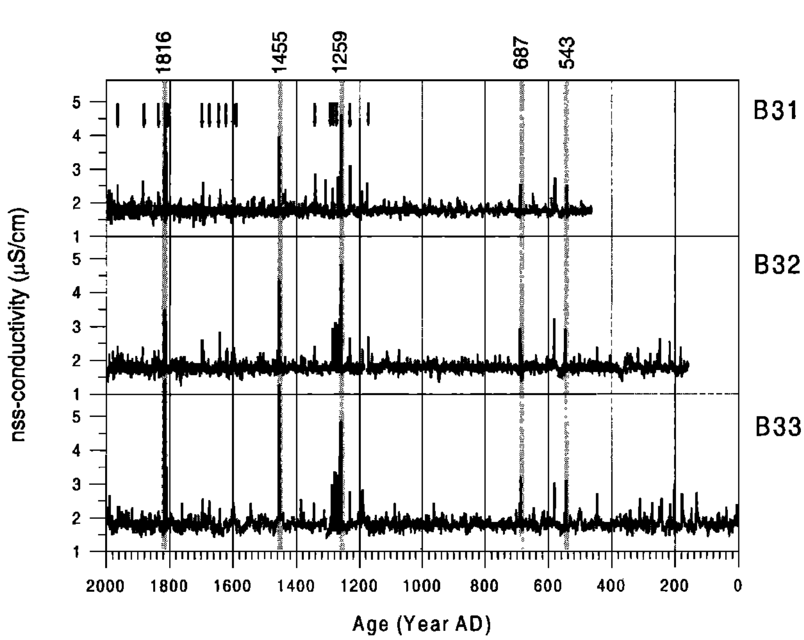

Figure 2. Nss conductivity (see text) of all three ice cores based on the timescale deduced from annual layer counting (until 1100 AD) and from the calculated depth-age scale, with the major volcanoes in emphasized areas. The additional 16 smaller volcanic horizons identified in the records are indicated by arrows.

arithmetical mean of the dating of our three cores, based on layer counting and on the densification model, we got ages for those peaks of 687, 578, and 543 AD, with an error (one standard deviation) of ±20 years. The differences in dating quality were taken into account by applying differing weights. At B31, the densification model gave no consistent result because the three distinct peaks are found above the expected depth. Since the peaks show a very similar shape, as Figure 3 indicates, and there are no known volcanic layers in the time period before, we may consider a distinct change in the accumulation rate at this site. This special feature will be discussed in a following section. Because the timing of volcanoes is not the subject of this study, the dating of the three peaks will be discussed only briefly. During the time period of interest, *Hammer et al.* [1997] found two volcanoes (639 and 505 AD) in the Byrd ice core, which do not match exactly with our dates. However, since three volcanic horizons could be identified in all the DML cores and also in the Dome C core, we are quite confident to have detected three eruptions. However, from a historical view, a classification is difficult. Only for the 544 AD horizon there is clear evidence for a strong volcanic eruption in Papua New Guinea (Rabaul, 540 AD) [*Simkin and Siebert*, 1994; *Stothers*, 1984].

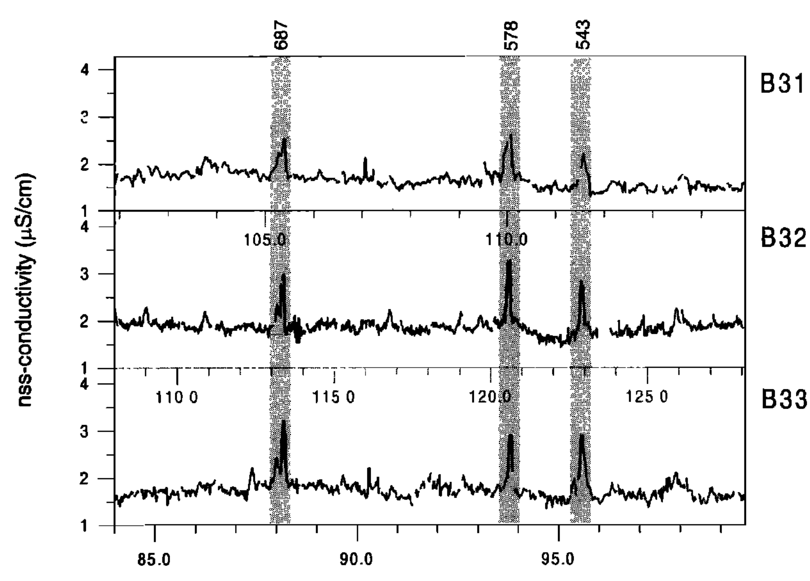

Figure 3. Nss conductivity (see text) of all three ice cores in the range of the three unknown volcanoes, as a function of depth.

3.2. Annual Layer Counting

Atmospheric measurements at South Pole [*Tuncel et al.*, 1989] and at Neumayer [*Legrand et al.*, 1998] show a seasonal signal of sea-salt aerosols with peaks during wintertime. A similar feature can also be observed in ice cores drilled at different locations in Antarctica [*Legrand and Delmas*, 1984; *Wagenbach et al.*, 1994; *Whitlow et al.*, 1992]. As already mentioned, the depth resolution of our measuring system is close to 0.7 cm of ice. Assuming that six data points are required to resolve a seasonally varying parameter, an accumulation rate of 42 mm of ice or 38 mm of H_2O yr^{-1} would be necessary. To prove whether the sodium variations in our records represent seasonal signals, we counted the peaks between common volcanic layers. This has been done in Figure 4, where the years between the four eruptions of the 1259 event (1270, 1278, and 1286) [*Langway et al.*, 1995] could be clearly identified. Not only do the sea-salt-related components sodium and calcium show interannual variability, but also the ammonium record display seasonal concentration changes. Therefore it is possible to detect annual layers by using this multiparameter record. As expected [*McConnell et al.*, 1998], a seasonal signal in H_2O_2 is preserved only in the first 1-2 m. Below this, the annual variability was smoothed out due to diffusion processes.

However, not every years signal is equally evident, as Figure 4 shows. By comparing layer counted periods between known volcanic horizons we usually got an error of 3% in B31 and B32, and 5% in B33, respectively. Because this error accumulates only between the volcanoes, we reach maximum uncertainties of about ±5 and ±8 years within the last 9 centuries. Since the error for counting was uniformly distributed, we did not have an indication for a loss of complete years of snow accumulation in general.

3.3 Densification Model

In the deeper part of the ice cores, where the volcanic chronology is not well-known, the dating uncertainty by layer counting is summing up constantly. To obtain a robust timescale, we therefore used a dynamic model for firn densification described by *Schwander et al.* [1997]. With the two input parameters mean accumulation rate and temperature one can derive density profiles for different locations. Thus a theoretical depth-age relationship can be determined on the assumption of constant accumulation. The model is basically an approach described by *Barnola et al.* [1991], which makes use of the empirical density model from Herron-Langway [*Herron and Langway*, 1980] and a sintering model with spherical bubbles [*Wilkinson and Ashby*, 1975]. The mean accumulation rate, which is the main input parameter, was calculated by using the 1259 volcanic layers, while temperature input to the model came from the 10 m borehole temperatures [*Oerter et al.*, 2000].

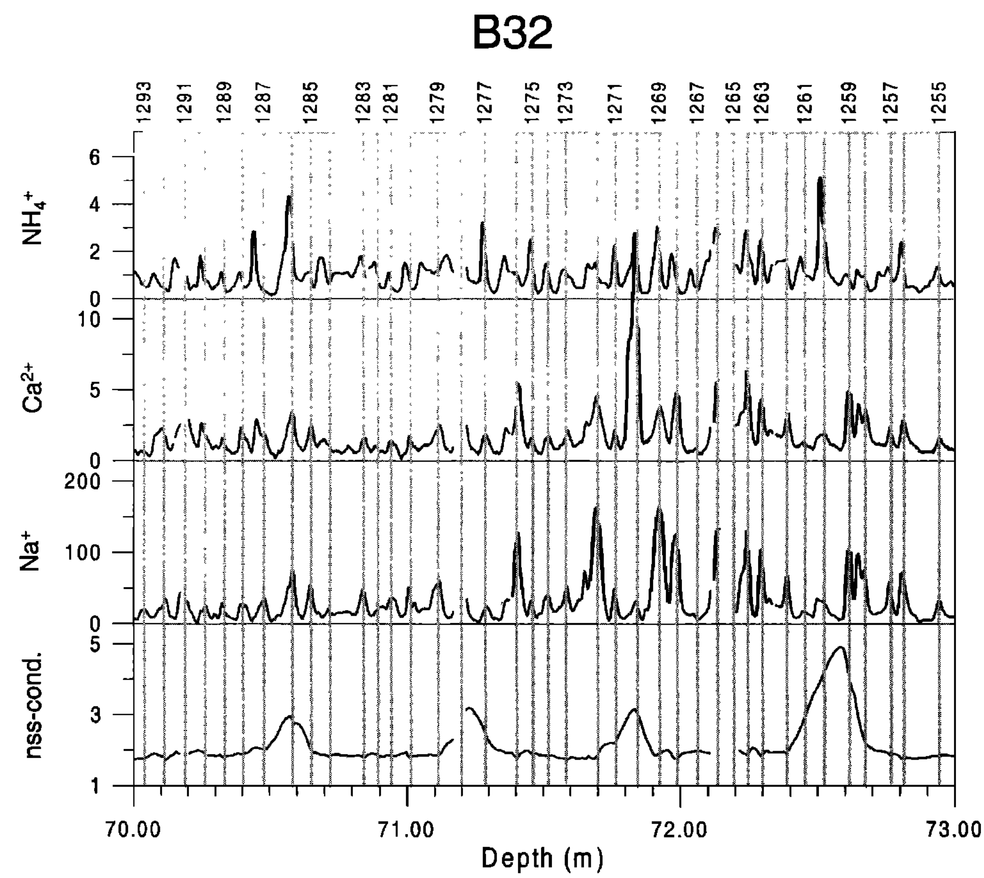

Figure 4. Example for the layer counting method, based on the trace species ammonium, calcium, and sodium (concentrations given in ppb). Vertical lines indicate years, deduced from the sodium winter peak. The nss conductivity shows the four volcanoes, deposited in the years 1259, 1270, 1278, and 1286 AD [*Langway et al.*, 1995].

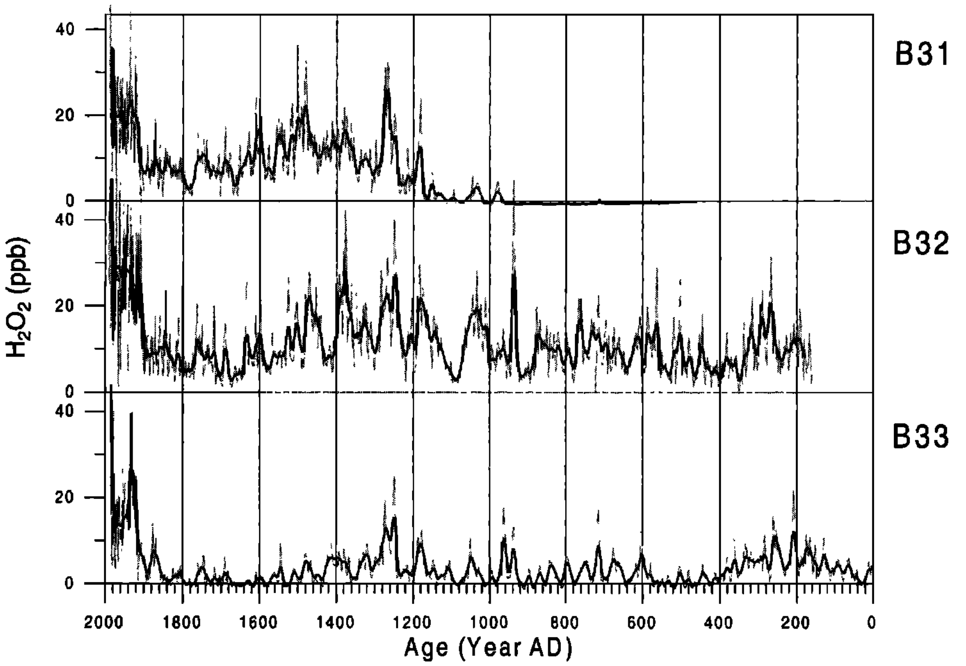

Figure 5. H_2O_2 concentration of all three ice cores based on the timescale deduced from annual layer counting (until 1100 AD) and from the calculated depth-age scale. Thin lines indicate annually resolved measurements; thick lines are the 30 year filtered data (gaussian filter).

3.4. Dating Control by H_2O_2

As the only chemical component described in the frame of this study, the hydrogen peroxide data show a significant intersite similarity, at least for the last 9 centuries (see Figure 5). In order to test the dating quality independent of single events like volcanic layers we therefore used these records. Note that this section concerns only the last 900 years: the distinct H_2O_2 concentration change occurring in B31 around the turn of the millennium will be discussed later.

H_2O_2, which is produced in the atmosphere by photochemical reactions, is incorporated in the snow reversibly. The concentrations preserved in the firn depend not only on atmospheric concentrations, but are influenced also by the deposition temperature, the accumulation rate, and the seasonal accumulation distribution [*McConnell et al.*, 1997]. Higher deposition temperature causes lower snow concentrations due to the equilibrium process between snow and air concentrations. Conversely, higher accumulation rates lead to increased snow concentrations because rapid burial limits exchange with the atmosphere. The latter effect can be observed in the mean H_2O_2 concentration of B33, which is lower due to the lower accumulation rate than those of B31 and B32. Because none of the cores reveal a correlation on decadal timescale between accumulation and H_2O_2 concentrations, the decadal variations in the H_2O_2 profiles are very probably caused only to a minor part by changes of the accumulation rate. Owing to the lack of both atmospheric measurements and the knowledge of an exact temperature history at the drilling sites, it is not possible at the moment to verify in detail the causes of the long-term variation of the H_2O_2 profiles.

However, highly significant correlation coefficients in H_2O_2 between all three cores of 0.63-0.78 (99% level according to Monte Carlo simulation) were found (see Table 3). Since a cross-correlation analysis between the records shows the highest correlation coefficient solely within a time lag of ±5 years, we conclude to have determined a rather accurate dating of all the ice cores within this period.

4. Results and Discussion

For all three cores, high-resolution density measurements were performed by gamma ray attenuation [*Gerland et al.*, 1999]. However, due to bad core quality in some parts, the measurements could not be applied continuously over the whole core. In order to improve the partly interrupted data record we compared the measured values with our density model. Because of a very good correspondence between both data sets ($R = 0.99$), we therefore calculated the accumulation rates, determined by the annual layer counting, with the modeled density values.

In addition to the dating errors described above, the annually resolved accumulation rates are further disturbed by a large portion of noise due to redistribution of snow by wind and subannual timing uncertainties. By using low-pass filters (standard triangular filter) with different lengths the high-frequency part was removed, as will be discussed below. For the calculation of the thinning of annual layers, only the vertical compression of firn by densification but no deformation by stress is taken into account. Because the core lengths are small compared to the ice thickness at the drilling sites [*Steinhage et al.*, 1999], correction factors due to plastic deformation [*Nye*, 1963] would not exceed 2% for 900 year old layers and 4% for core bottom layers and are therefore negligible.

As mentioned in the previous section, the dating quality and therefore the accuracy of the high-resolution accumulation rates are different for the first and the second

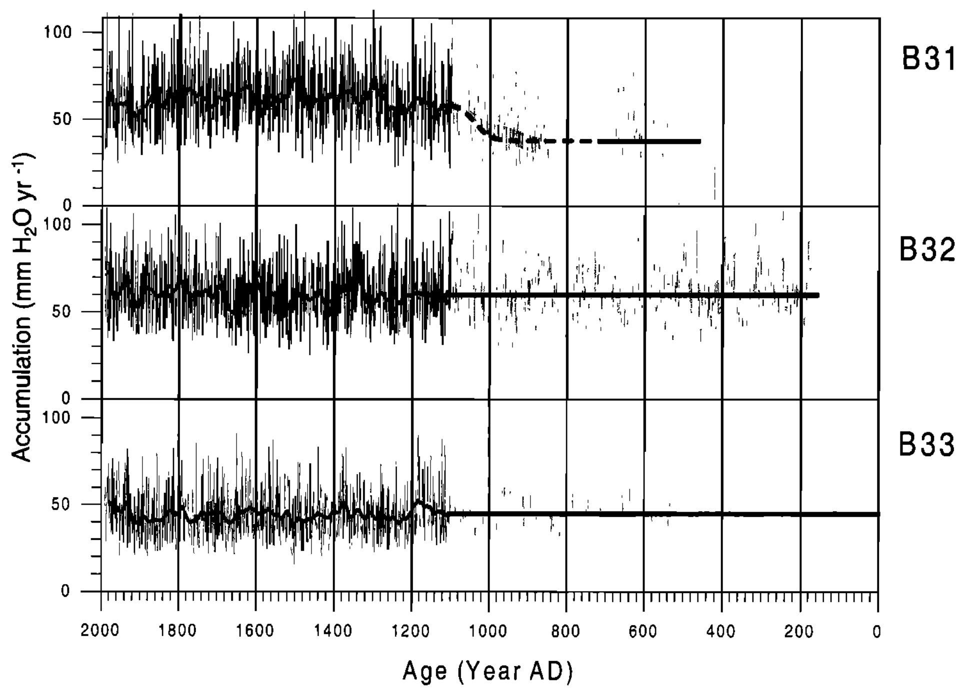

Figure 6. Accumulation rate records of all three ice cores. Thin black lines indicate annually resolved accumulation rates of the last 9 centuries; thick black lines are the same data calculated with a 30 year filter (standard triangular filter). Weak thin lines show annually resolved accumulation rates for the remaining periods which were counted (but biased by high uncertainties). Very thick grey lines indicate calculated accumulation rates based on volcanoes for the total ice depth of the particular cores. The dotted section in B31 shows a distinct change (see text), together with the estimated uncertainty (shaded area).

millennium. Hence we will discuss the two different time periods separately.

4.1. Accumulation Rates Between 1100 and 1996 AD

Figure 6 shows the annual accumulation histories of all three ice cores. Whereas the mean accumulation rates for the last 9 centuries at B31 and B32 are almost equal (63 mm and 61 mm H_2O yr^{-1}), there is a lower value at B33 (44 mm H_2O yr^{-1}). The annually resolved records have similar year-to-year variability of the order of 30%, with only little higher values at the low accumulation site (see Table 2). There is neither an indication of a change nor a trend in the accumulation rate apparent during this time period. In particular, if we consider the long-term variability apparent in the records, there is no recent trend due to global warming visible.

The annually resolved accumulation rates show no correlation within the three cores. Only by removing the high-frequency part by means of increasing the filter length to more than 30 years, a statistical significant correlation coefficient of 0.38 (99% level according to a Monte Carlo simulation considering the filter quality) between B32 and B33 is obtained. However, still no correlation is found with core B31 (see Table 3).

To investigate spectral properties of the time series, we used a Morlet wavelet analysis as described by *Torrence and Compo* [1998]. The statistical significance of the local wavelet power spectrum was tested by a Monte Carlo method (null hypothesis states that the accumulation rates are autoregressive noise time series with an autocorrelation coefficient α estimated from the observed data; all accumulation rates are mainly white with $\alpha < 0.03$). The local wavelet spectra of the three accumulation rates (Figure 7) reveal no clear indication of any variability with preferred timescales. The spotted time sequences with spectral power above the 99% confidence level resemble the spectra of white

Table 2. Mean Accumulation Rates and Their Variation During Different Time Periods[a]

Core	1997-1817		1817-1259		1259-687	687-543
	Accumulation, mm H_2O yr^{-1}	Variation, %	Accumulation, mm H_2O yr^{-1}	Variation, %	Accumulation, mm H_2O yr^{-1}	Accumulation, mm H_2O yr^{-1}
B31	59	29	64	27	46	38
B32	62	27	60	28	60	59
B33	45	33	44	32	45	44

[a]Variation is given in one standard deviation.

Table 3. Correlation Coefficients of the Accumulation Rate and the H_2O_2 Concentrations Within the Three Cores During the Last 900 Years Calculated With 30 Year Filtered Data

	Accumulation			H_2O_2		
	B31	B32	B33	B31	B32	B33
B31	1.00	0.02	0.04	1.00	0.65	0.63
B32		1.00	0.38		1.00	0.78
B33			1.00			1.00

noise time series. While the spectrum of B32 shows slightly significant frequency throughout a larger part of the record with a period of about 50 years, in B33 there are several smaller parts with periods around 20 years. However, no persistent frequencies can be observed in either core.

Given the location of all drilling sites within a few 100 km, one would expect a large-scale change in the atmospheric moisture transport should be recorded in all cores. Certainly, this is not the case for the high-frequency part with periods below 30 years. However, no homogenous picture is obtained by examining accumulation changes on longer timescales either. With the exception of a weak correlation between B32 and B33, explaining roughly 14% ($=R^2$) of the temporal variation in the accumulation rate, the changes at B31 are not at all related to the other two cores. Similar results were obtained by comparisons of other accumulation records from DML. *Isaksson et al.* [1996] found no uniform variations between a more coastal core with a plateau core (75°S, 2°E), nor did *Karlöf et al.* [2000], who compared different time periods from a 120 m ice core situated at 76°S, 8°W with the plateau core from *Isaksson et al.* [1996]. The redistribution of snow by wind seems to mask a possibly existing atmospheric signal in areas with such low accumulation rates, at least in periods without drastic changes. A comparison of a stacked accumulation record obtained from 12 firn cores from DML with the composite $\delta^{18}O$ record showed a significant correlation [*Oerter et al.*, 2000], despite the lack of intersite similarity in single records. The analysis of a large number of cores may reduce the high-frequency noise fraction; however, the irregular spatial as well as the highly variable temporal accumulation pattern seen in the DML area question that the residual signal contains significant climatic information.

Several authors have already reported a recent accumulation increase in different regions of Antarctica [*Morgan et al.*, 1991; *Petit et al.*, 1982; *Thompson et al.*, 1994]. *Morgan et al.* [1991], who reported recent rates about 20% above the long-term mean at a coastal site, suggests a lowering of sea level as a result of increasing accumulation rates all over Antarctica, deduced from a few records published so far. Our results do not support this study. First, there is no recent increase detectable in our records. Second, the variability on decadal timescale is characterized throughout the last 9 centuries by changes greater than 20%, although the accumulation rates stay stable over the whole time period. A similar result is reported by *Van der Veen et al.* [1999], who found no climatically significant changes in accumulation in two South Pole ice cores covering the time period between 1050 and 1956 AD.

4.2. Accumulation Rates Between 0 and 1100 AD

Owing to the long nonvolcanic period within the first millennium, a possible systematic error of the annual layer counting method may sum up to very high uncertainties. Therefore we focus on the discussion of mean accumulation rates, obtained by the three volcanoes from 687 AD and earlier. Nevertheless, the accumulation rates estimated from layer counting serve as an indicator of relative changes within time markers. At B32 and B33 the same accumulation rates are obtained as they were found in the last 9 centuries. However, at B31, a distinct change has occurred somewhere around 1000 AD, where the accumulation rate has increased from about 38 to more than 60 mm H_2O yr^{-1} (see Figure 6 and Table 2).

The major question that arises is why this distinct change is recorded only in B31. Although the absolute dating of the three volcanoes in all cores may be masked by a higher uncertainty, there is a good confidence with the time periods in between the peaks. In fact, the accumulation rates for B31 deduced from these sections show consistently low values. However, also the H_2O_2 measurements support a decline in accumulation rate around 1000 AD, as can be seen in Figure 5. While the mean H_2O_2 concentration in B31 is more than 10 ppb between 1100 and 1900 AD, it drops to values around 0 ppb for the time period before 1000 AD. However, no such change is apparent in the other two cores. (Note: negative H_2O_2 values indicate that our MilliQ blank contained slightly higher H_2O_2 concentrations than there is in the ice.) Air-to-snow-to-firn transfer modeling of H_2O_2 for the South Pole conditions indicates that the strong concentration change might be explained with the 60% increase in accumulation rate (38 to 63 mm H_2O yr^{-1}) between 900 and 1100 AD [*McConnell et al.*, 1998]. Despite quite similar accumulation rates, the H_2O_2 concentrations in the B31 core are much lower and flatter than the ones in B33 before 1000 AD. This is not necessarily inconsistent with the transfer model results revealing a highly nonlinear accumulation dependence of the H_2O_2 preservation in snow with an especially strong decrease at low accumulation rates. However, other environmental factors such as temperature might also have contributed to the difference of the two H_2O_2 records. Finally, also the layer counting method indicates a distinct change in accumulation rate (see Figure 6). Because we missed nearly 100 years by counting the layers in B31 between the volcanoes of 1259 and 687 AD, one can only describe the broad change, but an exact reproduction of the accumulation rate is not possible. The missing years can be explained by the very low accumulation rate, which does not allow a resolution of all annual layers.

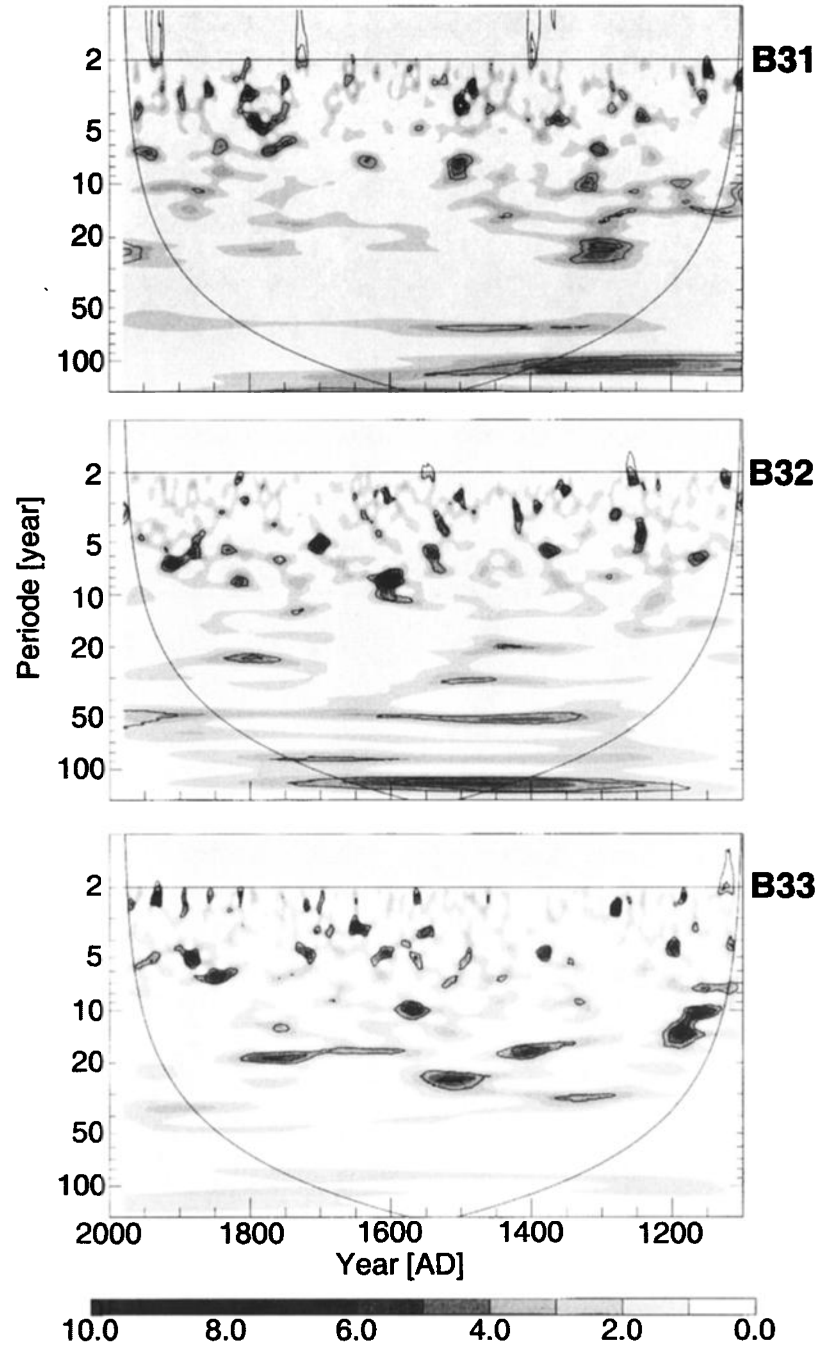

Figure 7. Local wavelet power spectrum of all three accumulation records, based on a Morlet wavelet. Logarithmic vertical axes indicate equivalent periods; horizontal axes indicate time. The 95 and 99% confidence limits are shown as thin lines, and the cone of influence marks regions where edge effects might underestimate the amplitudes.

With the knowledge of the mean accumulation rates between different volcanoes and the information deduced from the H_2O_2 record we constructed a theoretical accumulation rate by means of a Hyperbolic Tangent Function. While we are very confident about the low accumulation rate in the middle of the first millennium, the timing and the shape of the transition remain somewhat unclear, as the error bars in Figure 6 indicate.

Because this significant change could be found only in one core, this suggests a cause other than variation in the atmospheric moisture transport. Two scenarios are possible: (1) According to an accumulation map, based on all ice and firn cores drilled between 1995 and 1998, there is an area with lower accumulation rates upstream of B31 [*Oerter et al.*, 2000] (note that in their paper core B31 corresponds to location 07, B32 to 05, and B33 to 17). This area, which is situated close to B31, has an extent of about 60 km with accumulation rates of less than 45 mm H_2O yr^{-1}. Since no firn cores exist in the middle of this area, the minimum accumulation rates as well as the exact location are not determined in an accurate way. With a horizontal ice velocity of the order of 5-10 m yr^{-1} it is possible that the distinct change in the layer thickness of B31 is caused by lower accumulation rates upstream of the drilling site. (2) The spatial variation of accumulation rates may be influenced also by surface undulations with wavelengths of 5-30 km [*Gow and Rowland*, 1965; *Van der Veen et al.*, 1999]. In general, there is more snow accumulated in troughs than on crests. *Nye* [1959] suggests that the underlying bedrock may cause the surface waves on ice sheets. Since bedrock topography starts to vary strongly toward the coast [*Steinhage et al.*, 1999], there are likely more distinct undulations close to B31 than at the other sites. Both scenarios, which influence the records in a similar way, may explain a change of the accumulation record in only one core. However, most probably the correct explanation lies in a combination of the two processes. Thus it could be possible that the accumulation rate has changed in an abrupt way. However, with the constant rates determined from the other two records over the last 2 millennia we have good reasons to believe that no drastic change in the atmospheric moisture transport has occurred within this time period.

With core B31 a drilling site has been discovered with an irregular accumulation history. This special deposition feature may be used for further studies to investigate deposition processes for chemical species. The atmosphere-to-ice transfer of volatile components, such as hydrogen peroxide, nitrate, and chloride, is reversible and depends among other things on the accumulation rate. Assuming that only the accumulation rate has changed, it would be possible to test existing transfer models [*McConnell et al.*, 1998] for their sensitivity to such changes.

5. Conclusions

By using a high-resolution multiparameter chemical record, annually resolved accumulation rates were obtained from three intermediate depth ice cores. No significant trend in the accumulation rates within the last 9 centuries was found. The accumulation and therefore the atmospheric moisture transport seem to have been very constant during this time period. However, no correlation in the annually resolved data between the three cores is apparent. The correlation reaches significant values by increasing the filter length to 30 years, but only between cores B32 and B33. By examining the records in the frequency domain, no coherent signal could be found in the three cores. An abrupt change in the layer thickness of only one core (B31) could be explained by either a low accumulation area upstream of the drilling site, or surface waves, which influence the deposition pattern in that region.

We find the following conclusions:

1. A possibly existent climatic signal in the rather constant accumulation rate records of DML is masked by high local variability at each core site. There is no recent change in the accumulation rate, which would be significantly higher than the natural variability.

2. An interpretation of only one accumulation record, obtained in an area with such low accumulation rates, has to be done very carefully, since the accumulation rate may be influenced by unforeseeable variations upstream of the drilling site.

3. The annual layer thickness of ice cores may vary also in very stable climatic periods due to undulations of the snow surface, which can cause spatial accumulation rate variations. One has to keep this in mind by performing theoretical depth-age relationships for deep ice cores, in particular by estimating errors.

4. The planned drilling site for the second EPICA ice core deep drilling will be situated close to B32. According to this study we can support this choice, since there is evidence presented here of a regular accumulation history upstream of B32 toward B33, for at least 180 km over the last 2000 years. There is no reason for a displacement of the drilling site toward the coast, which might have been desirable to find a more pronounced Atlantic influence. A distinct change in the recorded layer thickness at B31, downstream of B32, would suggest a difficult construction of the timescale for the DML ice core deep drilling.

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