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Effects of seasonal variability of accumulation on yearly mean $\delta^{18}O$ values in Antarctic snow

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ABSTRACT. The annual mean oxygen-isotope content of Antarctic snow is strongly influenced by the seasonal variability of accumulation. Since the annual mean $\delta^{18}O$ value is frequently used to derive mean annual temperatures from ice cores, changes in atmospheric circulation pattern can lead to large errors in the deduced temperature record. At the German Antarctic wintering base, Neumayer, accumulation measurements have been carried out continuously over the last 16 years. Weekly readings of accumulation stakes combined with snow pits and shallow firn cores are used to investigate the influence of the seasonal variability of accumulation on the annual mean $\delta^{18}O$ values and to estimate the possible error in the determination of annual mean temperatures from ice cores by using the oxygen-isotope record.

1. INTRODUCTION

One of the most successful methods in climatological research is the study of ice cores from the two large ice sheets of Greenland and Antarctica. Especially in Antarctica, instrumental temperature records are short and rare, so ice cores are the only means of providing information about past temperature, recent trends and, at sites remote from weather stations, present temperature. The stable oxygen-isotope ratios of snow are fairly well correlated to the annual mean air temperature at the deposition site, although they depend in a complex way on the source and distance to the source of precipitation and on fractionation processes during the transport of moisture to the deposition site of the snow (Dansgaard, 1964; Dansgaard and others, 1973). In spite of this complicated physics, a linear relationship is found between the mean annual $\delta^{18}O$ value of snow and the mean annual air temperature at the deposition site.

However, the $\delta^{18}O$ content depends not only on temperature, but on several other factors which are discussed in section 2. This study concentrates on the influence of seasonal variations of accumulation.

Changes in the seasonal distribution of accumulation can change considerably the mean annual $\delta^{18}O$ value of the snow. Thus, changes in the atmospheric circulation pattern, and consequently in the mean position and tracks of low-pressure systems, can lead to large errors in temperatures derived from ice cores. Unfortunately, at most drilling sites it is not possible to determine the seasonal variations of accumulation, since there are no measurements of high temporal resolution available. Precipitation measurements in Antarctica are extremely difficult due to the high wind speeds and, in the interior, due to the extremely low amounts of precipitation, and stations with continuous accumulation measurements are rare.

At the German Antarctic wintering base, Georg von Neumayer (70°37′ S, 8°22′ W), on Ekströmisen, Dronning Maud Land, which was established in 1981 and replaced by the new building, Neumayer, 7 km to the southeast in 1992, detailed accumulation measurements have been carried out continuously for the last 16 years. Weekly readings of accumulation stakes were complemented by sampling snow pits and shallow firn cores, whose isotope contents were analyzed. Neumayer is also a meteorological observatory, where routine observations of all important meteorological parameters are made 3 hourly (SYNOP observations; König-Langlo and Marx, 1997). Thus the Neumayer data give us the unique opportunity to study the seasonal variations of accumulation and their influence on the stable-isotope contents of the snow.

2. STABLE-ISOTOPE–TEMPERATURE RELATIONSHIP

Since the early studies of Picciotto and others (1960) and Aldaz and Deutsch (1967) the stable-isotope–temperature relationship has been studied extensively by many authors in polar areas (e.g. Jouzel and others 1983; Robin, 1983; Aristarain and others, 1986; Peel and others, 1988; Peel, 1992; Jones and others, 1993; Jouzel and others, 1997). In the absence of reliable series of air-temperature data close to ice-core drilling sites, the annual mean air temperature (determined by measuring the 10 m snowpack temperature) is often correlated to a mean δ value (averaged over several years) at different sites in order to derive the $\delta^{18}O/T$ gradient. However, there is increasing evidence that the spatially derived $\delta^{18}O/T$ gradient is different from the temporally derived one, as discussed by Peel and others (1988) and Jouzel and others (1997). In order to derive the temporal relationship between the mean annual temperature and the isotope content of the snow, a longer series of drilling-site climate data is desirable. Unfortunately, most drilling sites are located in remote regions. The climate data used are from the nearest stations, which are often several hundred km from the drilling site. Jouzel and others (1983) investigated the $\delta^{18}O/T$ relationship at South Pole, one of the few sites where both temperature and isotope data are available. Problems arise mainly from the strong inversion that usually develops over the South Pole plateau. Jouzel and others correlated δD values and temperatures at different atmospheric levels for different times of year and found that the correlation is quite good in summer (December–January), but poor in winter due to the strong inversion. The correlation for yearly values remains usable. Aristarain and others (1986) and Peel and others (1988) calculated the $\delta^{18}O/T$ gradient by comparing ice-core data from the Antarctic Peninsula region to climate data from Faraday, Esperanza and other Peninsula stations. They found that the temporally derived gradient is considerably smaller than the spatially derived one. Sources of this discrepancy are discussed in detail by Peel and others (1988):

Variations of sea-ice extent may influence the isotope content by changing the distance to the moisture source of precipitation.

The isotope content is primarily determined by the condensation temperature, which is not always directly related to the surface air temperature. How important this influence is depends on different factors, such as the amount of surface riming or the strength of the inversion layer.

A biasing may occur due to irregular snow-deposition patterns. To investigate this effect, Peel and others (1988) calculated an annual temperature weighted with accumulation (see also Steig and others, 1994). In the absence of a long-term monthly snow-accumulation record, the number of days on which precipitation was observed to fall at Faraday was used. Peel and others found that the weighted temperature is highly correlated to the standard synoptic temperature ($r = 0.97$, sig. $<0.01\%$). Thus they concluded that the mean annual isotopic composition is relatively insensitive to the accumulation pattern throughout the year.

However, this conclusion is valid only if the accumulation is distributed relatively evenly over the year, as at Faraday, where the number of precipitation days usually exceeds 300 per year and precipitation is mainly connected to many small events rather than single events with large amounts of accumulation.

Unfortunately, there are hardly any stations in Antarctica with high-time-resolution accumulation measurements. Even at South Pole there was no continuous accumulation-measurement programme; several different stake arrays were operated over different time periods, the stakes usually being read only at yearly intervals (Mosley-Thompson and others, 1995). However, a 7.25 year record of monthly accumulation measurements does exist for South Pole, which was used by McConnell and others (1997) to investigate the influence of the seasonal variability of accumulation on the core interpretation in a more statistical approach. They found that a 300 year record is required to ensure that snow from each month of the calendar year is represented in an ice core.

At Neumayer we have a long-term (16 year) monthly accumulation record, which enables us to investigate the influence of the seasonal distribution of accumulation on the isotope composition in the cores (see section 5).

The isotopic record may contain a further biasing because it represents only those time periods during which snowfall occurs. Especially in winter, the temperatures during snowfall are usually higher than during clear weather periods, the latter not being sampled in the ice cores.

At Neumayer the "snowfall temperature" was determined using the 3 hourly SYNOP observations. The mean monthly temperatures were calculated using only the periods when snowfall or drift was observed at the station. Figure 1 shows the difference between the "snowfall temperature" and the standard synoptic temperature at Neumayer. Monthly mean values were calculated for 1981–97. The difference varies between 0° and 8°C, maximum values always being observed in winter. Precipitation events are usually accompanied by high wind speeds, so the inversion layer formed during clear periods is removed. Additionally, warm air is advected from the north. Therefore the "snowfall temperatures" are much higher than the average over all days.

Peel and others (1988) concluded that this observed biasing is the main contributor to the discrepancy between the spatial $\delta^{18}O/T$ ratio and the ratio required to deduce temperature change from an isotopic record.

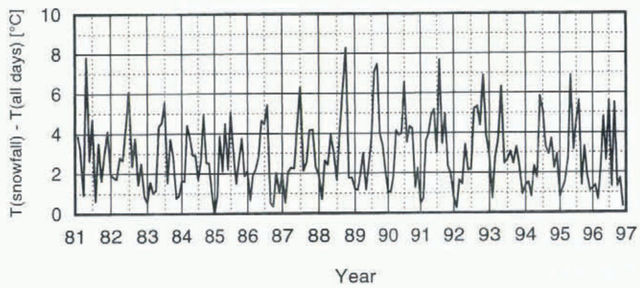

Fig. 1. Difference between monthly mean "snowfall temperatures" (defined in the text) and standard synoptic temperature at Neumayer, 1981–97.

3. DATA

3.1. Stake measurements

A stake array was set up 600 m southeast of the base on 18 March 1981. It consisted of 25 wooden stakes (length 1 m), which were set up in a 5×5 grid with a distance of 10 m between the stakes. On 21 February 1984 it was extended to 49 (7×7) stakes. Since March 1987 the stake array has been situated about 1500 m southeast of the base, and has consisted of 25 (5×5) 2 m metal stakes with a spacing of 5 m. The prevailing wind direction at Neumayer is easterly, and northerly winds are the least frequent. Thus the influence of the station building should be small at this site. The stakes have been measured weekly (with only a few exceptions) until today. Although a small amount of melting is observed close to the surface during summer, the stakes remain frozen to the surrounding snow at lower levels and thus do not melt in. Once a year, usually at the end of summer, the stakes were taken out and set afresh next to the old holes. They could be removed only using a plumber's wrench, evidence that they were firmly frozen into position.

The surface was usually fairly rough and showed sastrugi of different sizes. The mean of the height change at the 25 stakes should nevertheless give a representative value for the accumulation.

3.2. Snow pits and shallow firn cores

Snow pits were dug and shallow firn cores were taken at irregular intervals, mostly during summer. Additionally, surface snow samples were taken when snowfall occurred at low wind speeds, to avoid mixing of the snow due to snowdrift. These samples, as well as the ones taken from snow pits and the cores, were analyzed in Germany at the GSF, Institute for Hydrology, Neuherberg, the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, and the University of Heidelberg (e.g. Reinwarth and others, 1985; Moser and Reinwarth, 1990).

The electrolytical conductivity and oxygen- and hydrogen-isotope contents (^{18}O, ^{2}H, ^{3}H) were measured. Usually the dating of the snow pits and cores was done using isotope contents, which show a relatively clear seasonal variation. Visual stratigraphy and electrolytical conductivity, which also depend on the season, were helpful when the isotope signal was not clear enough for an exact dating.

4. ACCUMULATION AT NEUMAYER

4.1. Wind erosion and redistribution of snow

At Antarctic coastal sites, snowfall events are usually accompanied by strong winds, and snow is whirled up from the surface. Thus the snow particles suspended in the air represent not only the precipitation itself, but also particles coming from the surface. This is called "blowing snow". The isotope content measured in a core would therefore be a mixture of the fresh snow and older snow from earlier events. The vertical transport of snow particles due to turbulent diffusion is proportional to wind speed. Under undisturbed conditions, as above an ice shelf, a constant wind speed soon leads to a state of equilibrium, with a constant particle concentration in the air. The particle flux from the surface to the air due to turbulent diffusion equals the sedimentation due to gravity. If the wind speed increases, more particles flow into the air, and the snow surface is eroded. Decreasing wind speed results in snow accumulation on the ground (Liljequist, 1979). If there is snow in the air without snowfall, it is called "drifting snow". In most cases it is impossible to distinguish between blowing snow and drifting snow. A storm event can bring accumulation, as well as ablation due to erosion of the snow surface. Thus it is useful to investigate how much of the total accumulation is removed by wind erosion and cannot be found in the cores or pits by the end of the year.

Negative values of change in snow height can be measured at the stake array not only due to erosion, but also due to melting and settling of the snow cover. Melting rarely occurs, and normally the meltwater refreezes within the annual layer, which means no loss for the mass balance. The amount of settling of the snow cover depends strongly on the amount and initial density of the fresh snow and on the temperatures after the snowfall, and can be estimated by comparing stake and core/pit data or by looking at the stake data during quiet weather periods. Usually the settling of the snow cover leads to a decrease in snow height at the stake array of a few mm $week^{-1}$. In summer, under certain conditions, this value can increase to a few cm $week^{-1}$.

To determine the amount of wind erosion, the 3 hourly SYNOP observations at Neumayer were used to find out during which periods negative snow-height changes occurred without snowdrift being observed. Figure 2a shows the net accumulation, the cumulative ablation (sum of negative snow-height changes) and the ablation due to wind erosion. Melting and settling of the snow cover are almost negligible compared to erosion. Figure 2b shows the sum of positive stake values and of negative stake values, and ablation as a percentage of the total accumulation. Up to 50% of the accumulated snow is removed afterwards by wind influence, but on average only about 30% of the total accumulation is lost. The highest amounts of ablation occur after heavy snowfall or drift events, with >10 cm of snow accumulated within 1 week. Values up to 13.5 cm within 4 days occur. It is possible that entire snowfall or drift events are missing in the cores, but generally the ablation is distributed evenly over the year, and in most cases (at least for major events) only part of the preceding accumulation is removed, so part of it remains in the cores and snow pits.

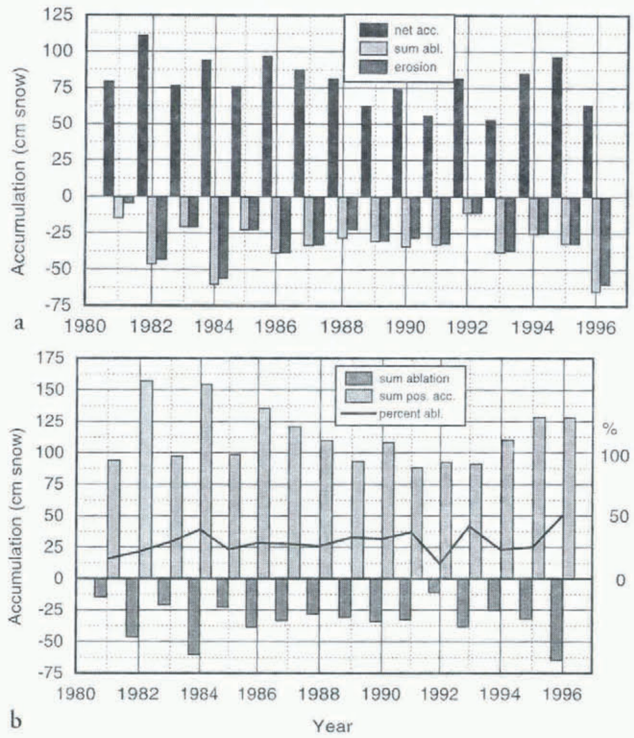

Fig. 2. Net accumulation, sum of negative snow-height changes, and amount of ablation due to wind erosion (a), and sum of positive and negative stake values, respectively, and ablation as percentage of total accumulation (b) at Neumayer, 1981–96.

4.2. Temporal accumulation distribution

Yearly accumulation rates were determined from the cores using isotope stratigraphy, in cases of doubt sometimes together with visible stratigraphy and the conductivity profile.

Figure 3a shows the mean, maximum and minimum monthly accumulation at the Neumayer stake array during the period 1981–96. (Values are given in cm snow and not in mm w.e., because there are no surface snow-density measurements available and it is not possible to calculate the water equivalent on a monthly basis. Water equivalents calculated using only a constant density would pretend an undue level of accuracy. However, using the snow heights instead of water equivalents does not change the features described below.)

The interannual variability of accumulation is obviously

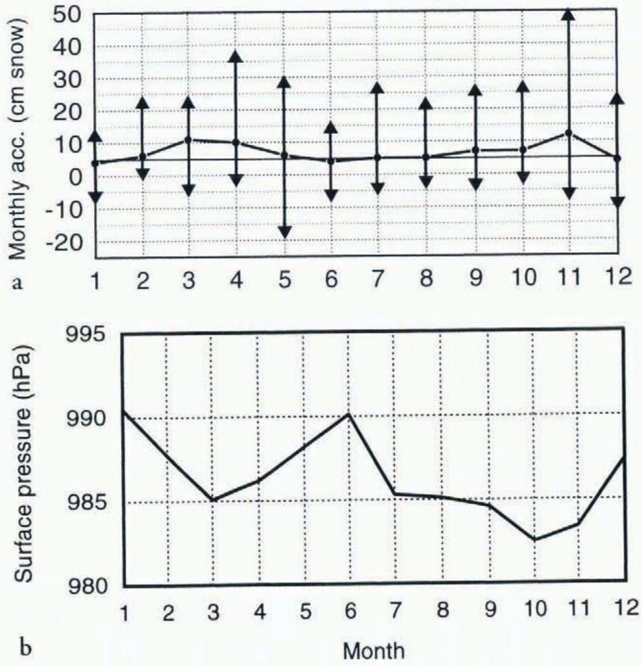

Fig. 3. Mean, maximum and minimum monthly net accumulation (a), and monthly mean surface pressure (b) at Neumayer, 1981–96. Negative values in (a) imply net ablation.

very high. For most months, positive deviations from the mean are much larger than negative ones. The highest accumulation values are usually observed in spring and autumn. These are well correlated with the values for monthly mean surface pressure, which are shown in Figure 3b. As at most Antarctic coastal stations, the pressure at Neumayer exhibits a semi-annual oscillation, with minima in spring and autumn, which indicates that there is maximum cyclonic activity during the equinoctial months. The circumpolar trough is deepest and also closest to the continent at that time (King and Turner, 1997). Since precipitation and thus accumulation are closely related to synoptic-scale activity, the observed accumulation distribution is not surprising.

Detailed information about the accumulation at Neumayer can be found in Pfaff (1993) and Schlosser and others (1998).

5. COMPARISON OF TEMPERATURE AND ISOTOPE CONTENTS

Figure 4 shows the annual mean temperatures at Neumayer, and the annual mean $\delta^{18}O$ values from two shallow firn cores

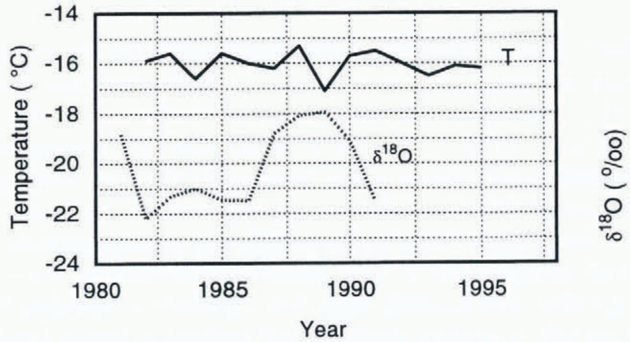

Fig. 4. Annual mean temperature and mean $\delta^{18}O$ values derived from two shallow firn cores at Neumayer. The scale is valid for both temperature and $\delta^{18}O$.

taken at Neumayer in 1989 and 1992, respectively. (The cores were analyzed by H. Oerter at the Alfred Wegener Institute.) Whereas the temperature is nearly constant, the $\delta^{18}O$ shows relatively low values until 1986 and quite high values during the second half of the 1980s. The year with the lowest temperature, 1989, has the highest $\delta^{18}O$ value. This is contrary to the linear relationship between temperature and isotope content mentioned above.

It is clear that the problem here cannot be the difference between the spatial and the temporal $\delta^{18}O/T$ gradient mentioned above, since this would still imply a linear relationship. To explain the observed difference between the behaviour of temperature and $\delta^{18}O$, other influences must be taken into account.

Of course, it would not make sense to try to derive a general relationship between temperature and $\delta^{18}O$ from such a short data series, especially from a coastal station having a high noise level like Neumayer. However, the observed discrepancies between measured temperature and $\delta^{18}O$ at Neumayer can be explained using detailed meteorological and glaciological data. The processes causing the observed isotope profile are basically the same as for a deep drilling in the interior of the continent, but can be studied here on a smaller time-scale. The interannual variability of accumulation patterns at Neumayer can have the same influence on the isotope profile that a change in the general circulation, for example due to a change in sea-ice extent, might have had on the isotope profile of a deep drilling in the interior.

6. EFFECTS OF SEASONAL VARIATIONS OF ACCUMULATION

Unfortunately, the cores taken most recently (1995) had not yet been analyzed at the time this study was carried out, so only about 10 years of measurements were available for our investigation, which is much too short a period to do any statistical calculations on the data. Nevertheless, we can learn much from looking at the average of monthly accumulation and pressure for the periods 1982–86 and 1987–90, respectively. These two groups of years were chosen because the years in each group show a common typical behaviour concerning the seasonality of the accumulation distribution and pressure.

Figure 5a shows the monthly mean accumulation for these two periods. In autumn no striking feature is found. But in late winter/early spring a large difference between the two periods occurs: during the years with high $\delta^{18}O$ values the accumulation was very low in August–October, whereas the years with the lower isotope values show a distinct accumulation maximum during that time. This again corresponds well to the surface pressure. Figure 5b shows the monthly mean surface pressure at Neumayer for 1982–86 and 1987–90. As for the pattern of accumulation, there are no large differences from summer to late winter, but in late winter/early spring the pressure is fairly high for 1987–90, which are the years with low accumulation and high yearly isotope values. In 1982–86 (high winter/early-spring accumulation, low yearly isotope averages) the pressure shows a distinct minimum in September and is still very low in October.

This means that the contribution of the relatively cold months, August, September and, to a lesser degree, October,

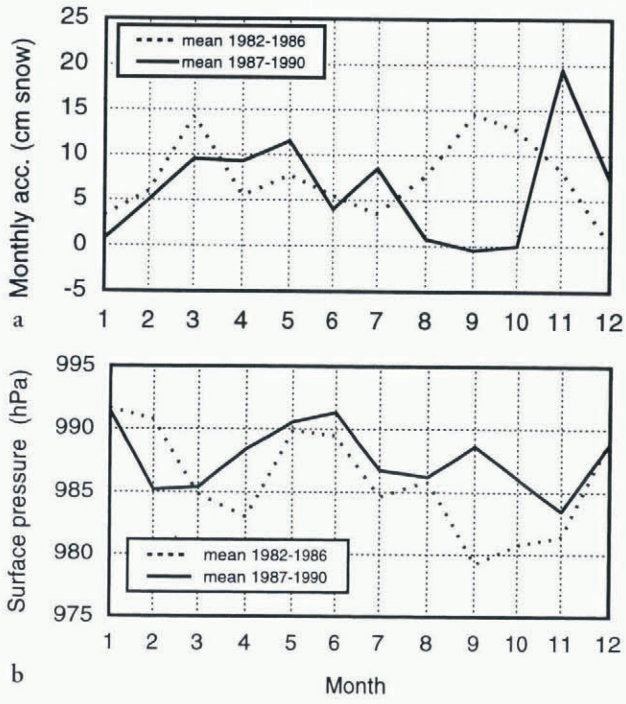

Fig. 5. Monthly mean accumulation (a) and monthly mean surface pressure (b) at Neumayer, 1982–86 and 1987–90.

to the accumulation and therefore to the annual mean $\delta^{18}O$ value is comparatively low during 1987–90, which leads to a higher mean isotope value than for the years 1982–86 with a more even accumulation distribution.

7. DISCUSSION AND CONCLUSION

The circumpolar trough must have been situated far to the north in winter/early spring during the late 1980s, so that cyclonic activity did not affect the coast around Neumayer as much as in the first half of the decade. This is confirmed by comparison of the monthly storm tracks from the European Centre for Medium-range Weather Forecasts analysis for August–October 1982–86 and 1987–90. During the late 1980s the number of low-pressure systems moving over Neumayer is lower than in the early 1980s, and often the storm tracks end near Neumayer, which indicates that the cyclones are already occluded and no longer bring much precipitation. Also the systems passing to the north of Neumayer, from west to east, are further away in the second half of the decade; therefore their influence on the weather at Neumayer is relatively weak.

The difference between the highest and the lowest annual mean $\delta^{18}O$ value is $>4‰$, which would correspond to a change in temperature of about 5°C using a gradient of $0.8‰\,°C^{-1}$ (Robin, 1983), whereas the amplitude of the observed temperature variation does not exceed 1°C. The mean annual temperature at Neumayer is −15.9°C (mean 1981–96); in most years the deviation from the average is <0.5°C. Without the directly measured temperature records the conclusion might have been drawn from the ice cores that the temperature at Neumayer had changed considerably during the last decennium.

The temperature difference of 5°C can give only an estimation of the possible error, since $0.8‰\,°C^{-1}$ is a mean value, which can vary considerably between sites. Some authors report that the linear relationship between temperature and $\delta^{18}O$ value is not valid below 1000 m a.s.l. (e.g. Dansgaard and others, 1973), but on both the Filchner–Ronne Ice Shelf (Graf, 1994) and Ekströmisen (Pfaff, 1993) such linear relationships were found. Pfaff (1993) investigated the oxygen-isotope contents of snow surface samples at Neumayer and their dependence on different meteorological parameters. He found the best correlation between monthly means of isotope content of the snow samples and monthly mean temperature at the lifting condensation level ($r = 0.93$), but the 2 m temperature (measured at the meteorological mast with a shielded and ventilated Pt-100 resistance thermometer) is also well correlated with the $\delta^{18}O$ values ($r = 0.85$). The correlation is better for monthly mean temperatures than for the temperatures during single snowfall events. Pfaff did not correlate yearly means of $\delta^{18}O$ with mean yearly temperatures, though, and his results cannot be compared directly with the core data, since he used surface snow samples, which were taken only after fresh snowfalls occurring without wind influence.

Of course, the time period considered is fairly short. However, we have to be extremely careful when looking at temperature records derived from ice cores. For shallow firn cores, which have recently been taken quite frequently to enlarge the spatial resolution of accumulation studies (e.g. Isaksson and Karlén, 1994a, b), often mean values over only a few years are calculated, which might be affected by the error described. But even the deep drillings, which provide time series of millennia, have to be considered with care, since over longer time periods the atmospheric circulation pattern might have changed in a way that causes differences in annual mean $\delta^{18}O$ values, which are not caused by a change in the local temperature.

Further continuous accumulation stake measurements are necessary to confirm the results presented here and to provide a dataset large enough to obtain statistically significant values.

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