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# SURFACE MASS-BALANCE VARIABILITY NEAR "BYRD" STATION, ANTARCTICA, AND ITS IMPORTANCE TO ICE CORE STRATIGRAPHY*

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Abstract. The local variability in surface mass balance (net snow accumulation) up-glacier from "Byrd" station, Antarctica, is due to the combined effects of year-to-year "climate" variations and of the surface microrelief due to snow drifts and sastrugi. These variabilities are consistent with the variability in surface mass balance obtained from core stratigraphy (Gow, 1968), and are used in a discussion of the difficulties encountered with the deep "Byrd" station core in detecting annual layering by the stable oxygen-isotope ratio and the microparticle concentration techniques. The recognition of annual layers by these techniques requires that the snows of certain seasons be present in the measured section, but near "Byrd" station the microrelief is such that summer snow layers are not horizontally continuous and may be absent from a given section. At other sites on ice sheets, where the microrelief is less (less wind activity) or where the surface mass balance is larger, or both, less difficulty is anticipated in using the stable oxygen-isotope ratio and microparticle-concentration techniques to identify annual layers.

Résumé. *Variabilité des bilans superficiels près de la station "Byrd" en Antarctique et son importance pour le stratigraphie des carottes.* La variabilité locale des bilans superficiels (accumulation nette de neige) du glacier supérieur de la station "Byrd" dans l'Antarctique est due à l'effet combiné des variations du "climat" d'une année à l'autre et du micro-relief superficiel engendré par les congères et les zastrougi. Ces variabilités sont cohérentes avec la variabilité dans les bilans superficiels obtenus par stratigraphie des carottes prélevées (Gow, 1968); on les utilise pour discuter les difficultés rencontrées dans les carottes profondes de station "Byrd" pour détecter la stratification annuelle par les techniques de la teneur en oxygène stable isotopique et de la concentration en microparticules. La reconnaissance des couches annuelles par ces techniques nécessite que les neiges de certaines saisons soient réellement présentes dans la section mesurée, mais près de la station "Byrd", le microrelief est tel que les couches de neige de l'été ne sont pas continues horizontalement et peuvent être absentes de certains points. Sur d'autres sites de calottes glaciaires dont le microrelief est moindre (moindre activité du vent) ou dont le bilan superficiel est plus fort, ou les deux, on escompte moins de difficultés pour utiliser les techniques de la teneur en oxygène isotopique stable ou de la concentration en microparticules pour identifier les couches annuelles.

Zusammenfassung. *Schwankungen der Massenbilanz an der Oberfläche bei der "Byrd"-Station, Antarktika.* Die lokalen Schwankungen der Massenbilanz (Netto-Schneeakkumulation) an der Oberfläche gletscheraufwärts von der "Byrd"-Station, Antarktis, werden durch die kombinierte Wirkung von jährlichen Klimaunterschieden und der Schneedrift sowie Sastrugibildung in Abhängigkeit vom Mikrorelief der Oberfläche verursacht. Diese Schwankungen stimmen mit denen der Massenbilanz an der Oberfläche überein, die aus der Stratigraphie von Bohrkernen ermittelt wurden (Gow, 1968), und werden zur Klärung der Schwierigkeiten herangezogen, die bei der Feststellung von Jahresschichten am Kern der Tiefbohrung an der "Byrd"-Station mit Hilfe des Verhältnisses der stabilen Sauerstoff-Isotope und der Konzentration an Mikropartikeln auftraten. Die Feststellung von Jahresschichten mit diesen Verfahren erfordert das Vorhandensein des Schnees bestimmter Jahreszeiten im untersuchten Abschnitt; bei der "Byrd"-Station ist das Mikrorelief der Oberfläche jedoch so gestaltet, dass die Schichten des Sommerschnees horizontal nicht kontinuierlich sind und deshalb in einem bestimmten Abschnitt fehlen können. An anderen Stellen von Eisschilden mit weniger ausgeprägtem Mikrorelief (geringerer Windeinwirkung) oder mit grösserer Massenbilanz an der Oberfläche oder mit beidem dürften die Schwierigkeiten bei der Feststellung von Jahresschichten aus dem Verhältnis der stabilen Sauerstoff-Isotope und aus der Konzentration an Mikropartikeln geringer sein.

## Introduction

It is important to understand the variability in surface mass balance (net snow accumulation) on ice sheets so that ice core stratigraphy can be properly interpreted and so that limits of confidence can be placed on the seasonal values of surface mass balance that are used in glacier flow models. The variability can be caused by significant variations in ice-sheet climate, by the effects of drifts and sastrugi, by the movement of the ice sheet through a surface mass-balance pattern, and by short-term climatic variations. Many of these influences can be investigated using surface mass balances obtained from pole height measurements.

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Bamboo poles were placed in two rows, 3 km apart, which ran 168 km up-glacier from "Byrd" station, Antarctica, along the "Byrd" station strain network (Fig. 1). The exposed lengths of poles at 267 sites were measured at two- or three-year intervals between 1964–65 and 1973–74 (some poles were also measured in 1963–64). Surface mass balances have been calculated using these data, taking account of the depth variation of firn density, and of firn and pole settling (Whillans, 1975[b]); vertical strain associated with the ice flow (Nye, 1968; Vallon, 1968) does not affect the measurements significantly. Figure 2 shows the distribution of surface mass balance along the traverse.

There are two surface mass-balance regimes along the traverse. The large surface mass balances near 0 km may be related to orographic effects on air masses coming from the Amundsen Sea (from the left in Figure 2) (Rubin and Giovinetto, 1962). The region to the right of 40 km is on the lee side of the ice sheet with respect to the Amundsen Sea air masses, and the snow accumulation may be related to the more uniform radiational cooling over the ice sheet. The region between 0 km and 40 km appears to be affected by both surface mass-balance regimes.

The region to the extreme left of Figure 2, near the ice crest at 0 km, experiences variations in surface mass balance, epoch to epoch, that differ from the variations in surface mass balance to the right of 40 km. Near the ice crest, both the value of the surface mass balance and the horizontal gradient vary with time. The remaining region, identified by the thicker axis lines, experiences much simpler variations, and it is this simpler region that is considered in this analysis.

Figure 2 also shows that the region between 40 km and 160 km has a consistent areal pattern in surface mass balance that varies in a simple fashion among the measured epochs. The pattern is related to surface slope and is due to snow re-distribution by katabatic or inversion winds (Whillans, 1975[a]). The uniform change in surface mass balance, epoch to epoch, in this region indicates that secular variations in surface mass balance on a scale of about 40 km are not important to surface mass balances measured over two- or three-year intervals. Frontal storms might be expected to remove snow from, or deposit snow in, restricted areas but such activity does not appear in the data. Perhaps the rather large distance from the sea, high elevation, simple surface form, and uniform albedo of the ice sheet contribute to a weaker development of frontal systems near "Byrd" station. The variability in surface mass balance as measured at one site is due to the separate contributions of short-term climate changes and surface relief of snow drifts and sastrugi. The simplicity of the change in surface mass balance in this region is important because it allows calculation of these separate contributions.

The surface mass balance at any site is thus the combined effect of:

(1) the long-term mean surface mass balance,

(2a) epoch-to-epoch variations in surface mass balance associated with such factors as the general vigour of atmospheric circulation, or sea-ice limits,

(2b) chance variability in the number of storms affecting the region, and

(3) the position of the measured pole with respect to local drifts and sastrugi both at the beginning and the end of the measurement epoch.

A possible fourth factor, local snowfall or drift events, is not important, as discussed above. Factors (2a) and (2b) cannot be separated using the present data, and are grouped together as "short-term climatic effects".

Expressing this as an equation, the annual surface mass balance $b$ is equal to the time mean for the site ${}^{t}\bar{b}$ with variations due to climate $\Delta b_c$ and to drifts and sastrugi, $\Delta b_s$:

$$b = {}^{t}\bar{b} + \Delta b_c + \Delta b_s. \qquad (1)$$

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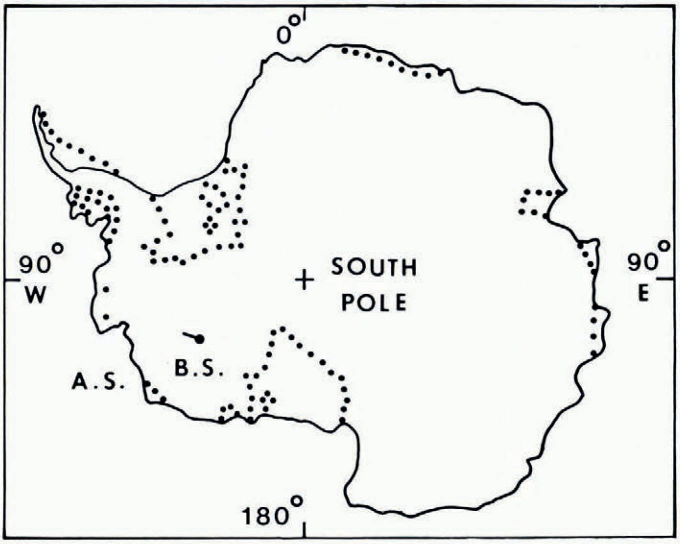


*Fig. 1. Antarctica. The study area is the short straight line leading to "Byrd" station* (B.S.). *The Amundsen Sea is labelled* A.S.

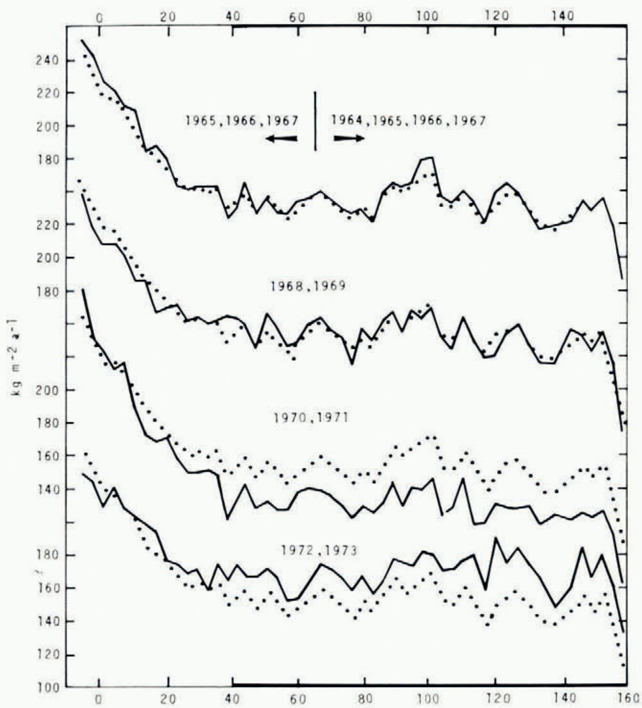


*Fig. 2. Surface mass balances for the epochs as labelled. Each data point represents the mean for poles in a 3 by 3 km² square (4 to 10 poles). The long-term mean is shown as a dotted line. "New Byrd" station is at 162 km.*

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## Climate variation

The variability due to climate during the years 1965–73 can be assessed by taking the mean of all pole sites in the region between 40 and 160 km that have uninterrupted records (206 sites):

$$\left.\begin{aligned} {}^{\mathrm{a}}\overline{b} &= {}^{\mathrm{t,a}}\overline{b} + {}^{\mathrm{a}}\overline{\Delta b_{\mathrm{c}}}, \\ \text{or} \qquad {}^{\mathrm{a}}\overline{\Delta b_{\mathrm{c}}} &= {}^{\mathrm{a}}\overline{b} - {}^{\mathrm{t,a}}\overline{b}, \end{aligned}\right\} \tag{2}$$

where ${}^{\mathrm{a}}\overline{\phantom{x}}$ signifies that the mean of the 206 sites is taken. The variation due to drifts and sastrugi $\Delta b_{\mathrm{s}}$ does not appear in these equations (Equations (2)) because this variability is due to features having a horizontal extent of the order of 10 m or less, which do not significantly affect the average of many poles whose minimum spacing is 1 km. The variance due to climatic effects $S_{\mathrm{c}}^2$ is given by

$$S_{\mathrm{c}}^2 = \{2.25/(N-1)\}\, \Sigma({}^{\mathrm{a}}\overline{\Delta b_{\mathrm{c}}})^2,$$

where $\Sigma$ signifies summation over the various epochs, $N$ is the number of epochs, and 2.25 is the average length of measurement epoch. Implicit in this is the assumption that the mean areal surface mass balance of one year does not affect that of the following year. A meteorological feedback mechanism with this time scale is difficult to envisage and the assumption seems to be appropriate. The standard deviation for climatic effects is thus found to be

$$\begin{aligned} S_{\mathrm{c}} &= \sqrt{S_{\mathrm{c}}^2} \\ &= 20 \text{ kg m}^{-2}. \end{aligned}$$

## Drifts and sastrugi

The surface mass balance as measured at a single pole site, in addition to being affected by the "climate" common to the region, is strongly influenced by the surface microrelief. A measure of the effect of this microrelief on the surface mass balance is obtained from Equation (1) and the climatic variations, ${}^{\mathrm{a}}\overline{\Delta b_{\mathrm{c}}}$.

The surface of the ice sheet is usually rough. During the summer, when measurements were taken, the relief is 0.1 to 0.3 m, varying on a horizontal scale of 1 to 10 m. The surface is rougher after certain storms but measurements were not taken until the relief had decreased to a more normal condition (partly because travel is difficult on a rough surface). The relief develops in snow deposits that are partly eroded by the wind and associated drifting snow. The eroded forms are called sastrugi and new depositional drifts form in the lee of the sastrugi. The surface is continually evolving and the shapes can be complex. If the wind decreases, the relief decreases within a few days due to sublimation, to the filling of hollows with new snow accumulation (Gow, 1965; Giovinetto and Schwerdtfeger, 1966), and to densification and vertical settling of the positive relief elements.

The "climatic" variations ${}^{\mathrm{a}}\overline{\Delta b_{\mathrm{c}}}$, according to the arguments discussed earlier, are taken as affecting the entire region between 40 and 160 km uniformly and additively, that is, $\Delta b_{\mathrm{c}} = {}^{\mathrm{a}}\overline{\Delta b_{\mathrm{c}}}$, and Equation (1) can be used to describe the variations in surface mass balance due to the remaining effects of drifts and sastrugi:

$$\Delta b_{\mathrm{s}} = b - {}^{\mathrm{t}}\overline{b} - {}^{\mathrm{a}}\overline{\Delta b_{\mathrm{c}}}.$$

Since the annual surface mass balance along the traverse between 40 and 160 km is nearly constant at (Fig. 2)

$${}^{\mathrm{t,a}}\overline{b} = 150 \text{ kg m}^{-2},$$

it is not possible to determine whether the "climatic" effects vary in proportion to the mean balance or as constant linear additions to, or subtractions from, the mean balance. For the same reason, however, it is immaterial which model is used and we choose the simpler linear addition model.

Time epochs of two or three years are used for $b$ and $^{a}\overline{\Delta b_c}$, so that the summed effect of drift and sastrugi relief at the beginning and end of the epoch is given by $\Delta b_s T$ where $T$ is the length of the epoch. The variance due to drift and sastrugi relief at a single time is

$$[2(N-1)(M-1)]^{-1}\Sigma^{e}\Sigma^{p}\Delta b_s T,$$

where the summation $\Sigma^{p}$ is taken over the pole sites, the summation $\Sigma^{e}$ over the epochs, $M$ is the number of pole sites with uninterrupted records, and the factor of 2 makes the variance applicable to the relief at only one end of the epoch. The standard deviation so calculated is $S_s = 20$ kg m$^{-2}$ for each surface.

The drift and sastrugi relief can be calculated in another manner. In 1969–70 new bamboo poles were set out, so that for the epoch 1970–71 148 pole sites have surface mass balances available from both the old and the new bamboo poles. The pole pairs are separated by 1–2 m and were set at about the same elevation in 1969–70. The drift and sastrugi pattern, of course, changed many times before the next re-measurement in 1971–72 and the differences between the surface mass balances calculated for the two poles is a measure of drift and sastrugi relief in 1971–72. The standard deviation obtained from this information is 19 kg m$^{-2}$ which confirms the meaning of the value of $S_s$ calculated above. Less reliance is placed on this second method, however, because it is not certain that the pole pairs are sufficiently widely spaced to be independent measures of relief in 1971–72, and furthermore, this result is relevant only to the relief in 1971–72.

## Core stratigraphy

The record discussed above is short, covering only nine years, but it is valuable because it has wide areal coverage and is relevant to the core studies conducted at "Old" and "New Byrd" stations (168 km and 162 km respectively on the scale of Figure 2). For example, snow deposited at 40 km will take 20 000 years to reach the "New Byrd" station deep core site and will be at a depth of about 1 600 m according to the usual ice flow models (Johnsen and others, 1972; Gow and others, 1973; Whillans, 1976).

A good record of annual stratigraphy is available from the "Old Byrd" station core covering the period 1549 to 1959 (Gow, 1968). By the model described here, that record will show variations due to the combined effects of short-term climatic variability and to the roughness of the buried snow surfaces. If such a record is to be interpreted in terms of meaningful climate change, the variability due to the other effects must be evaluated.

Gow (1968) measured the distance between hoar-frost layers that form in the buried summer snow during the autumn, and multiplied this factor by the firn density to obtain a record of surface mass balance. Assuming that the results of Gow's method and the pole height method used here are comparable, the present work predicts that the variability in Gow's data will be the combined effect of "climatic" variations $S_c$ and the roughness of the summer layers defining the lower $S_s$ and the upper $S_s$ limits to each annual increment. The standard deviation for the data of Gow (predicted from the results of the research reported here) is thus

$$(S_c^2+S_s^2+S_s^2)^{\frac{1}{2}} = 35 \text{ kg m}^{-2}.$$

This compares well with the standard deviation of 39 kg m$^{-2}$ obtained from Gow's data, thus confirming the interpretation which Gow gave to the core stratigraphy.

The somewhat larger variability in Gow's core data is probably because surface mass balances in the present work are obtained from measurements on well-dated surfaces (the surfaces on the days of measurement), but the core data are obtained from measurements between levels in the summer snow dated less precisely.

Long-term changes in the surface mass balance due to movement of the core-hole site through a horizontal, geographically-fixed variation in surface mass balance (such as shown in Figure 2), or to climatic change on a scale of 30 years or larger are of minor importance in Gow's profile.

Gow (1965) notes that, at the South Pole, the surface relief due to drift and sastrugi does not confuse the stratigraphy as much as may be expected. Positive features are exposed longer to deflation as preferentially snow accumulates in the hollows, so the relief becomes subdued during burial. If this were an important mechanism near "Byrd" station, the variability in core stratigraphy should be much less than that inferred from pole-height measurements. Because of the agreement between pole height and core variabilities, we suppose that, at "Byrd" station, the surface relief is largely preserved in the stratigraphy.

The variabilities predicted and obtained from Gow's core data are larger than the values of 15, 7, 27, and 14 kg $m^{-2}$ given by Cameron (1971) and of 11 and 24 kg $m^{-2}$ by Benson (1971) very close to "New Byrd" station. The surface mass balance is smaller at "New Byrd" station (Fig. 2, 162 km) than elsewhere along the traverse and "New Byrd" station is protected from the most active katabatic- or inversion-wind action by a low hill. Perhaps this protection explains the low variability in surface mass balance close to "New Byrd" station.

## Discussion

The distribution of surface relief due to drifts and sastrugi is shown in Figure 3. Because the present data are derived from pole height differences, a positive relief feature of the upper surface affects the surface mass balance in the same way as a negative feature in the lower surface, and it is not possible to use the data to test for skewness in surface relief. Figure 3 thus depicts the magnitude, not the sign, of surface mass-balance differences from the mean due to the effects of drift and sastrugi.

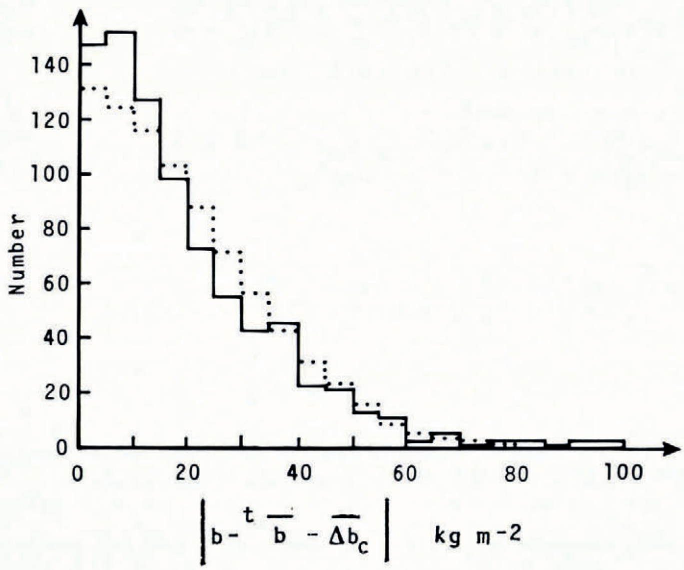


*Fig. 3. Frequency distribution of surface mass-balance deviations from the mean due to snow drifts and sastrugi. The dotted line is a normal distribution for comparison. (Total number of observations = 824.)*

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The distribution is not "normal" and a normal distribution is drawn for comparison. Most of the ice-sheet surface is close to the mean value. Most local surface slopes are very similar to the regional slope, and large hollows and hills constitute a small proportion of the surface. The narrowness of the small-value (left-hand) part of the distribution is probably due to the processes that lower the positive relief features and fill the hollows. Larger variations at about 40 kg $m^{-2}$ are however important, probably because a large variation in surface mass balance during one epoch must be approximately balanced by a large variation of the opposite sense during the following epoch because of those processes which act to maintain the surface as fairly flat. Thus, large variations tend to occur in matched pairs, and there is important variability at about 40 kg $m^{-2}$.

The distribution of both climatic and drift and sastrugi effects cannot be evaluated with the pole data because the time length of the record is too short. A distribution is however obtained from the data of Gow discussed above and is plotted as Figure 4. This distribution is

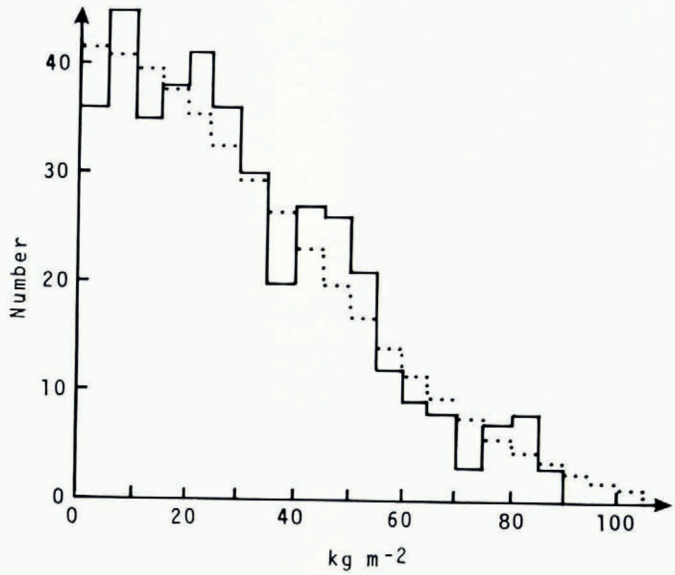


*Fig. 4. Frequency distribution of deviations from the mean in core stratigraphy. The variations are due to the combined effects of the surface relief and "climatic" variations in the regional mean surface mass balance. Data obtained from Gow (1968; personal communication, 1977). Dotted line is a normal curve for comparison. (Total number of observations = 408.)*

different in shape from the drift and sastrugi distribution because it includes both the climatic variability and the uncertainty in the time position of hoar-frost layers. The standard deviation is, as shown earlier, similar to that predicted from the pole-height data (two-thirds of the variance being due to drift and sastrugi and one-third to climatic variability).

The mean surface mass balance between 40 and 160 km of the traverse is 150 kg $m^{-2}$ $a^{-1}$ and, by Figure 4, the probability of a missing year in core stratigraphy is very small.

Other methods of annual stratigraphic core dating have more stringent requirements for success. The detection of stable oxygen-isotope or microparticle variations (Johnsen and others, 1972; Thompson and others, 1975) requires that the snow of a particular season be present. The oxygen-isotope method may require, for example, that each summer snow layer be present. If the summer snow layer is of, say, 50 kg $m^{-2}$, then the probability of it being absent in a core due to drifts and sastrugi alone is 0.03 or 1 : 36 (Fig. 3). This neglects the additional possibility that, due to climatic variability, the summer layer may be thin anyway and therefore more prone to being absent from a core. Methods which require the recognition of the winter layer may present greater difficulty because the standard deviation in winter surface mass balance is twice that of the summer (Benson, 1971).

Figure 5 shows the oxygen isotopic ratio and the microparticle concentration profiles from the walls of shallow pits at 106 and 108 km on the traverse. The dating is based on nearby pole height measurements, and on gross-beta-activity measurements on the samples used for the isotopic analysis. The microparticle profile was taken about 1 m from the oxygen isotopic ratio profile in that pit. Neither the oxygen isotopic ratio nor the microparticle concentration profiles record every annual layer unambiguously. (Note the problems with the 1971 layer in both the microparticle and oxygen isotope stratigraphies in pit 2 803). The detection of seasonal variations using data for oxygen isotope ratios is, in some cases, also made difficult by isotopic diffusion during firnification (Johnsen, 1977).

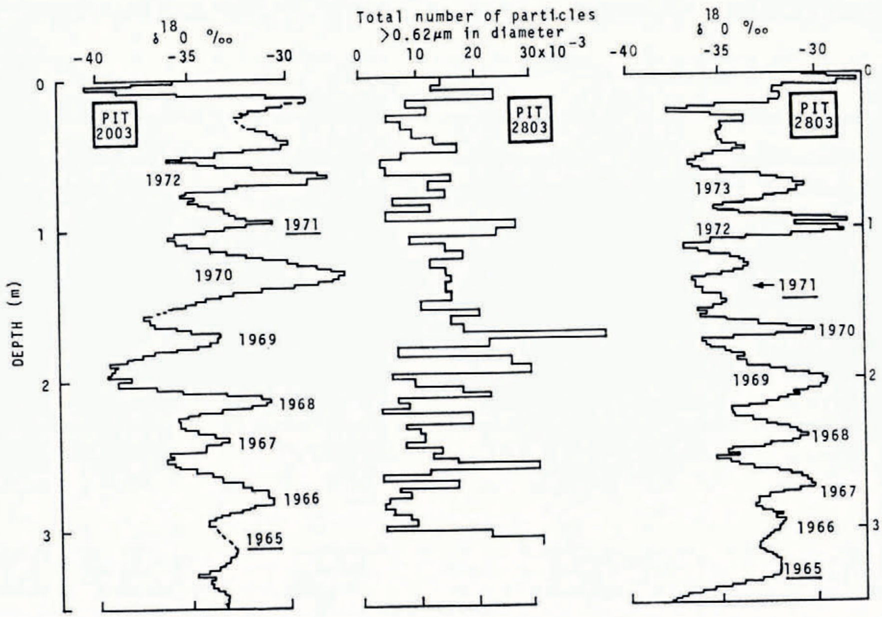


*Fig. 5. Oxygen isotopic ratio ($\delta^{18}O$) as defined by Dansgaard and others (1973) and microparticle concentration (Thompson, unpublished) profiles from 106 km (pit 2 003) and 108 km (pit 2 803). The underlined dates are obtained from gross-beta-activity peaks in the samples that were also used for $\delta^{18}O$ measurements. The other dates are interpretative. The samples were collected in 1973–74 and allowance must be made for the possibility of erosion of the surface before final burial. Data gaps are joined by dotted lines.*

The importance of drift and sastrugi relief and of short-term climatic variability varies from site to site. At "Plateau" station, for example, Koerner (1971) found the standard deviation in the annual surface mass balance to be only 14–20 kg m$^{-2}$, much less than the 35 kg m$^{-2}$ along our traverse and the 39 kg m$^{-2}$ in the "Old Byrd" station core. Estimates of surface mass balance variability for the South Pole area (Giovinetto, 1964, table 7A) are comparable with (one estimate) or somewhat larger than (two estimates) our variabilities. At the South Pole, the mean annual surface mass balance is 70 kg m$^{-2}$ (Bull, 1971), with the probability of a missing year in core stratigraphy being 0.029 if the distribution of Figure 4 can be applied to the South Pole area. Giovinetto (1960), at the South Pole, obtained a better record than this prediction would suggest because he worked with wide sections and was able to trace layers horizontally and so detect any missing layers due to drifts and sastrugi.

## Conclusion

The studies demonstrate the importance of the surface microrelief to the interpretation of ice core stratigraphy. The largest part of the variability in annual layer thickness at "Byrd" station is due to the effect of drifts and sastrugi, and not to climatic variations. The variability is sufficient to cause many seasonal snow layers to be absent, and techniques of stratigraphic interpretation that depend on the presence of snow layers of specific seasons will have difficulty with the reliable counting of years.

These considerations are important for the interpretation of existing ice cores and for the selection of new sites for core drilling. If the annual stratigraphy is to be capable of interpretation, both the value of surface mass balance and the surface relief need to be considered. Even though seasonal variations cannot be reliably detected near "Byrd" station (Fig. 5) where the surface mass balance is 150 kg $m^{-2}$ $a^{-1}$ (Johnsen and others, 1972, 1977), other sites of about the same, or even smaller, surface mass balance may have an annual stratigraphy which can be interpreted if wind action is less important than near "Byrd" station.

## Acknowledgements

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