OPTICAL LEVELLING ACROSS AN ANTARCTIC ICE SHELF

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ABSTRACT. A 66 km. optical levelling profile was measured approximately along a flow line from the inland ice sheet to the ice front. A second profile 69 km. in length was measured across the direction of flow. The flow-line profile was re-levelled after an interval of 3 years to test whether the ice shelf was in steady state. There were no significant changes and it was concluded that an interval of at least 10 years would be required to smooth out random short-term fluctuations in surface level.

IF only a fraction of 1 per cent of the Antarctic ice sheet were to melt, there would be a noticeable rise in world sea-level. Any large change in area of the ice cover would alter the average albedo of the South Polar regions and so affect the climate of at least the Southern Hemisphere. Studies of the fluctuations of the Antarctic ice sheet are therefore of concern both to scientific and to practical interests. Giovinetto (1970) suggested that the Antarctic ice sheet was responding bi-modally to present climatic conditions, with an interior zone thickening while the peripheral zone was thinning to give a negative net balance. Partial support for this model was given by Hollin (1970), who summarized independent evidence pointing to thickening in parts of central Antarctica. More recently, however, Hughes (1973) has proposed that West Antarctica is unstable and now in a stage of retreat. A reliable estimate of mass balance for any area requires measurements of ice velocity, strain-rate, snow accumulation, ice thickness and surface elevation, all made along a flow line together with bore-hole measurements of strain-rate, density and ice velocity. On an ice shelf, the bore-hole measurements can reasonably be omitted, since in this case ice velocity is independent of depth, and boundary conditions at the upper and lower surfaces are known. With this in mind, a programme of field work was begun in 1966 on the Brunt Ice Shelf (lat. 75° 30′ S., long. 26° W.), one of several small ice shelves fringing the east coast of the Weddell Sea. The general results of this work have been described in Thomas (1973), where reference is made to more detailed topics published elsewhere. Here we describe the levelling techniques employed in measuring elevation profiles across the ice shelf, and we discuss the glaciological significance of the results.

During the austral summers of 1966–67 and 1967–68 a number of optical levelling profiles were measured on the Brunt Ice Shelf (Fig. 1). The purpose of the main profile (profile 1) was the measurement of surface slope along a flow line, and most of this profile was re-levelled late in 1970 with the intention of checking whether the Brunt Ice Shelf was in steady state. Steady state implies a surface profile, related to geographically fixed coordinates, that is invariant with time. Profile 1 followed a line of stakes inserted for movement studies in 1966 (Thomas, 1970). When these studies were completed, it was found that near its mid-point the profile deviated from a true flow line by up to 5 km. However, a transverse level profile (profile 2), which ran at an angle to profile 1 and crossed it near its mid-point, gave additional information that allowed a flow-line profile to be deduced.

A Hilger and Watts "Autoset Level 2" equipped with stadia lines was used in conjunction with "Nedo" 4 m. wooden staves. The staves were placed on metal plates of diameter 25 cm. that were steadied by a spike knocked into the underlying snow. In an attempt to minimize errors due to sinking into soft snow of staff or tripod, the metal plates and tripod legs were painted white, and the snow at each station was well trodden before setting up either instrument or staff. The heights of the plates and of the instrument above the snow surface were recorded at each station. The profiles were measured along staked routes marked with flagged stakes every 3–5 km. In the earlier survey at least one additional stake was planted between the main stations, and an appropriate stake would be used as a datum to carry the elevation over to the next section. A straight line was levelled between the main stations except near the hinge line, where a zig-zag route was dictated by the terrain. Detailed comparison between the 1967–68 and 1970–71 observations are possible over two-thirds of profile 1, where identical routes were followed. Elsewhere we can deduce general trends from the characteristics of the surface undulations.

The lengths of back and fore sights were paced and, unless the surface was unusually steep, they were in the range 50–55 m. Whereas in the earlier surveys one back sight and one

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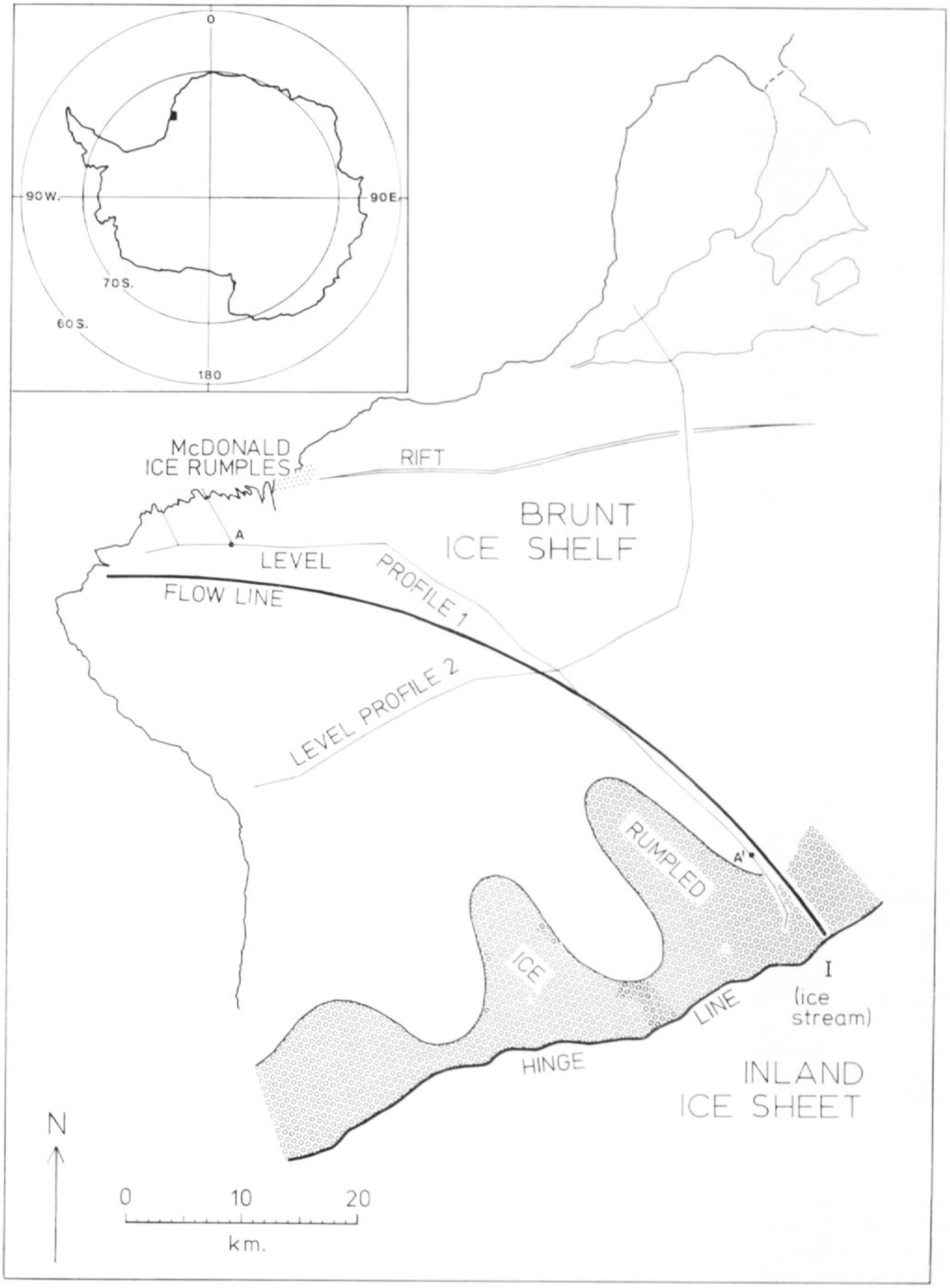

Fig. 1. The western part of the Brunt Ice Shelf showing a flow line and the routes of levelling profiles across the ice shelf.

fore sight was observed at each instrument station, during 1970–71 an additional intermediate sight was observed in each direction giving four sightings at each station and snow-surface elevation at intervals of 40–45 m. In 1967–68 levelling was completed in both directions between main stations so that a misclosure could be assigned to each 3–5 km section. During the later survey, temporary stations were planted at 0·5 km. intervals to serve as datum levels. Two-way levelling was completed between each of these temporary stations to give misclosures every 0·5 km. By staggering the instrument positions occupied on the outward and return legs it was possible to obtain surface elevations every 25 m. When two staff men were used, almost instantaneous back and fore sights could be observed and up to 5 km. one-way levelling could be completed in a day. However, the rate of progress was usually slower since most of the time there was only one staff man.

Misclosures in levelling runs taken from actual sea-level up on to the ice shelf were not significantly larger than those levelled on smoother parts of the ice shelf, indicating that the ice was rising and falling freely with the tide. Sea-level was taken either from the free water surface in a wide crack in the sea ice or from a hole drilled through the ice. In the latter case, melt water drained into the hole from the surrounding snow, and sea-level was found by applying a correction to the water level, assuming that melt water extended to the bottom of the sea ice and that its density was that of pure water. On one occasion, when levelling to sea surface in a deep crack in the sea ice, a surge of some 3 cm. was observed and the mean of a series of "highs" and "lows" was taken as sea-level. Levelling on to the ice shelf from two independent sources of sea-level gave station elevations that agreed to within 1 cm.

A frequency distribution of misclosures revealed by two-way levelling is shown in Fig. 2. For this purpose, observed values were standardized to values representing a 5 km. leg by assuming that the misclosure increased linearly with the distance levelled. Errors expressed by the misclosures include:

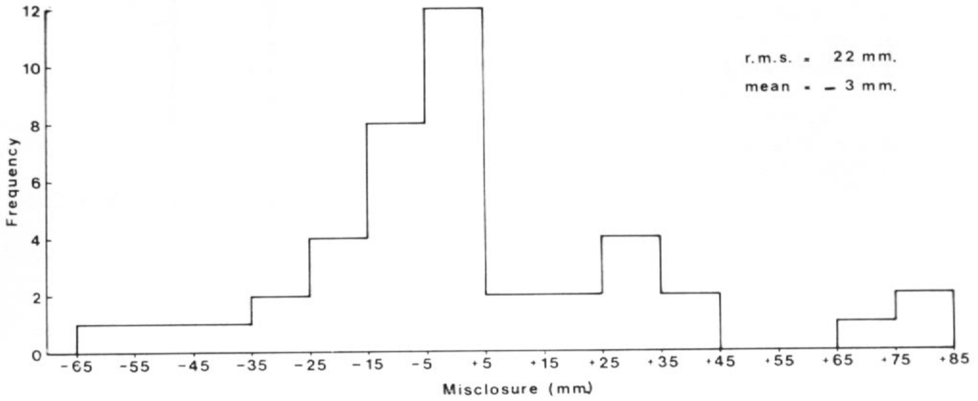

Fig. 2. Histogram of levelling misclosures.

i. Random observing and instrument errors.
ii. Short-period flexing of the ice shelf resulting, for instance, from temporal variations in atmospheric pressure gradient along the levelling route, changes in winds or sea currents, or the action of long-period ocean waves.
iii. Sinking of the instrument tripod or of the staves into soft snow. This type of error should be cumulative, giving rise to a systematic positive misclosure. The group of large positive misclosures shown in Fig. 2 occurred when levelling over particularly soft snow and these were probably due to sinkage. A linear distribution of misclosures should largely correct this type of error; the group of large positive misclosures has not therefore been included in the calculation of average and root-mean-square values.
iv. Errors due to dissimilar refraction conditions or to unequal lengths of back and fore sights. Frequent checks indicated that refraction was variable with time and when

only one staff man was used there was considerable delay between observations of back and fore sights. Similarly, any imbalance between the lengths of back and fore sights must increase refraction errors. However, lengths determined from the stadia readings revealed an average imbalance of only 0·5 m. per 50 m. leg.

The average misclosure for a 5 km. leg was found to be −3 mm., which is sufficiently close to zero to imply that errors causing the misclosures were random. A linear distribution of the relevant misclosure was applied to the results from each leg so that the root-mean-square error after levelling a distance of 5 km. was $\pm 22/2 = \pm 11$ mm. After levelling 50 km. this leads to an error of $\pm 11\sqrt{10} = \pm 35$ mm.

The errors described here apply to each survey and refer to the profile relative to sea-level as observed at the ice front. They do not include possible errors due to very long-period flexing of the ice shelf, which would affect the observed differences between the two surveys. Such flexing can occur in response to:

i. Sustained atmospheric pressure gradients across the ice shelf, e.g. 1 mbar/50 km. would lead to an error of 1 cm. per 50 km.
ii. Salinity changes in the sea beneath the ice shelf. A change with time of 0·05‰ would result in an elevation change of between 0·5 and 1 cm., depending on the ice thickness.
iii. Spatial variation of the venturi pressure applied to the ice shelf by winds and sea currents. For instance, a 50 kt wind will raise the surface 5 cm. and a 2 kt sea current will depress the surface by a similar amount, the depression being proportional to the square of the sea current. This phenomenon will produce errors only when its influence varies along the profile. The effect of winds can be ignored, since observations were seldom attempted in winds greater than 15 kt and conditions were probably similar over the entire ice shelf. We might expect, however, that sea currents beneath the ice might vary and in particular the current beneath the sea ice where sea-level is measured might differ significantly from that beneath the ice shelf. The maximum error introduced to the profile in this way is unlikely to exceed 5 cm. and is probably of approximately equal magnitude and direction for each set of results along the repeated section of profile 1. Because the levelling extended over a period of several weeks in a variety of weather conditions, errors resulting from atmospheric pressure gradients were probably random. The cumulative error in elevation due to all these effects was probably not greater than ± 2 cm. Thus, in comparing the repeated sections of profile 1, errors increase from ± 2 cm. near the ice front to about ± 5 cm. at the southernmost point.

RESULTS

The 1967 results are shown in Figs. 3 and 4. Near the hinge line, the ice shelf consists of a matrix of icebergs cemented together by sea ice and drift snow. In this region the profile shows regular undulations with an approximately constant wavelength equal to the sum of the width and spacing of consecutive icebergs. As the ice moves forward, the gaps between neighbouring icebergs fill with drift snow, while creep increases the separation between icebergs, with the result that the wavelength increases while the wave height decreases. At the same time the ice shelf is progressively thinning due to the combined effects of creep and bottom melting, the result being a general reduction in surface elevation. However, since there is a pronounced variation in surface elevation across the line of flow (Fig. 4), some of the characteristics of the measured profile are evidently due to some deviation from the true flow line. Thus the rapid drop in elevation and increase in wavelength of undulations at 30 km. from the hinge line in Fig. 3 is associated with an eastward deviation of profile 1 from the flow line originating in the rapidly moving thick ice of ice stream I (Fig. 1) to one originating in large, widely separated icebergs associated with slower-moving and probably thinner land ice. The rise in elevation at 50 km. from the hinge line along profile 1 is partly a result of compressive straining as the ice shelf approaches the McDonald Ice Rumples (Fig. 1) but is also due to a return of the levelling route towards the thicker ice of the original flow line. Thus we note that quite small deviations from a flow line can introduce large errors into measured

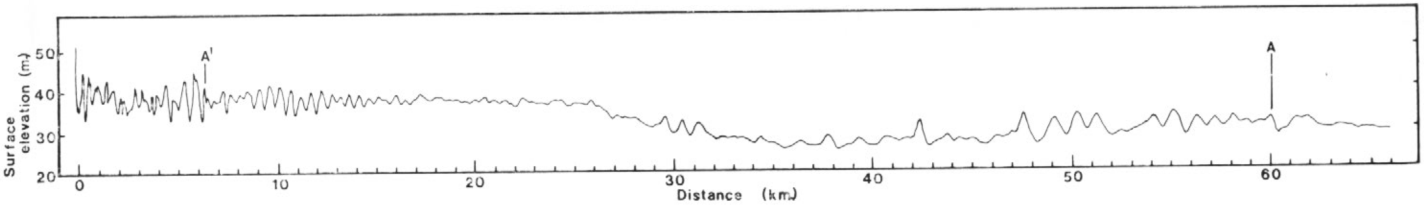

Fig. 3. Surface-elevation profile taken approximately along a flow line on the Brunt Ice Shelf (1967–68). The route is shown in Fig. 1. The section A-A′ was repeated in 1970–71.

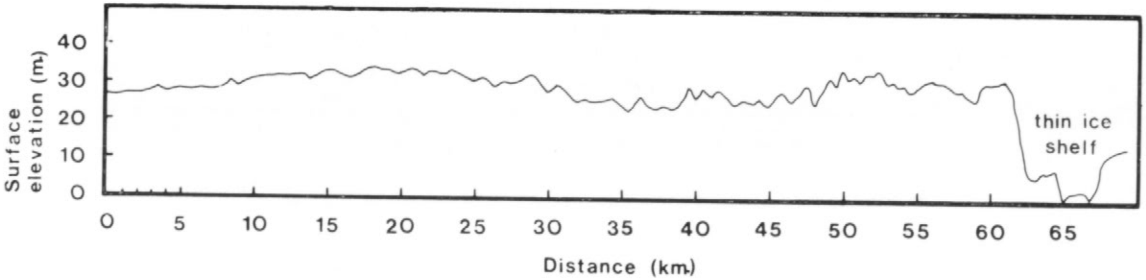

Fig. 4. Surface-elevation profile on the Brunt Ice Shelf taken across the direction of ice flow.

values of surface slope, and that these errors reach a maximum near points of grounding, where differences between neighbouring flow-line profiles are most pronounced.

COMPARISON OF REPEATED SECTIONS

The section re-levelled in 1970 (AA′ in Fig. 1) gave an elevation profile that is almost identical with that resulting from the earlier survey (AA′ in Fig. 3), apart from a slight reduction in wave height caused by preferential snow accumulation in the valleys. Although the ice shelf had moved forward by almost 1 km., there was very little drop in surface elevation. At first sight this is difficult to reconcile with a steady-state model which, using the strain-rates and bottom-melting rates given by Thomas and Coslett (1970), predicts a lowering of the surface over the period by up to 0·5 m. However, this steady-state model uses average accumulation rates, whereas actual accumulation during any particular 3 year period may well be above or below average. The period 1967–70 did in fact include 2 years of above-average accumulation.

An alternative approach by Thomas (1973, Equation (18)) makes use of an equation derived for calculating bottom-melting rates under conditions of variable accumulation. The equation can be used to deduce the change in surface elevation of a point on the ice shelf during a period of known snow accumulation and bottom melting. In this way, using steady-state bottom-melting rates and observed accumulation values for 1967–70, elevation changes at each of the marker stakes along the levelled profile were calculated for the period between the two surveys. Although there was good agreement between predicted and measured values, the 1970 survey gave elevations that were slightly higher than predicted with an average difference of 10 ± 3 cm. This consistent difference could result from the combined effects of systematic errors in the surveys and errors in estimating snow accumulation. Alternatively, it could represent a long-term deviation from steady state, associated with an increase in surface elevation of 3 cm. yr.$^{-1}$ and a corresponding increase in ice thickness of about 20 cm. Such an increase could be caused by a recent reduction in bottom melting, by a recent increase in snow accumulation, by a long-term thickening in the ice streams entering the ice shelf, or by any combination of these. However, since the observed changes are of the same order as the observing errors, we must conclude that any non-steady-state trends in the ice shelf are smaller than the errors involved in their measurement.

Renner (1969) made use of available observations to compare surface elevation and ice thickness for a number of ice shelves of differing thickness, and he used the results to deduce surface elevation from measurements of ice thickness. However, the surface elevation is dependent not only on the ice thickness but also on the average density, which is to some extent determined by meteorological conditions and in particular by the rate of snow accumulation, by its seasonal distribution, and by the temperature of the snow. We believe that the problem is simplified by considering the air content of the ice in terms of an equivalent length of air (C) contained in a unit vertical column of ice shelf. For an ice shelf of thickness H and surface elevation h

$$(H-h)\rho_w = (H-C)\rho_i,$$

where ρ_w and ρ_i are the densities of sea-water and solid ice, respectively.

Then $C = H - \frac{\rho_w}{\rho_i}(H-h)$.

Fig. 5 shows average density for the Brunt Ice Shelf and C plotted against distance from the hinge line. The air content is almost constant across the ice shelf except near the inland margin, where the rapid decrease is probably associated with the low accumulation rates in this region.

CONCLUSION AND RECOMMENDATIONS

Repetition of optical levelling across the Brunt Ice Shelf after an interval of 3 years revealed no significant changes in surface profile. Errors involved in levelling and in correcting the measured profile for observed snow accumulation were of the same magnitude as the difference between the predicted and observed profiles (10 cm.). Consequently, we propose that future surveys designed to determine whether an ice sheet is in steady state should (a) allow a greater

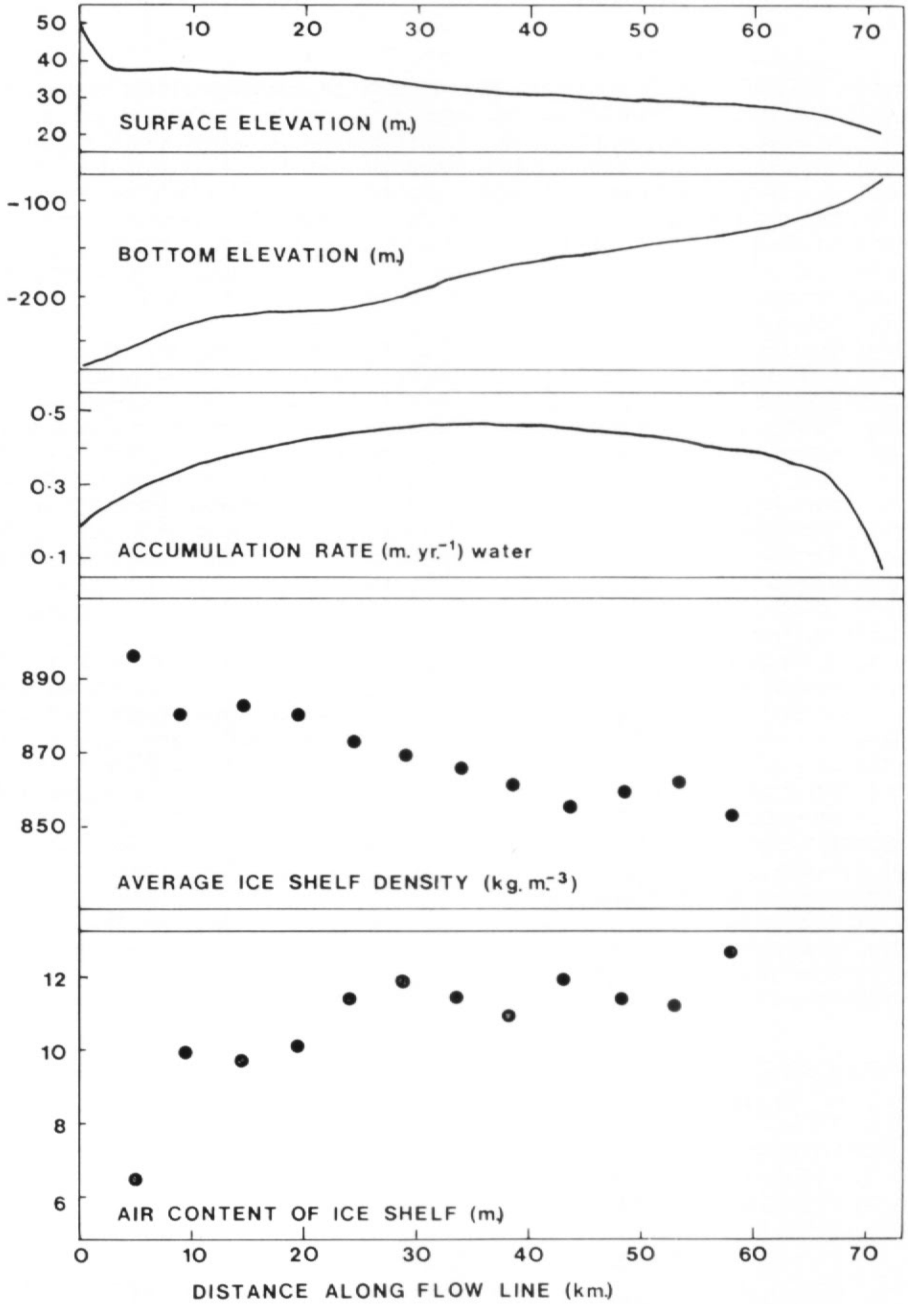

Fig. 5. Various parameters for the Brunt Ice Shelf plotted against distance from the hinge line.

interval between measurements ($>$ 10 years), and (b) should be planned to give precise measurements of snow accumulation along the levelling route. For this purpose, accumulation stakes should be barbed in some way at the level of the original snow surface, so that sinking with respect to that surface is minimized.

We suggest that the air content C of an ice shelf is a very useful parameter. In conjunction with either ice thickness or surface elevation, it is sufficient to define the vertical dimensions of the ice shelf and to determine the average ice density. Using available data, values of C from several regions could be interpreted in terms of prevailing meteorological conditions, and criteria could be developed to relate the two. Using this relationship, values of C could be assigned to ice-shelf regions and, together with ice-thickness measurements, would be sufficient to give first-order contours of surface elevation and average ice density.

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