Snow accumulation and ice movement on the Anvers Island ice cap, Antarctica: a study of mass balance*

BY

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ABSTRACT

The mass balance of a representative part of the Anvers Island ice cap is approximately in equilibrium. Between November 1965 and January 1968 the average annual accumulation over a 230 km^2 area was 380 × 10^6 metric tons. During the same period the average annual loss was 360 × 10^6 metric tons. The physical dimensions of the ice cap appear to be stable. The 20 × 10^6 metric tons, or 5·3 per cent, of the recorded accumulation, is comparable to the possible errors and assumptions in the mass balance equation, and is not regarded as a significant real positive balance. Snow accumulation rates vary considerably from year to year and it is suggested that a longer period of observations would be more suitable for a mass balance evaluation.

Introduction

Anvers Island, the largest and most southerly member of the Palmer Archipelago, is located off the western coast of the Antarctic Peninsula between lats 64° and 65° south and longs 62°30′ and 64°30′ west. It is rectangular in shape, approximately 60 km long in a northeast-southwest direction and 45 km wide, with an area of about 2700 km^2 (Fig. 1).

In January 1965, Arthur Harbour, on the south-west coast of Anvers Island, was the construction site of "Palmer Station", a research installation of the United States Antarctic Research Programme (USARP) which served as the base for glaciological investigations on the ice cap of Anvers Island by personnel from the Institute of Polar Studies, The Ohio State University.

This paper concerns part of these investigations carried out between February 1965 and January 1967 when the author was Principal Investigator of a combined programme of glaciological and meteorological study, but makes use of field data collected by his successor, R. A. Honkala and his colleagues in the following year, to January 1968.

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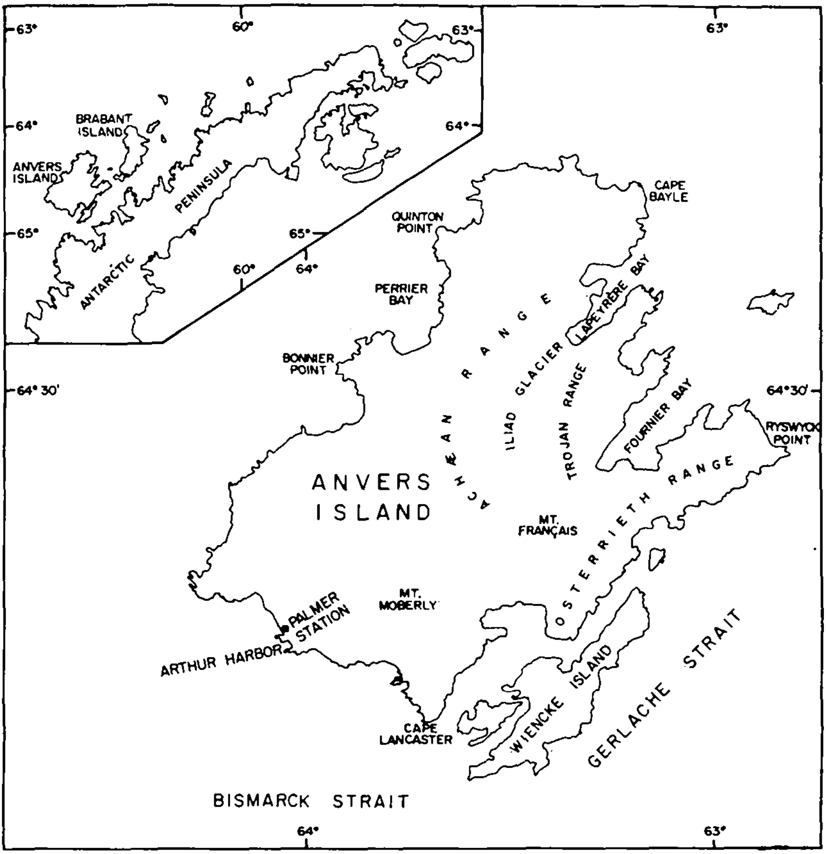

FIG. 1. Location map of Anvers Island and Palmer Station showing major physiographic features of Anvers Island.

Physiography of Anvers Island

Physiographically, Anvers Island can be divided into two distinct parts. The eastern side consists of glacierized mountainous terrain, dominated by Mount Français, which rises to 2750 m. The Achaean, Trojan, and Osterrieth Ranges trend northward and eastward from this point and form a discordant north-east coastline. From Mount Moberly (1660 m) a fourth range trends southward. The long Iliad Glacier flows northward from Mount Français to Lapeyrère Bay.

The western side of the island consists of an unbroken ice cover which reaches a maximum elevation of 850 m near the mountains. The peripheral 1 to 5 km are heavily crevassed and vehicular access to the inland regions is difficult. The ice cap surface exhibits quite pronounced topography, especially in the Perrier Bay area and in the south-western part, where wave-like undulations, ridges and basins are frequent.

For the most part, the ice cap terminates in cliffs ranging in height from 20 to 80 m above sea level. Small ice ramps occur in only a few isolated locations where the ice cap terminates on land (Fig. 2).

FIG. 2. Ice cliffs and crevassed ice cap margin around Biscoe Bay. Land promontory in centre is Biscoe Point. Ramps to right of photo are typical of several around periphery of ice cap. (U.S. Navy photo).

The ice cap has not been adequately mapped, and the only aerial photographs were taken by the Falkland Islands Dependencies Survey (now British Antarctic Survey) in 1956 and by United States Navy and Coast Guard aviators, in support of USARP, between 1963 and 1967. Two map sheets showing the western coastline and peripheral crevasses have been produced by the British Antarctic Survey. These maps and photographs show virtually no change in the position of the ice cliffs and indicate that they are stable features. It is uncertain how much of the peripheral ice is afloat. The British maps show grounded ice at only a few scattered locations. The oblique aerial photographs taken by the U.S. Navy, however, show bedrock exposures along most of the coastline. Thus the ice cap boundary appears to be governed by sea level. The heavily-crevassed peripheral ice is not sufficiently cohesive to float and consequently calves on reaching the sea.

Climate of Anvers Island

Introduction. Anvers Island is within the sub-polar low pressure belt and its climate exhibits predominantly cyclonic characteristics. There is a very high incidence of low cloud cover and high annual precipitation.

Meteorological data are available for the period February 1, 1965, to December 31, 1966 (Rundel *et al.*, 1968; Rundel and DeWitt, 1968), and have been summarized by Rundle (1967).

Temperature. At Palmer Station the mean temperature for the 23-month period February 1965 through December 1966 was −3·7°C. The coldest month was July 1966 with a mean temperature of −13·8°C. The warmest month was March 1965 (+2·1°C). The extreme temperatures were +9·0°C on November 22, 1966 and −29·5°C on July 16, 1966. Mean daily air temperatures vary greatly from day to day.

Other meteorological parameters. Winds at Palmer Station are generally light though persistent. Storms are frequent but rarely does the wind exceed 60 knots (110 km/hr). The prevailing wind is in the north-east quadrant and the principal storm and snow-bearing wind is north-northeast. A secondary, almost due easterly wind, is also a heavy snow carrier.

The average cloud cover during 1965 was 7·9 tenths and for 1966 it was 8·2 tenths. The principal cloud type is stratus, often with a ceiling at 300 m or less. A summary of 1965–1966 meteorological conditions is given in Fig. 3.

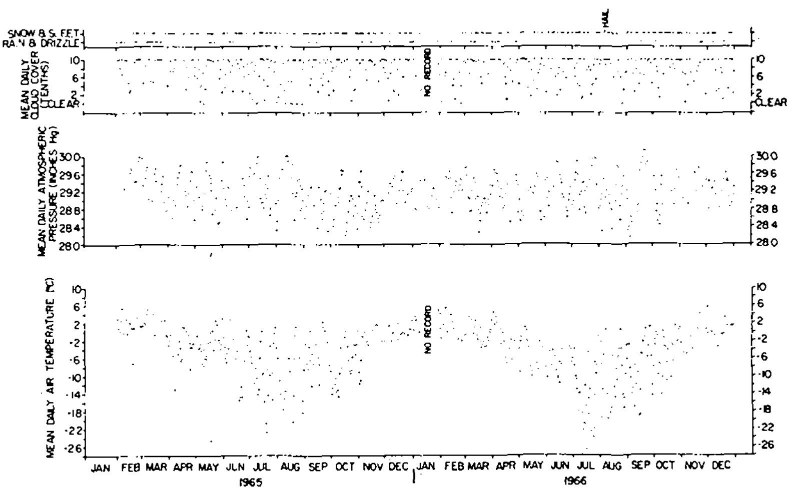

FIG. 3. Graphical summary of meteorological conditions at Palmer Station February 1, 1965, to December 31, 1966.

The mass balance investigation

Introduction. Soon after field activities began on February 3, 1965, it was realized that the extremely inhospitable climate would prevent a detailed study of the entire 1350 km² ice cap. Consequently, the southwestern "lobe" was selected as a study area, probably representative of the ice cap. This 380 km² area is bounded by the coastline from Cape Monaco to Cape Lancaster, the mountains from Cape Lancaster to Mount Français, and the high divide from Mount Français to Cape Monaco. This area appears to be a distinct drainage basin, with ice flowing outward into Wylie Bay, Bismarck Strait, and Neumayer Channel.

Stake measurements of accumulation and ablation. During early 1965, two lines of bamboo poles (the Main and Mountain, the Neumayer and

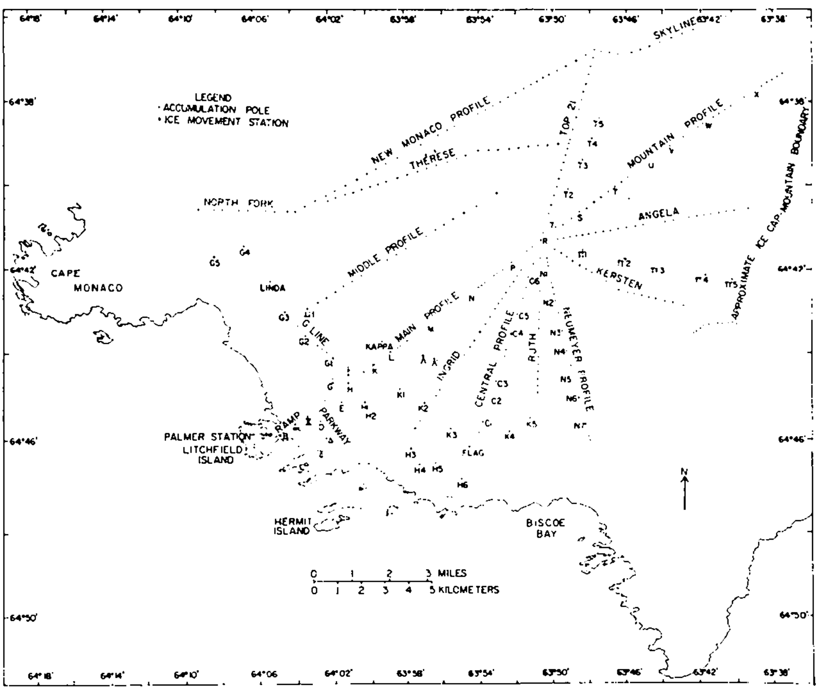

FIG. 4. Accumulation and ice movement stake network. (Station "R" does not represent a high point or significant topographic feature. This was site of depot and refuge hut from which distant field operations were carried out.)

top 21 lines, Fig. 4) were set out to measure snow accumulation and ice ablation. These stakes were remeasured frequently until January 1968.

Late in 1965, the number of stakes was increased to over 600 as shown in Fig. 5. Measurements, three or four times a year, were made until

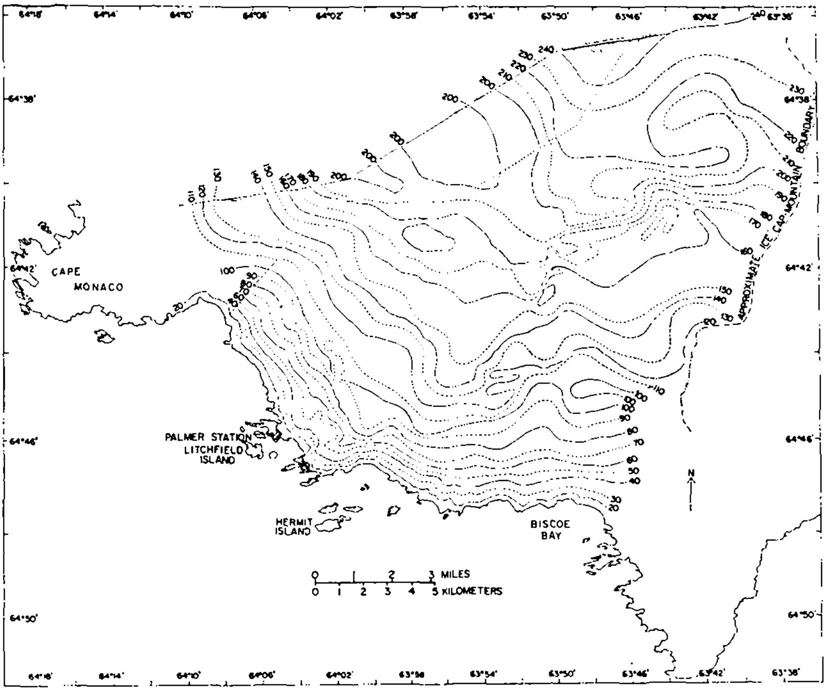

FIG. 5. Distribution of average annual accumulation 1966 and 1967. Isoline interval 10 g cm^2.

January 1968. Nine of these stakes recorded a net loss, while the remainder all recorded a net gain.

Snow density. The densities used to convert snow accumulation to water equivalent values have been derived from snow pit measurements and core samples taken at 14 locations along the Main and Mountain Lines. In the highest parts of the accumulation zone, between about 650 m and 850 m elevation, the average density for the previous year's accumulation was 0·453 g cm^3. From 450 m to 650 m elevation the density was 0·445 g cm^3. At lower elevations the density was 0·429 g cm^3 (300 m–450 m), 0·518 g cm^3 (60 m–300 m), and 0·850 g cm^3 (20 m–60 m).

The variation in these values probably results from the degree of percolation and saturation of the firn cover and the amount of compaction resulting from the weight of accumulated snow. Percolation above about 300 m elevation is not severe, but annual accumulation of snow increases markedly with increase in elevation, ranging from about 170 cm at 300 m, 350 cm at 450 m, 450 cm at 650 m, and 550 cm at 850 m elevation. The slight increase, with elevation, of the average densities above 300 m, is probably due to the increase of overburden. Below 300 m elevation the degree of percolation and saturation increases and is probably the cause of the increase in average density. The value 0·85 g cm³ between 20 m and 60 m elevation is used in the superimposed ice accumulation and ice ablation zones.

Annual accumulation values from February 1965 to January 1968 are available for two lines only; values for the entire stake network are available from November 1965 to January 1968. Annual accumulation values from the November 1965–January 1968 data have been used for the preparation of the accumulation map shown in Fig. 5.

Ice movement. A network of ice movement stations was established on the ice cap for the determination of absolute surface movement. These stations were surveyed with tellurometers and theodolite in a system of open traverse lines, similar to the method used by Hofmann on the Ross Ice Shelf, Antarctica (Hofmann *et al.*, 1964; Dorrer, 1970). Absolute surface movement derived from the results of two surveys are shown in Fig. 6.

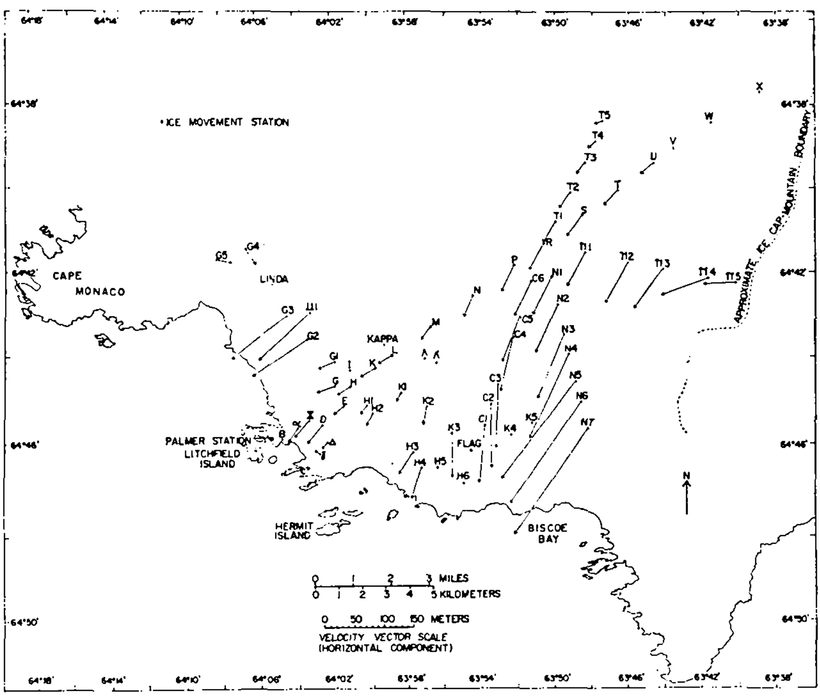

FIG. 6. Distribution of surface velocity in metres per year. Based on two surveys between September 1965 and January 1967.

The mass balance of the ice cap

Introduction. Insufficient field data are available for a mass balance evaluation of the entire 380 km² study area. Access to the Cape Lancaster promontory by surface vehicle was prevented by crevasses and no data were obtained from that area. Ice movement station "Linda" was lost in crevasses during the early stages of the field investigation. This station had been established in what appears to be a distinct, and probably fast-moving, ice stream, and would therefore have provided important information for the calculation of ice discharge.

The section of the accumulation zone believed to discharge between stations G3 and G5 is that to the north of the dotted line on the accumulation map (Fig. 5). For the calculation of the mass balance, this section of the accumulation zone has therefore been omitted.

Mass income. The area bounded by each 10 g cm^2 yr isoline or positive balance line on the accumulation map was obtained with a polar planimeter and the volume of water represented was calculated. The total annual positive balance above the equilibrium line is 407 $\times$ 10^6 metric tons. However, the equilibrium line is at approximately 60 m elevation, and closely follows the cliff edge. To assess the mass balance, it would be necessary to calculate the throughflow at the cliff face, for which movement and thickness are not known. The closest profile to the cliffs, for which throughflow can be calculated, is defined by the line G3 through the "G" stations to E, then to H1–H2–H3 passing through K3 and C1 to N7 (Fig. 6). Total annual positive balance above this line is 380 $\times$ 10^6 metric tons.

Volume of throughflow. The surface area of ice passing annually through the profile has been calculated, using the measured surface velocities and the computed values of the azimuth of ice flow at each ice movement station. To obtain the volume of ice passing through the profile this area has been multiplied by known ice thickness and a factor of 0·95.

Ice thickness was measured gravimetrically by G. Dewart of the Institute of Polar Studies, The Ohio State University, during January and February 1967. The constant 0·95 is based on values obtained by Bull and Carnein (1970) from calculations made from bore hole data from Meserve Glacier, Antarctica, and elsewhere, and accounts for the variation of velocity with depth.

Assuming an ice density of 0·9 g cm^3 the total mass flowing annually through the profile has been calculated as 360 $\times$ 10^6 metric tons.

The resulting mass balance equation is:

Total positive balance above the throughflow profile	380 $\times$ 10^6 metric tons	100·0%
Total throughflow at the profile	360 $\times$ 10^6 metric tons	94·7%
Excess of positive balance over throughflow	20 $\times$ 10^6 metric tons	5·3%

Discussion of the mass balance equation

The excess of positive balance over throughflow is the equivalent of approximately 8·8 g cm^2 distributed evenly over the surface area of the accumulation zone considered, and could represent a positive balance for the entire study area. However, insufficient information is available to conclusively show this.

From the survey data, it is not possible to show whether surface elevations are stable or not. The vertical angles, measured during the surveys, were not simultaneously reciprocal and are suspect to an unknown (but perhaps large) probable error. In some cases, the change in elevation of the movement stations closely approximates the change in surface elevation over the distance that the ice moved. In many cases, however, the survey data show a change in surface elevation, sometimes positive, but usually negative. Where positive change is indicated, it does not exceed 5 per cent of the recorded accumulation.

Consideration of the errors in the mass balance calculation. Several parameters used for the calculation of the mass balance are subject to possible error. Snow accumulation was measured against the stakes using a 2 m "tally rod", and an error of $\pm$ 1 cm at each reading can be estimated. Some stakes were measured as many as nine times during a year and all stakes were measured at least three times a year.

The snow densities have been derived from snow pit and ice core studies and it is difficult to assign a possible error to these values. A small change in the density values used could significantly alter the mass balance equation.

Annual accumulation rates vary considerably from year to year. The records of positive balance for the main profile can be divided into three periods of approximately one year each. These records are shown in

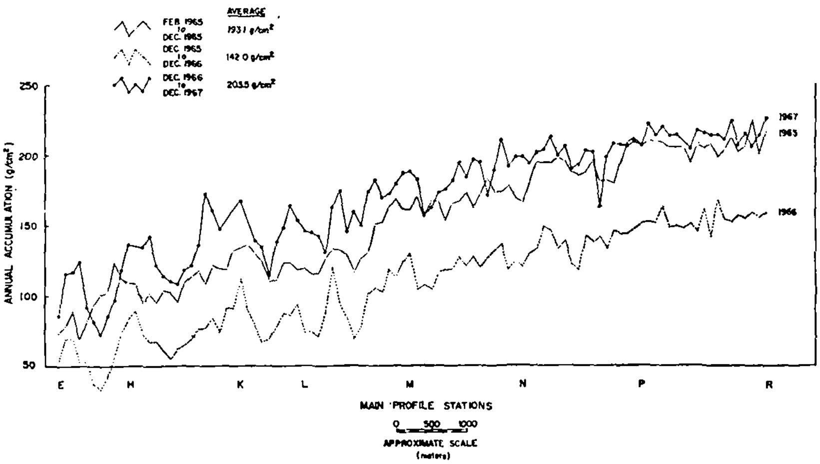

FIG. 7. Annual accumulation on Main Profile between 300 m and 640 m elevation for 1965, 1966, and 1967, in g cm^2.
These figures represent: 26 per cent decrease in second year over first year,
5 per cent increase in third year over first year,
43 per cent increase in third year over second year.

Fig. 7. The accumulation map, on which the mass balance equation is based, is derived from only two of these years' records, which show considerably different final positive balance values.

Meteorological records also are limited, both for Palmer Station and for the surrounding area. Thus it is not possible to assess the stability of climatic conditions and, therefore, of snow accumulation conditions on the Anvers Island ice cap. The difference between the 1965 and 1966 positive balance records for the main profile are not readily explainable from the contemporary Palmer Station meteorological records (Fig. 3).

It seems, therefore, that before the excess of positive balance over throughflow can definitely be shown as real positive balance for the study area, the mass balance equation should be based on longer records of snow accumulation and meteorological conditions. Iti s suggested that a five-year period would be more suitable for the assessment of the mass balance.

Maximum observational control was imposed during the ice movement survey, because errors are compounded as a traverse line progresses, and because triangulation adjustment was not possible. The position of station R, however, has been computed twice for each survey as it lies on a closed traverse loop. The error of closure at station R for the 26 km loop passing through the Main and Central profiles and the "K" stations was 3 m for the first survey and 5 m for the second survey. The movement of this station computed from the Main profile traverse was 49·89 m (true azimuth 233). When computed from the "K" station—Central profile traverse, the movement was 49·40 m on aximuth 237·3. A possible error of $\pm$ one per cent is therefore assigned to the ice movement values.

The ice thickness values are subject to a possible error which is inherent on gravimetrically-determined ice thickness measurements. The survey by G. Dewart indicates that the sub-glacial surface along the Main profile consists of two, almost level plateaus, separated by a slight break of slope in the vicinity of station M. In the vicinity of stations E and H1 he determined ice thickness to be 240–247 m. Dr. C. W. M. Swithinbank of the British Antarctic Survey obtained poor but readable radio-echo results from the same vicinity and determined ice thickness to be 250–290 m. The radio-echo sounder gives a discrete value at a point, whereas the gravity meter gives an average value for the area surrounding the point. The radio-echo results, therefore, are likely to be the more accurate. The performance of the radio-echo sounder in "warm" ice is not good, but from his poor record, Swithinbank has guardedly suggested a standard deviation for his observation of $\pm$ 24 m (personal correspondence). The results of the two measurements are reasonably close and an error of $\pm$ 5 per cent is assigned to the gravimetrically-determined ice thickness.

The factor of 0·95 used to account for the variation of ice velocity with depth is estimated. On the Meserve Glacier, which is cold, Bull and Carnein used a value of 0·83 to 0·92 (1970). Temperature measurements on the Anvers Island ice cap indicate much warmer conditions. The lowest ice temperature measured at 12 m depth was −4·9°C. A horizontal bore hole, drilled into the cliff face a few centimetres above the bed, indicated an ice temperature of −0·8°C ± 0·2°, 8 metres into the ice. The variation of velocity with depth in the ice cap is therefore likely to be less than on Meserve Glacier and the factor of 0·95 may be low.

An ice density of 0·90 g cm³ has been assumed for the throughflow calculations. This value may be high by 2 per cent.

The major error in the mass balance calculation lies with the isoline accumulation map, from which total positive balance was calculated. The position of each isoline is accurate only at the points of measured accumulation. Between these points the lines are subjective. The inaccuracy is likely to be greater in the northern part of the study area where known positive balance values are more scattered. The areas bounded by the isolines are also, therefore, subject to error.

Conclusions

The possible errors in the mass balance evaluation are sufficient to account for the apparent positive balance of the study area. The physical dimensions of the ice cap do not appear to be changing significantly; the coastal boundary seems to have been stable for at least the past ten years. The mass of the study area amounts to about 90×10^9 metric tons, and if the 20×10^6 metric tons is real positive balance, it would represent a gain to the study area of less than one-tenth of one per cent annually, which is an insignificant departure from equilibrium.

It is concluded that the study area is approximately in equilibrium, and if the study area is representative of the Anvers Island ice cap as a whole, then the ice cap itself is close to equilibrium.

Appendix I

Mechanisms of accumulation and ablation and their significance in the mass balance equation

All the stakes in the study area recorded net balance figures which account for all mechanisms of accumulation or ablation. In the equation presented above, the total positive balance above the throughflow profile has been equated with the throughflow at the profile, and equilibrium has been concluded.

In the following discussion, consideration is made of the various mechanisms of ablation and accumulation which occur on the entire ice cap area. In the case of ablation, the 360×10^6 metric tons is regarded as 100 per cent of the ablation and can be subdivided into processes of loss. In the case of accumulation, the mechanisms operating above the throughflow profile are limited to snowfall and rime formation. Accumulation below this profile occurs in other forms but has not been considered in the preceding equation.

Accumulation

Snowfall is the major mechanism by which mass accumulates on the Anvers Island ice cap. Rainfall is a source of accumulation, but is also a prominent cause of ablation during the summer months. Rainfall has not been recorded above about the 200 m elevation contour although sleet occurs above this level.

In the higher parts of the ice cap, accumulation occurs on the surface in the form of rime. The remains of these layers, often up to 1·5 cm thick, were seen in snow pit walls, but were too thin to individually sample. Their contribution to the total accumulation is less than one-tenth of one per cent.

Drifting snow causes a redistribution of accumulation over the ice cap surface and its contribution to the net positive balance may vary from one location to another. It has not been possible to identify this contribution quantitatively in the study area though it must be assumed that snow did drift onto the area from the northern part of the ice cap. However, an equal amount of snow may have been blown from the study area into the sea.

Core studies on the Norsel Point ramp during 1965 indicate that superimposed ice forms between about 50 m and 150 m elevation. Above about 150 m elevation there is a rapid transition to an alternation with depth of ice layers and layers of dense iced firn. Plummer's work during 1965 (unpublished) showed that "with the exception of 1 cm of fine-grained ice that evidently formed during the winter", there was no superimposed ice at 50 m elevation. At about 75 m elevation the superimposed ice was 52 cm thick. At about 100 m elevation, 312 cm of superimposed ice was recorded, and at 150 m elevation it was 512 cm thick. Above this elevation the upper 134 cm of ice contained layers of consolidated iced firn.

Later core studies at the same locations in 1966, and weekly measurements of 26 stakes, failed to show any further superimposed ice formation. Either the accumulation by this mechanism was too small to detect or did not occur at all during that year.

Ablation

Of the 360×10^6 metric tons passing through the throughflow profile, over 99 per cent is lost by calving at the coastal cliffs.

Nine stakes recorded negative balance in the sudy area. Six were on the Norsel Point ramp and showed an average surface lowering of 12 cm yr. Three stakes on the Bonaparte Point ramp recorded an average lowering of the surface of 20 cm yr. These records indicate that the equilibrium line lies at about 60 m elevation. Over the 312,000 m^2 area actually recording negative balance (obtained by planimeter), this represents $0{\cdot}045 \times 10^6$ metric tons. Other parts of the study area, below 60 m elevation and occurring as ramps and not calving cliffs, again obtained by planimeter, account for 0·600 × 10^6 metric tons. Total loss by melt, therefore, is estimated as 0·645 × 10^6 metric tons.

Evaporation and sublimation probably occur over the entire ice cap throughout the year. However, it is not possible to identify these parameters quantitatively and they are considered insignificant.

Melting at the base of the ice cap also may occur, though outwash streams at the base of the cliffs have not been recorded. More information is needed regarding the amount of the ice cap which is afloat before an estimate can be made. However, bottom melting may make only a small contribution to ablation from the ice cap.

A more refined mass balance equation, therefore, is:

Positive balance		
Snowfall and rainfall	approximately	100·0%
Surface rime	Trace	< 0·10%
Drifting snow	Not definable—insignificant	—
Superimposed ice	did not occur during investigation	—
Total positive balance		100·0%
Negative balance		
Calving	359·355 × 10^6 metric tons	
Melt. Arthur Harbour ramp	0·045 × 10^6 metric tons	
Melt. all other ramps	0·600 × 10^6 metric tons	
Bottom melt and snow drift	Trace	
Total negative balance	360·000 × 10^6 metric tons = throughflow =	94·7%
Positive balance for study area/error estimates		5·3%
		100·0%

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References

Bull, C. *and* Carnein, C. R. 1970. The mass balance of a cold glacier: Meserve Glacier, south Victoria Land, Antarctica. In: Gow, A. J. *et al.*, Eds., *International Symposium on Antarctic Exploration (ISAGE), Hanover, New Hampshire, U.S.A.*, 3–7 *September* 1968. Cambridge (Pub. No. 86 of IASH), p. 429–46.

Dorrer, E. 1970. Movement determination of the Ross Ice Shelf, Antarctica. In: Gow, A. J. *et al.*, Eds., *International Symposium on Antarctic Exploration (ISAGE), Hanover, New Hampshire, U.S.A.*, 3–7 *September* 1968. Cambridge (Pub. No. 86 of IASH), p. 467–71.

Hofmann, W., Dorrer, E. *and* Nottarp, K. 1964. The Ross Ice Shelf Survey (RISS) 1962–1963. In: Antarctic Snow and Ice Studies, Mellor, M., ed. Washington, *Amer. Geophys. Union, Antarctic Res. Ser.*, Vol. 2, p. 83–118.

Rundle, A. S. 1967. Meteorological observations at Palmer Station, 1965–1966. *Antarctic Journal of the United States*, Vol. 2, No. 5, p. 159–60.

Rundle, A. S., Ahrnsbrak, William F. *and* Plummer, Charles C. 1968. Glaciology and meteorology of Anvers Island, Vol. 1. *Ohio State Univ. Res. Foundation (Preliminary Data Report).*

Rundle, A. S. *and* DeWitt, S. R. 1968. Glaciology and meteorology of Anvers Island, Vol. 2. *Ohio State Univ. Res. Foundation (Preliminary Data Report).*

Snow accumulation on the Fimbul Ice Shelf, western Dronning Maud Land, Antarctica

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Introduction

During the austral summer of 1962, South Africa established a 16-man wintering-over base SANAE in western Dronning Maud Land (Fig. 1). The present long-term glaciological project was initiated by the author during the same year (Neethling, 1963), and, has been continued up to the present by geologists of successive expeditions as part of an Earth Science Programme (Neethling, 1966).

Area of investigation. The Fimbul Ice Shelf, which is located between latitude 69°20′ and 70°30′S, longitude 3°W and 4°E, has been described by Swithinbank (1957) and Lunde (1961). The ice shelf is divided into three distinct physiographical regions: (1) a western part of typical flat-lying shelf and a prominent series of large ice rises (Fig. 1); (2) a central part located between extensively crevassed zones which are caused by the northerly extension of the Jutul Glacier into the ice shelf—this part also includes Trolltunga, the 90-km long ice tongue at longitude 1°W; (3) an eastern part of flat-lying shelf and a few ill-defined, low, ice rises.

Glaciological studies by South African expeditions have been made mainly in the western part of the ice shelf in the region of SANAE Base