

MASS BALANCE STUDIES IN ANTARCTICA

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ABSTRACT. The general characteristics of the coastal regions between long. 45° E. and long. 80° E. are described. The features and conditions are similar to those found along the coasts of the Australian sector further to the east. Measurements of accumulation, snow transport, ice flow and ablation are described and results are given.

Accumulation, measured from stakes and pits, is 1.0×10^{14} gm./yr. in a 1 km. wide strip running 850 km. inland from the coast of MacRobertson Land. The methods of gauging drifting snow and extrapolating the results are given and a meridional mass transport of 0.16×10^{14} gm./km. yr. is deduced. Iceberg calving rates given in a previous paper are again quoted, although they are now felt to be too low. Net ablation is 0.053×10^{14} gm./km. yr. and additional evaporation above the firm limit accounts for 0.045×10^{14} gm./km. yr. The estimates are compared with old and new observations from other parts of Antarctica and the problem of bottom melting beneath ice shelves is discussed.

A distinction is made between the meteorological water budget for Antarctica and the glaciological mass balance for the ice sheet. Mass budgets for the sector between long. 45° E. and long. 80° E. and for the whole of Antarctica are drawn up. In each case a surplus of accumulation over losses appears, but it is felt that the data are insufficient to claim that the ice sheet is growing at the present time. The drift snow and ablation losses are added to the net accumulation to give a figure of 14 cm. of water as the mean annual precipitation over Antarctica, a value lying between the estimates of Meinardus and Kosack.

RÉSUMÉ. Les caractéristiques générales des régions côtières entre les longitudes 45° E et 80° E sont décrites. Les aspects et les conditions de cette région ressemblent ceux des côtes du secteur australien plus vers l'Est. On donne les mesures de l'accumulation, transport des neiges, écoulement et ablation de la glace ainsi que descriptions et résultats.

L'accumulation, mesurée au moyen de balises et de fosses, est de $1,0 \times 10^{14}$ gm/an dans une bande d'un km de largeur pénétrant à 850 km à l'intérieur à partir de la côte de MacRobertson Land. On donne les méthodes pour jauger les apports de neige et extrapoler les résultats, et on conclut à un transport de masse méridien de $0,16 \times 10^{14}$ gm/km an. Le vêlage des icebergs mentionné dans une communication antérieure est donné à nouveau quoique ces grandeurs sont estimées trop basses à présent. L'ablation nette est de $0,053 \times 10^{14}$ gm/km an et au surplus $0,045 \times 10^{14}$ gm/km an sont attribuables à l'évaporation supplémentaire au delà de la ligne de névé. Ces évaluations sont comparées avec des observations anciennes et récentes faites dans d'autres régions antarctiques. On examine également le problème de la glace qui fond à la base sous les plateformes de glace.

On fait une distinction entre le budget d'eau météorologique pour la région antarctique et le bilan glaciologique pour la nappe de glace. On a établi l'économie matérielle pour le secteur compris entre les longitudes 45° E et 80° E et pour la région antarctique entière. Dans chaque cas on a constaté un surplus d'accumulation par comparaison avec les pertes, mais on pense qu'il n'y a pas assez de données à présent pour pouvoir conclure que la nappe de glace est en état de croissance. L'apport de neige et les pertes d'ablation ont été ajoutés à l'accumulation nette pour produire une valeur de 14 cm d'eau comme précipitation annuelle moyenne sur la région antarctique, valeur qui se situe entre les valeurs estimées par Meinardus et Kosack.

ZUSAMMENFASSUNG. Eine allgemeine Beschreibung des antarktischen Küstenstreifens zwischen 45° und 80° östlicher Länge wird gegeben. Topographische Einzelheiten und Bedingungen ähneln denen der Küste des östlichen australischen Sektors. Messungen des Zuwachses, des Schnee- und Eistransportes und der Abtragung werden beschrieben und ihre Resultate werden angedeutet. Der Zuwachs gemessen an Pegeln und in Gruben kommt auf $1,0 \times 10^{14}$ g/Jahr für einen 1 km breiten Streifen, der sich 850 km von der MacRobertsonlandküste nach Süden erstreckt. Die Methoden der Treibschneemessung und Dichteschätzung werden beschrieben; sie geben einen meridionalen Massentransport von $0,16 \times 10^{14}$ g/km Jahr. Die Zahlen für das Kalben der Eisberge werden einer früheren Arbeit entnommen, obwohl sie jetzt zu niedrig erscheinen. Die gesamte Abtragung kommt auf $0,053 \times 10^{14}$ g/km Jahr und zusätzliche Verdunstung oberhalb der Firngrenze trägt weiter $0,045 \times 10^{14}$ g/km Jahr bei. Diese Schätzungen werden mit alten und neuen Beobachtungen aus anderen Teilen der Antarktis verglichen und das Problem des Schmelzens unter den Eisschelfen wird erörtert.

Der Unterschied zwischen einer meteorologischen Wasserbilanz für die Antarktis und einer glaziologischen Massenbilanz für das Inlandeis wird eingeführt. Massenbilanzen für den Sektor zwischen 45° und 80° östlicher Länge und für die ganze Antarktis werden aufgestellt. In allen Fällen zeigt sich ein Überschuss an Zuwachs über Verluste, aber die vorhandenen Beobachtungen reichen wohl nicht aus, daraus mit Sicherheit auf ein gegenwärtiges Wachsen des Inlandeises zu schließen. Die Treibschnee- und Abtragungsverluste werden zu dem gemessenen Zuwachs addiert und die Summe ergibt den Betrag von 14 cm Wasser als durchschnittlichen Jahresniederschlag für die Antarktis, eine Zahl, die zwischen den Schätzungen von Meinardus und Kosack liegt.

INTRODUCTION

In 1957 mass economy studies were made by the Australian National Antarctic Research Expeditions at Mawson in MacRobertson Land and at Davis in Princess Elizabeth Land. Measurements of ablation and ice flow were made in the Mawson area, further ice flow measurements extended west to Kemp Land, accumulation was measured along tractor trails running south from Mawson; at the station itself drifting snow was gauged. At Davis accumulation and ablation were measured in an area surrounding the base. It was possible to become acquainted with the general characteristics of the coastal, and some inland, regions between long. 45° E. and long. 80° E. by frequent aircraft flights and by examination of the comprehensive collection of trimetrogon air survey photographs. Survey photographs also permitted superficial comparisons with other parts of Australian Antarctic Territory to be made, and summer visits to Wilkes Land, Terre Adélie and Oates Land helped to put the 1957 results into perspective.

Basic observations from Mawson and Davis were maintained in 1958 and studies made by U.S. glaciologists at Wilkes base will be continued in 1959 by the A.N.A.R.E. Work carried out prior to the I.G.Y. has now been published and the later results will eventually be given in detail in an A.N.A.R.E. Report. However, it may be of interest to present here some estimates based on preliminary results, together with some conjectures on the mass balance of Antarctica.

GENERAL FEATURES AND CONDITIONS

Along the greater length of coast between long. 45° E. and long. 80° E. continental ice meets the sea directly without an intervening ice shelf. Except for floating glacier tongues and the extreme fringe this ice is land-based. The coasts of Enderby Land and Kemp Land have several small ice shelves and in a number of areas ice shelves cover tortuous inlets and surround coastal islands. The largest shelf, the 50,000 sq. km. Amery Ice Shelf, is situated in MacRobertson Land at the head of the Mackenzie Bay-Prydz Bay indentation. The line of the continental ice cliffs is occasionally broken by rock exposures which range in size from small rocky knolls to extensive hills, such as the Vestfold Hills in Princess Elizabeth Land. Many sections of the coast are of the skerry type and groups of small islands lying within 15 km. of the mainland are common.

Coastal regions between Princess Elizabeth Land and Oates Land are generally similar to those described above, and summer landings in Wilkes Land, Terre Adélie and Oates Land brought evidence of glaciological similarity with the more western parts of the Australian sector.

Sea ice begins to form in March but it is common for the ice to be broken up and dispersed by gales before July. The maximum ice thickness of about 150 cm. is reached in late September at Mawson. Heavy melting in December causes rapid deterioration of the ice and the final breakout generally occurs in late January. In some areas stable sea ice never forms; new ice can be persistently broken up by katabatic winds, cyclonic gales or ocean currents.¹

In MacRobertson Land the continental ice rises steeply from the coast to about 1,500 m. altitude 80 km. from the edge, but further inland gradients are much less and maximum plateau heights 600 km. inland are around 3,000 m. The annual mean temperature falls rapidly from -11° C. at Mawson to -23° C. at a distance of 60 km. inland, and further to -38° C. at a height of 2,500 m. and 300 km. from the coast.²

The sub-glacial terrain south of Mawson is rugged and elevations of the rock surface vary from valleys 500 m. below sea level to mountains 3,500 m. above sea level which break through the ice surface.³ For a distance of at least 700 km. inland the surface form of the ice cap is strongly influenced by the underlying topography and resulting major features of the ice sheet can have a profound effect on mass economy processes. The speeds and directions

of flow of ice and gravity winds are largely determined by these contours, so that all wastage processes are affected. Precipitation may also be influenced to some extent by large marginal features such as the Enderby Land peninsula.

Steep marginal slopes are generally swept by katabatic winds which remove most of the snow below the 600 m. level and limit accumulation to about the 2,000 m. level. The width of the ablation zone between the coast and the firn limit (which has a maximum height around 900 m.) is usually not more than 20 km. On ice shelves the firn limit is virtually at sea level but continental ice slopes south of the shelves often have the same blue and wind-scoured appearance as steep coastal slopes. On the Lambert Glacier, which feeds into the Amery Ice Shelf, melt channels can be seen cutting into bare hard ice 450 km. from the sea at 950 m. altitude and the ice is kept snow-free over a wide area by strong winds pouring into this enormous depression. The inland belts of disturbed ice often referred to as "ice domes" appear to lose ice by wind scouring also.

ACCUMULATION

So far the windy conditions of Mawson have precluded direct measurement of precipitation. Inland, however, stake and pit measurements of net accumulation are available. At Davis there is an annual mean wind speed of only 4.7 m./sec. and precipitation measured in a conventional gauge corresponded with figures obtained by stake readings during the winter months of 1957, so that the annual precipitation measured by the gauge is probably acceptable at this station.

In 1954 stakes were placed along a weasel trail from Mawson to the Prince Charles Mountains by R. Dovers and they were re-measured in 1955 and 1956 by P. Crohn.⁴ The accumulated quantities of snow varied considerably from stake to stake but, after grouping stakes and taking mean values, accumulation rates were obtained. The stake measurements show a rise in the annual net accumulation, averaged over 2 years, from 5 cm. of water 50 km. inland to 20 cm. of water 300 km. inland (Crohn's conversion to water equivalents gives somewhat higher values).

New groups of stakes were placed by the writer between Mawson and a depot 400 km. to the south in 1957 and some of these were checked in the summer of 1958-59 by Blake and Jesson of the 1958 seismic party. The following table gives stake measurements over a 10-month period together with estimates made from pit sections in the summer of 1957-58.

<i>Distance south of coast</i>	<i>10-month accumulation</i>	<i>Annual net accumulation</i>
(km.)	(stakes, Feb. to Dec.)	(pit sections)
	(cm. water)	(cm. water)
60		8
130		12
160 (ice dome belt)		2
230	11.5	12
275	0.0	
300 (immediately south of ice dome belt)	15.0	8
330	16.5	11 (possibly much higher)
350	0.0	} 9-17 (interpretation doubtful)
365	9.0	
650		

During a 6-week period in December 1957 and January 1958 about 4 cm. of water accumulated between 200 and 400 km. inland. On the return journey to Mawson in February 1958, tractor and sledge tracks made in November 1957 were intermittently visible, although for much of their length they were buried by snow up to 30 cm. deep. There was ample evidence of wind transport during the 100-day southern journey: deep drifts built up around the tractor trains night after night in cloudless weather and on other occasions knee-depth deposits of soft snow which fell in calm whiteout periods were quickly dispersed and packed

when the wind regained its usual strength. On the highest, relatively wind-free part of the traverse it is possible that accumulation could be as high as 35 cm. of water, but south of this area the traverse skirted a large bowl-like depression which falls away to the Lambert Glacier, and accumulation 500 km. inland may be limited by katabatic winds stronger than usual for this distance from the coast.

It is widely accepted that the bulk of the Antarctic snow accumulation takes place in a peripheral zone, and this zone is assumed to have a width of about 850 km. in MacRobertson Land. The writer's first estimate of net accumulation is 1.0×10^{14} gm./km. yr., being the mass of snow collected annually in a strip 1 km. wide running 850 km. inland from the coast in a radial direction.

An estimate made from a most interesting accumulation profile supplied privately by Professor P. A. Shumskiy of the U.S.S.R. Antarctic Expedition, gives a value of 1.8×10^{14} gm./km. yr. to 850 km. south of Mirnyy. There, apparently, the deepest accumulations, up to 85 cm. of water, lie within 60 km. of the coast; there is between 20 and 30 cm. of water from 70 to 450 km. inland, and 850 km. inland the accumulation is 8 cm. It will be apparent from the foregoing that these conditions are very different from those of MacRobertson Land, where there is virtually no net accumulation for the first 25 km. inland, only 8 cm. of water 60 km. inland, and the average quantity from 100 to 600 km. would not be above 15 cm. of water.

There were no accumulation measurements south of Davis, but it is believed that precipitation gauge readings are fairly reliable at this station, which has a mean wind velocity of only 4.7 m./sec. Stake measurements on the sea ice during the winter checked with gauge results and the annual precipitation was measured as 6.5 cm. of water. This is surprisingly low, but 1958 figures are not available for comparison at the time of writing (precipitation quantities transmitted in the telegraphic code have proved unreliable).

In the Scientific Results of the Norwegian-British-Swedish Antarctic Expedition Schytt⁵ gives mean accumulation rates for the ice shelf, the continental ice slopes, and the margin of the high plateau. The values given are:

Shelf	36.5 cm. water
Plateau slopes	25 ,,
Border of high plateau	12 ,,

Taking suitable distances to represent each condition from a map of the area and extrapolating the results to 850 km. inland an estimated quantity of about 1.5×10^{14} gm./km. yr. is derived.

No further meridional accumulation profiles are available at the time of writing, but the magnitudes of values given above are confirmed by certain results from other areas. Loewe⁶ has given the accumulation in Terre Adélie as 20 to 30 cm. of water between 20 and 50 km. inland, which is in agreement with Schytt's measurements on the plateau slopes of Dronning Maud Land. From banding in the ice cliffs in Davis Bay, Wilkes Land, the writer estimates an ice shelf accumulation of 35 to 40 cm. (although coastal downslopes in the same area may have net ablation). Accumulation rates inland from Wilkes base have not yet been published, but there appears to be an annual deposition in excess of 20 cm. of water. Vickers⁷ gives 20 cm. of water as the accumulation at Little America on the Ross Ice Shelf and suggests 17 cm. on the Victoria Land plateau. From a popular article by Siple⁸ there seems to be 5 to 6 cm. of water for 10 months accumulation from February to November at the Pole.

ICE FLOW

Measurements of ice movement were made along the ice cliffs adjacent to Mawson, along a line 12 km. inland between Mt. Henderson and Casey Range, and on the tongues of the Jelbart, Taylor, Dovers and Hoseason Glaciers in MacRobertson Land and Kemp Land.

Details of this work were given in an earlier paper⁹ and the photogrammetric technique used on the glacier tongues has been described elsewhere.¹⁰

Three types of ice movement were discussed: the general seaward movement of the continental ice, termed "sheet flow", flow of "ice streams" channelled and accelerated by the subglacial terrain, and the movement of ice shelves. By making suitable assumptions regarding ice depth, ice density, and geographical distribution of the various features it was possible to estimate the mass of ice removed from Antarctica by calving. The calving rates given were:

Ice shelf	0.64×10^{14} gm./km. yr.
Stream flow	0.47×10^{14} „
Sheet flow	0.018×10^{14} „

It is found that calving from ice shelves is by far the most important process of the three in terms of total ice export from the continent, but unfortunately the calving rate quoted above is based on few data and is therefore somewhat dubious. All the estimates are likely to be on the low side as conservative velocities were taken along with ice thicknesses which are now felt to be rather too small for average values.

WIND-BLOWN SNOW

In recent years Antarctic drift snow has been discussed at some length and it has generally been concluded that snow transport across the edge of the ice sheet is of little significance to the regime.⁶ Prior to the I.G.Y. the only quantitative consideration of the problem was that made by Loewe¹¹ as a result of studies in Terre Adélie in 1951-52. Although Loewe's minimum estimate of mass transport was 0.18×10^{14} gm./km. yr. it was believed that results obtained in the exceptionally windy Terre Adélie would be applicable to few other places in Antarctica.

In 1957 new drift gauges were developed at Mawson and a number of measurements of drift density, including vertical profiles, was made.¹² Analysis of the results indicated that drift density measured by Loewe's imperfect traps were too low, perhaps only half the true values, and it was also shown that Loewe's vertical profile corresponded to a density decrease with height that was too rapid.¹³ The Mawson estimate gives a mean turbulent transport in the wind direction of 153 gm./cm. sec. in blizzard winds of 28 m./sec. against Loewe's figure of 28 gm./cm. sec. in winds of 36 m./sec. It might be useful to outline here the method of calculation.*

We first consider the stationary case in which snow settling under gravity is balanced by an equal quantity transported upwards by turbulence, the basic equation being:

$$-wn - \frac{A_z}{\rho} \cdot \frac{\partial n}{\partial z} = 0 \quad (1)$$

where w = free fall velocity of the snow particles

n = mass of snow per unit mass of air

ρ = air density

A_z = coefficient of vertical exchange (so that $\frac{A_z}{\rho}$ is the "eddy diffusivity", K)

z = height above the surface

Loewe used an exponential relation as a first approximation to the wind profile but for analysis of the Mawson results the logarithmic wind profile, with constants determined at Maudheim by Liljequist,¹⁴ was adopted:

$$u_z = \frac{u_*}{k} \ln \left(\frac{z+z_0}{z_0} \right) \quad (2)$$

* The basic equations governing the turbulent transport of snow particles appear to have been derived independently by Loewe (*Études de glaciologie en Terre Adélie, 1951-52*, Paris, Hermann, 1956. (Expéditions Polaires Françaises. Résultats scientifiques, No. 9)), and by Shiotani and Arai (A short note on the snow storm. *Proceedings of the 2nd Japan National Congress for Applied Mechanics 1952*. Tokio, Science Council of Japan, 1953).

where u_z = velocity at height z

u_* = "friction velocity"

and $\rho u_*^2 = \tau$, the shearing stress, which is constant in the boundary layer

z_0 = the surface roughness parameter

k = von Karman's constant, 0.4

For the logarithmic profile the exchange coefficient becomes

$$A_z = 0.4 \rho u_* (z + z_0) \tag{3}$$

and the solution of eq. (1) becomes

$$n_z = n_h \left\{ \frac{z + z_0}{h + z_0} \right\}^{-\frac{wp(h+z_0)}{A_h}}$$

or

$$n_z = n_h \left\{ \frac{z + z_0}{h + z_0} \right\}^{-\frac{w}{0.4u_*}} \tag{4}$$

where $n_h \rho$ is the drift density at a given height h .

The Mawson measurements led to the drift density $n\rho$ at heights of 4 cm., $\frac{1}{2}$ m., 1 m., 2 m., and 4 m. above the surface and numerical values of the exponent in eq. (4) were computed by comparing densities at 1 m. and 4 m. A mean drift density profile for a condition representative of moderate to heavy drift was determined, and integration between the limits 0 to 1,000 cm. and 1,000 to 12,000 cm. gave the mass of snow contained in vertical columns of unit cross-sectional area through the two layers. Above 12,000 cm., which was taken as the height of the maximum wind velocity, wind conditions are only vaguely known. It was assumed that above this height

$$A_z = A_{12000} - 0.03(z - 12000)$$

and thus from eq. (1)

$$n_z = n_{12000} \left\{ 1 + \frac{(z - 12000)}{A_{12000}} \frac{dA}{dz} \right\}^{-\frac{wp}{dA/dz}} \tag{5}$$

This expression was integrated between the limits 12,000 and 43,000 cm. to give the mass in a 1 cm. square vertical column through the layer.

By assuming suitable mean winds for the three layers the rate of turbulent transport in the direction of the wind could be calculated (strictly, it is $\Sigma n_z u_z$ which is required, but Loewe's general method was followed).

Measurements made 4 cm. above the surface gave values higher than those to be expected from the turbulence theory and an additional transport mechanism close to the surface was suspected. Bagnold¹⁵ has shown that the movement of wind blown desert sand takes place not by turbulent suspension but by particles bounding along the surface, the impact of a particle with the surface being followed by rebound or by ejection of another grain from the surface, and it is now believed that this "saltation" process affects snow movement.¹³ Rough estimates based on the preliminary results indicate that the mass of snow moved by saltation is small compared with the turbulent transport, although it remains of the same order as Loewe's original estimate.

A 4-year average drift frequency at Mawson is given below.

Weather code	36	37	38	39
No. of hours	481	58	246	321

The drift weather codes represent:

- 36—light to moderate below eye level
- 37—heavy below eye level
- 38—light to moderate above eye level
- 39—heavy above eye level

The mean rate of mass transport by turbulence was 153 gm./cm. sec. with a wind of 28 m./sec. at 10 m. height. This may be taken as representative of moderate to heavy drift and to obtain the annual mass transport we multiply by the total hours in Code 39 plus one quarter of the total hours in Code 38, since this last group covers light to moderate drift.

Saltation rates were estimated in an earlier paper¹³ and rates matching the mean winds of Codes 36, 37, 38, and 39 have been multiplied by the total drift hours of those groups to give the annual mass transport by saltation.

The resulting quantities are given below.

Turbulent transport	0.21×10^{14} gm./km. yr.
Saltation	0.012 ,, ,,
Total transport in wind direction	0.22×10^{14} gm./km. yr.

On the open snowfields at lat. 68° S. the blizzard dunes have a bearing of 135° true and the main sastrugi direction is 150° true. We have no information on changes of wind direction with altitude and for the purpose of this estimate the mass transport in the wind direction can be divided by $\sqrt{2}$ to give the meridional transport. In this way the annual meridional transport becomes 0.16×10^{14} gm./km. yr., which is close to Loewe's minimum estimate for Terre Adélie.

Mawson has an average wind velocity of 10.5 m./sec. and drift of one kind or another prevails for about 14 per cent of the time. At Port Martin in Terre Adélie the mean wind is 19 m./sec. and the frequency of all drift is about 50 per cent. Figures presented recently by Loewe⁶ show Mawson to have a lower drift frequency than several other Antarctic bases, although the mean winds of these bases are lower than the Mawson one. Though information is still lacking it seems that drift transport is not exceptionally high, so that the figure given above may be applicable to a considerable length of the Antarctic coastline.

ABLATION

Evaporation proceeds at an appreciable rate throughout the year in MacRobertson Land and Princess Elizabeth Land. When mean winter ablation rates of 0.7 mm. of water per day were first reported from Mawson¹⁶ they were thought exceptional, but subsequent observations by P. Crohn⁴ and by the present writer have confirmed the early measurements. At 425 m. above sea level and 16 km. inland from Mawson midwinter ablation rates are still as high as 0.6 mm. of water per day and it is believed that a mean rate of 0.5 mm. per day could well apply between 20 and 50 km. inland.

As early as October absorbed radiation can produce surface melting on the ice slopes with negative air temperatures and evaporation rates rise. Melting becomes more frequent in November, and in December and January the bare ice of the ablation zone melts regularly. Snow surfaces, with their higher albedos, suffer less melting but blue bands are formed on the ice-capped islands and big coastal drifts. Summer melting is intense on the bare ice below 200 m., and between 200 and 500 m. there is still sufficient water to form melt streams. The steep slopes near Mawson drain melt water efficiently and there is no significant formation of superimposed ice, but in other regions, e.g. Wilkes Land, there is widespread occurrence of superimposed ice. The determination of ice losses in a superimposed ice area will be rather difficult, as there is a continuous transfer of material, making it desirable to gauge melt water actually passing into the sea.

Summer melting on the lower slopes brings the annual net ablation to well over 500 mm. of water, but it seems that summer conditions do not greatly enhance the mean ablation rate at 500 m. altitude.

The mean wind velocity of Davis is less than half that of Mawson and the air has a higher humidity. Measurements by R. Dingle and B. Stinear in the Vestfold Hills show that winter ablation is less intense than in the Mawson area, a typical rate being 0.3 mm. against 0.7 mm. at Mawson. In spring the evaporation rate rises to a value which is comparable with the Mawson one: 1.3 mm. against 1.5 mm. per day. The mean air temperatures at Vestfold Hills in December and January are +0.2° C. and +0.3° C. respectively and heavy melting, followed by a certain amount of run-off to the sea, occurs. There are no ablation figures available for the summer months but it seems unlikely that the evaporation rate could be lower than 2 mm. of water per day, since 2.3 mm. per day has been measured in late November.

Both gauge and stake readings gave a result of about 5.5 cm. for the precipitation from the end of March to the end of November 1957, and evaporation in the same period was close to balancing precipitation during the winter. Although summer precipitation is only about 1 cm. of water, lakes in the Vestfold Hills receive a considerable inflow from melting snow. The lakes have been examined by the geologist Bruce Stinear and it is believed that their levels are fairly constant, in spite of the summer inflow and the absence of surface outlets or sub-surface drainage. This indicates a high summer evaporation over the limited area of the lakes.

On the evidence collected so far there seems no reason to believe that ablation losses in Princess Elizabeth Land are substantially less than those in MacRobertson Land.

For the measurement of ablation stakes were used, although there has been some criticism of the stake method due to the falling of untended stakes in summer when solar radiation is intense. Several methods were tried at Mawson but the most satisfactory one utilized ordinary bamboo stakes. Tapered bamboo stakes, 2.5 m. long, were painted white to reflect radiation and were set in 2.5 cm. diameter holes so that only 30 cm. of the thin end of the stake projected above the surface in spring. Separate marker flags were required, but the measuring stakes themselves did not become displaced.

Detailed results cannot be given here, but a few figures for the Mawson area are listed below. The 1954 measurements were made by R. Dovers¹⁶ and the 1955 and 1956 ones are due to P. Crohn.⁴

TABLE II. ANNUAL NET ABLATION AT 60 M. ALTITUDE, 1955-58

Period	Net ablation	
	mm. of ice	mm. of water
16 March 1955-16 March 1956	915	790
1 Jan. 1956-1 Jan. 1957	850	730
22 Feb. 1957-26 Feb. 1958	625	535

TABLE III. MONTHLY MEAN ABLATION RATES, 1954-1957 (60 M. ABOVE SEA LEVEL)

Month	Mean net ablation rates (mm. of ice per day)			
	1954	1955	1956	1957
January	—	—	11.4	—
February	—	—	3.7	—
March	—	{ 1.1	1.5	1.3
April	—	{ 1.1	1.0	1.2
May	{ 0.8	{ 0.8	0.8	0.9
June	{ 0.8	{ 0.8	0.8	{ 0.9
July	{ 0.8	0.6	0.5	{ 0.9
August	{ 1.1	0.8	0.6	0.6
September	{ 1.1	0.6	0.8	0.8
October	{ 1.5	1.4	0.9	1.4
November	{ 1.5	1.5	1.9	1.7
December	—	5.7	8.5	(4.8 mid-Dec. to late Feb.)

TABLE IV. NET ABLATION FROM 22 FEBRUARY 1957 TO 26 FEBRUARY 1958

Altitude (m.a.s.l.)	Net ablation	
	mm. of ice	mm. of water
60	625	535
150	575	495
180	570	490
305	300	260
335	270	230
365	255	220
425	275	235 (single measurement)

Most of the measurements given were made on the permanently snow-free ice of the ablation zone.

Before the winter evaporation is discounted as being abnormally high for Antarctica generally, it should be remembered that air descending steep marginal slopes of the continent undergoes a sharp temperature rise. Borehole temperatures show a rapid change of annual mean temperature in the fringe regions of MacRobertson Land² and from calculations based on these temperatures, and on atmospheric pressures at the surface, it is found that air flowing northwards may increase its capacity for holding water vapour by a factor of 10.

The 1957 Mawson figures give an ablation loss of 0.053×10^{14} gm./km. yr. between the coast and the firm limit. According to Table II the 1957 ablation at 60 m. height was 30 per cent below the mean loss in 1955 and 1956 and therefore it is unlikely that the above estimate is high. If 15 cm. is taken as the mean evaporation between 20 and 50 km. from the coast we get a further loss of 0.045×10^{14} gm./km. yr.

These ablation estimates are high in comparison with earlier measurements: David and Priestley¹⁷ give 18 cm. per year for McMurdo Sound, Wright and Priestley¹⁸ quote 15 to 30 cm. for the same region, Loewe⁶ estimates 10 cm. in Terre Adélie, and Wade¹⁹ and Swithinbank²⁰ both found negligible evaporation on the ice shelves at Little America and Maudheim respectively. Measurements were made by the writer on Lewis Island and on the neighbouring continental ice of Wilkes Land between 14 January and 9 February 1959. The slightly saline firn on the island lost 9 cm. of water (3.5 mm./day) and the mainland ice at 70 m. altitude and 0.5 km. from the sea lost 4.8 cm. (1.85 mm./day).

Whilst high evaporation is not to be expected at the seaward edge of ice shelves it seems quite likely that appreciable evaporation occurs over most of the steeply sloping fringe regions. In Terre Adélie, although there is a constant strong outflow of air from the interior, evaporation must be limited by the high humidity produced by drifting snow.

OCEANIC MELTING

With a scarcity of data on bottom melting beneath ice shelves there is consequently a diversity of opinion on its importance to the mass balance of Antarctica. In a survey of Antarctic problems Wexler²¹ assigned an enormous significance to oceanic melting, assuming that four times as much ice is lost by this means as by all the other loss processes. Wright²² has also stated that there is considerable melting beneath the Ross Ice Shelf. On the other hand, Debenham²³ believes that some ice shelves gain mass by bottom accretion and Simpson, during the discussion of Debenham's paper, supported the bottom accretion theory on different grounds. In a recent report Swithinbank²⁴ examines the problem in the light of various studies made at Maudheim and, although his two initial estimates vary by a factor of 5, it seems that the annual loss may be about 20 cm. of water at the seaward extremity of the ice shelf. Swithinbank also points out that the melting will decrease with distance from the ice front.

For a working estimate we might take 20 cm. of water for a distance of 30 km. from the ice front; this gives a loss of 0.06×10^{14} gm./km. yr. For the present purpose the melting of continental ice cliffs and glacier tongues can be ignored.

THE MASS BALANCE

In drawing up a balance for Antarctica it is important to distinguish between a meteorological balance, in which total water vapour import is estimated, and a glaciological balance, in which the mass gain is assessed from the net accumulation of snow. For a meteorological budget *total* ice losses must be balanced against water vapour import, but for a glaciological balance it is only necessary to estimate *net* ice losses and the *net* accumulation of snow on the continent. Thus wind-blown snow and ablation losses from areas above the firm limit do not enter into a balance in which mass gains are determined from measurements of snow accumulation. They remain important estimates, however, as they may be added to the measured net accumulation to give some idea of the precipitation over the continent.

In preceding sections estimated losses and gains in 1 km. wide radial strips have been given. These are now multiplied by appropriate effective lengths for each process to give a tentative budget for the sector between long. 45° E. and long. 80° E.

<i>Ice flow</i>	(shelf 230 km.)	1.5×10^{16} gm./yr.
	(stream 270 km.)	1.3×10^{16} „
	(sheet 1,600 km.)	0.3×10^{16} „
	Total	3.1×10^{16} gm./yr.
<i>Net ablation</i>	(2,100 km.)	1.1×10^{16} gm./yr.
<i>Evaporation</i> above firm limit	(2,100 km.)	0.95×10^{16} gm./yr.
<i>Drifting snow</i>	(1,600 km.)	2.6×10^{16} gm./yr.
<i>Oceanic melting</i>	(250 km.)	0.15×10^{16} gm./yr.
<i>Net accumulation</i>	(1,200 km.)	12.0×10^{16} gm./yr.

Thus the net losses amount to only 4.4×10^{16} gm./yr. whilst the gain is 12.0×10^{16} gm./yr. With such a wide discrepancy we must immediately suspect the basic estimates, but on the present data it is hard to justify any drastic revision. The estimated accumulation for Mac-Robertson Land is already rather low in comparison with results from other areas, and although the ice flow figure may well be low, it is not likely to be less than half the true value. The net ablation is believed to be reasonably accurate and oceanic melting is not effective over a sufficiently large area to be very significant. While feeling the need for more data we are at the same time forced to admit the possibility of an increasing ice volume in this sector.

The consideration may be carried further by taking the Australian data together with observations from other areas and extrapolating to obtain a mass budget for the whole of Antarctica.

Ice flow. The ice flow estimates were compared with rates for other regions in a previous paper ⁹ and they are now used directly to give export amounts.

Ice shelf	(7,500 km.)	0.48×10^{18} gm./yr.
Stream flow	(1,500 km.)	0.07×10^{18} „
Sheet flow	(11,000 km.)	0.02×10^{18} „
Total		0.57×10^{18} gm./yr.

Net ablation. Earlier ablation measurements are somewhat inadequate for estimating ice loss, but a reasonable estimate may be made by applying the Mawson rate over a length of 14,000 km. Thus we arrive at 0.074×10^{18} gm./yr.

Evaporation above the firm limit. Again we may apply the Mawson value over 14,000 km., giving 0.063×10^{18} gm./yr.

Drifting snow. If snow transport at the Mawson rate occurs over a circumferential length of 12,000 km. the total loss is 0.19×10^{18} gm./yr.

Oceanic melting. If 8,000 km. is the length of ice shelf subject to melting at the rate given, the total ice loss is 0.048×10^{18} gm./yr.

Accumulation. We have three meridional profiles:

Shumskiy	1.8×10^{14} gm./km. yr.
Schytt	1.5×10^{14} „
A.N.A.R.E.	1.0×10^{14} „

A mean value of 1.4×10^{14} gm./km. yr. might be taken over an effective length of 11,000 km. This gives the accumulation in the peripheral zone, to which a further 15 per cent might be added to allow for an average accumulation of 5 cm. of water over the heart of the continent. The accumulation on the whole of Antarctica is therefore about 1.7×10^{18} gm./yr.

Again there is an excess of accumulation, with net gain of 1.7×10^{18} gm./yr. and net loss of only 0.69×10^{18} gm./yr. Errors in the estimates are more likely to lie in the losses rather than in the accumulation; as stated before, the export of ice by calving may have been underestimated and this time it is possible that bottom melting beneath ice shelves could affect the balance. There is evidently an urgent need for new information on the problem of bottom melting, as this could form an important part of the mass budget.

In spite of the scarcity of data it is necessary to consider Loewe's suggestion⁶ that the level of the inland ice is rising. The writer's observations along the coasts between long. 45° E. and long. 80° E. indicate that the ice margins are neither advancing nor retreating to any appreciable extent at the present time²⁵ and more recent examinations in Oates Land gave the same result. However, Loewe considers that it may be some hundreds of years before the effects of increased accumulation are felt in coastal regions. Ice margin examinations in mountains which extend deep into the accumulation zone, e.g. the Prince Charles Mountains, could throw more light on the problem. The present estimates tend to support rather than to refute Loewe's theory, but it is felt that, until all the I.G.Y. results have been collated, no definite conclusions are possible.

Finally, the estimates can be used to derive a mean annual precipitation value for the ice sheet. By adding the ablation and drift snow losses to the net accumulation the precipitation estimate becomes 2.0×10^{18} gm./yr. or a mean precipitation of 14 cm. of water over the 14,000,000 sq. km. of Antarctica. This is higher than the estimates of Meinardus²⁶ but lower than Kosack's²⁷ figure of 20 cm.

ADDENDUM

Since this paper was first written Loewe has presented a new paper on the mass budget of Antarctica at the Symposium on Antarctic Meteorology held in Melbourne.²⁸ Loewe's appreciation of the situation is broadly similar to the interpretation given here and he concludes that the surplus of accumulation over losses is sufficiently decisive to indicate a gain of mass. He goes on to argue that the stationary state of the ice edges and the recent rise of sea level need not be taken as evidence against the theory of increasing ice volume.

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