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A RE-ASSESSMENT OF THE MASS BALANCE OF THE LAMBERT GLACIER DRAINAGE BASIN, ANTARCTICA

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Abstract. Re-definition of the interior drainage basin of Lambert Glacier, using the most recent sources of ice-surface elevations, has shown its area to be 902 000 km^2, that is, 17% less than previous estimates. Landsat imagery of the steepest sloping part of the basin shows there is bare ice over an area of 56 000 km^2. Other evidence also indicates exceptionally low mass inputs and the distribution of accumulation rates has been up-dated. The result is a positive mass balance for the interior basin (+2 Gt a^{-1}) and error limits which fall below zero. This is 47% less than the most recent calculation and illustrates the difficulty in deriving mass budgets in regions where data are scarce.

Résumé. *Redéfinition du bilan de masse du bassin versant du Lambert Glacier, Antarctique.* Une redéfinition du bassin versant du Lambert Glacier à l'aide des plus récentes sources de l'altitude de la glace a montré que sa surface est de 902 000 km^2, c'est-à-dire 17% de moins que les estimations antérieures. L'imagerie Landsat de la partie la plus inclinée du bassin montre qu'il y a 56 000 km^2 de glace nue. D'autres évidences indiquent d'exceptionnellement faibles apports de glace et une distribution d'accumulation plus recente. Le résultat est un bilan positif pour l'intérieur du bassin (+2 Gt a^{-1}) et des limites d'erreur qui tombent au-dessous de zéro. Ceci est de 47% inférieur aux plus récentes déterminations et illustre la difficulté à déduire des bilans de masse pour des régions où les données sont dispersées.

Zusammenfassung. *Eine Neuberechnung der Massenbilanz im Abflussbecken des Lambert Glacier, Antarktika.* Eine Neuabgrenzung des inneren Abflussbeckens des Lambert Glacier auf der Grundlage der neuesten Eishöhenbestimmungen ergab deren Fläche zu 902 000 km^2, also 17% weniger als früher abgeschätzt. Landsat-Bilder vom steilsten Teil des Beckens zeigen dort das Vorhandensein blanken Eises über eine Fläche von 56 000 km^2. Andere Hinweise deuten ebenfalls auf aussergewöhnlich niedrigen Massenzustrom, weshalb die Verteilung der Akkumulationsrate neu bestimmt wurde. Das Ergebnis ist eine positive Massenbilanz für das innere Becken (+2 Gt pro Jahr) mit Fehlergrenzen unter Null. Dies ist 47% weniger als die jüngste Berechnung und zeigt die Schwierigkeit der Massenbilanzbestimmung in Gegenden, für die nur wenige Daten vorliegen.

INTRODUCTION

That part of the Antarctic which drains into the Amery Ice Shelf has long been of interest to glaciologists because of its size. It forms a prominent and distinctive feature of the Antarctic ice sheet and has been identified as the continent's fourth largest drainage system (Giovinetto, 1964). Its main tributary is Lambert Glacier, which flows through the rift between the Prince Charles Mountains and the Mawson Escarpment. There, it is over 50 km wide and reaches a thickness of 2500 m (Morgan and Budd, 1975). Several attempts have been made to assess the mass balance of the Amery-Lambert drainage system (Mellor, 1959, 1964; Giovinetto, 1964, [1970]; Budd and others, 1967; Allison, 1979) and all have calculated positive mass budgets. Although based on conservative estimates of accumulation rates, a mean surface elevation rise of +0.04 m a^{-1} in the Amery-Lambert system (Allison, 1979) has supported the results of modelling the East Antarctic ice sheet (Budd and McInnes, [^{c}1978]) and has been taken to indicate that the system may, at present, be undergoing a post-surge build-up.

These mass-balance studies have all been hindered by the scarcity of data for this remote part of the Antarctic, particularly of accumulation rates in the interior of the drainage basin. The purpose of this paper is to re-assess the budget of this part of the drainage basin of Lambert Glacier in the light of new data concerning its area and the accumulation rates within it. The interior drainage basin is defined here as the accumulation area which drains into the Lambert Glacier system delimited by the eleven ice-movement stations reported by Allison (1979).

AREA OF THE INTERIOR DRAINAGE BASIN

Previous studies have been inhibited by the sparseness of surface elevation data with which to delimit the interior drainage basin of Lambert Glacier. Errors have typically been estimated to be 20 to 30% (Mellor, 1959, 1964; Giovinetto, 1964, [1970]; Budd and others, 1967). The most recent estimate of 1.09 x 10^6 km^2 ± 20% (Allison, 1979) was based on the American Geographical Society 1 : 5 000 000 map of Antarctica published in 1970. This was modified with data from airborne radio echo-sounding (Morgan and Budd, 1975) and oversnow survey (Allison, 1979) by the Australian National Antarctic Research Expeditions. Surface elevations were also available from traverses by the Japanese Antarctic Research Expeditions which intersected the south-western limits of the drainage basin (Fujiwara and others, 1971; Shimizu, 1977). However, there was a complete lack of data in the central parts of the drainage basin.

The present study used the most recent compilation of ice surface elevations in the Antarctic (Drewry, [^{c}1983]) to re-define the boundaries of the interior drainage basin. This includes altimetry from two sources (radio echo-sounding and constant-density balloons) not available to previous mass-balance studies. The distribution of these data in the interior drainage basin is shown in Figure 1 with the general ice-sheet surface, contoured at an interval of 500 m.

Surface elevations were available along 5100 km of flight track completed during the joint radio echo-sounding programme of the National Science Foundation, the Scott Polar Research Institute, and the Technical University of Denmark (Drewry and others, 1982). These cover the southern and south-eastern parts of the drainage basin. The method used to calculate elevations, based on barometric altimetry, has been described by Drewry and others (1982). Errors in areas away from control points, such as in the interior drainage basin, are estimated to be better than 50 m and, at best 30 m (Drewry, [^{c}1983]). Some 280 elevations, widely distributed across the drainage basin, are also available from constant-density, super-pressure balloons which opportunely drifted over the Antarctic during the Tropical Wind Energy and Reference Level Experiment (TWERLE) in 1975-76. The method and results have been described by Levanon (1982). Worst-case errors are thought to be of the order of ±60m.

The combination of these two new sources and those

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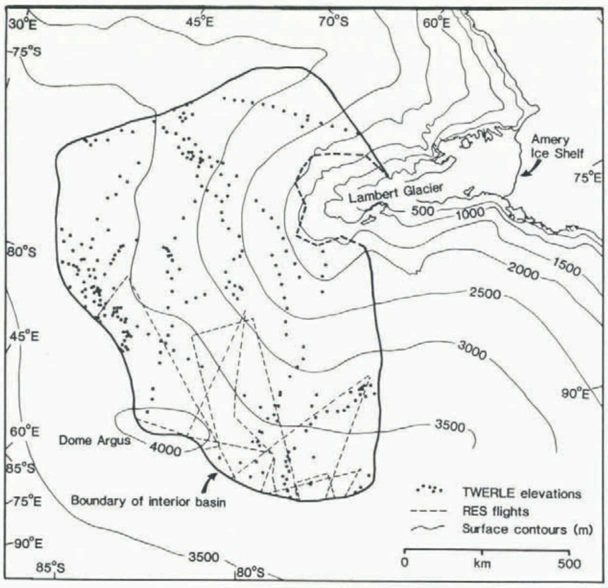

Fig. 1. Delimitation of the interior drainage basin of the Lambert Glacier system (redrawn from Drewry, [c1983]). The distribution of ice surface elevations from TWERLE (dots) and radio echo-sounding (dashed lines) is also shown.

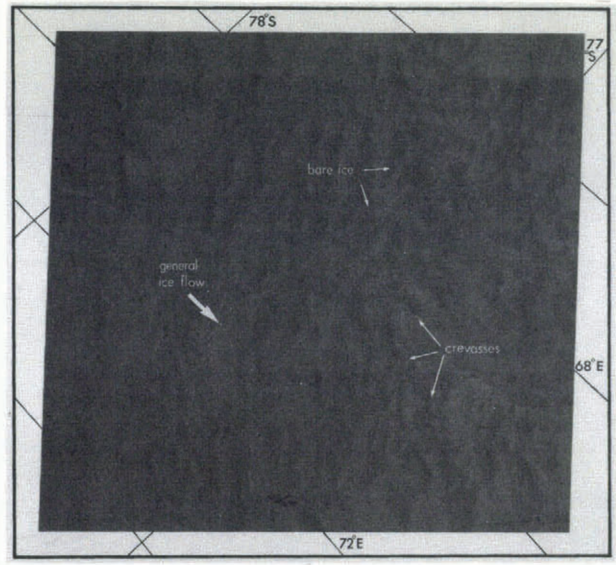

Fig. 2. Band 7 Landsat MSS image centred at lat. 76°15'S., long. 68°18'E. in the region of the subglacial Gamburtsev Mountains. Patches of bare ice (darker tones) can be seen as well as surface undulations and crevassed areas. Sun angle is 21°. Path 126, row 115. 1479-02223.

available to previous workers has enabled a more precise delimitation of the area contributing to the discharge of ice through the network of ice-movement stations reported by Allison (1979). Flow lines were constructed from a 1 : 6 000 000 map contoured every 100 m (Drewry, [c1983]) on the principle that, over distances several times the ice thickness, ice flow is normal to the trend of the contours. The resulting drainage basin has an area of 902 000 km^2. It is difficult to place an error on this figure but, given that the margin of the drainage basin has been located to within ±25 km, the actual area is likely to be between 813 000 and 994 000 km^2. This represents an error of ±10%. The significance of this re-calculation of the area is that it is 17% less than that defined by Allison (1979) which was used to estimate the mass balance.

PATTERN OF ACCUMULATION

Accumulation data within the drainage basin are also sparse, being largely confined to traverse routes along the southern periphery. In some areas, where interpolation between adjacent areas is necessary, interpretations have differed significantly (Bull, 1971; Kotlyakov and others, 1974). Allison (1979) modified the available data to account for the low values recorded at most of the ice-movement stations; this resulted in the 100 kg m^{-2} a^{-1} isopleth passing north of the head of Lambert Glacier. Despite these conservative values for the accumulation rate, there are several sources which suggest that the interior drainage basin is an area of exceptionally low accumulation. This may in part be the cause of the imbalance between accumulation within the basin and the discharge of ice from it (Robin, 1983).

Figure 2 shows a band 7 multispectral scanner (MSS) Landsat image centred at lat. 76°15'S., long. 68°18'E., 200 km south-east of the outlying nunataks of Mawson Escarpment. As well as substantial surface undulations and crevasse trains due to ice flow over the irregular subglacial Gamburtsev Mountains, there are considerable areas of what is interpreted to be bare ice (darker tones) interspersed with variable amounts of firn. Visual confirmation of this interpretation comes from comparison with Landsat imagery of blue ice in the Queen Fabiola Mountains area (Williams and others, 1983) and near Allan Hills, Victoria Land. Similar patterns of tonal variations across and between undulation crests occur in all three areas. Further confirmation could be achieved with an analysis of spectral response patterns derived from digital Landsat data.

Compilation of a mosaic of 16 MSS images, covering most of the drainage basin up to 500 km inland of Lambert Glacier, enabled the area of bare ice to be mapped (Fig. 3). Since the bare ice occurs in isolated patches which form a complex pattern, this was taken as the region in which more than half of the terrain was composed of exposed ice. It was found to cover 56 000 km^2, that is, over 6% of the area of the interior drainage basin.

Blue-ice areas have been attributed to ablation by sublimation, wind scouring, and surface polishing by wind-driven snow (Williams and others, 1983). They are, therefore, most likely to occur in areas of strong katabatic winds. Where mean surface slopes are greater than 0.002 radians, katabatic forces tend to exceed considerably those arising from synoptic pressure gradients (Ball, 1960). Within the drainage basin of Lambert Glacier, these gradients, calculated over 50 km segments, are exceeded below elevations of 3500 to 3800 m. In the area reported to contain blue ice, which is between 2000 and 3100 m, slopes range from 0.003 to 0.008 radians, with a mean of 0.0045 radians. This is the most steeply sloping part of the interior drainage basin and hence that which is most likely to be subject to the strongest katabatic winds. Although katabatic winds are funnelled downslope by topographic embayments, Parish (1981) reports that they are deflected by 30 to 50° left of the fall line by the Coriolis force. This can be seen in the present case where the main axis of the zone of bare ice lies approximately 30° to the left of the maximum regional slope. That these winds are capable of ablating the ice-sheet surface at a sufficient rate to produce blue ice is suggested by the observation at Mizuho Station (lat. 70°41'53"S., long. 44°19'54"E., 2230 m above sea-level). Here, sublimation (54 kg m^{-2} a^{-1}) is significant in reducing the annual accumulation (Fujii and Kusonoki, 1982). Gradients on the slope of the Mizuho Plateau with

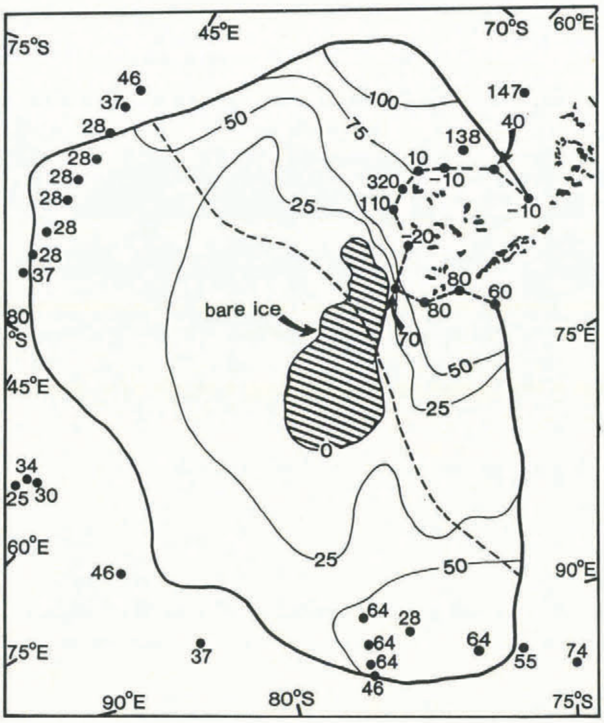

Fig. 3. Revised distribution of accumulation rates in the interior drainage basin of the Lambert Glacier system. Area of bare ice is shaded. Contours have been extrapolated between the bare ice and measured values on the basis of brightness temperatures. The 50 kg $m^{-2}a^{-1}$ isopleth of Allison (1979) is shown (dashed line). Measured accumulation rates are given for the 11 ice-movement stations (Allison, 1979) and previously published values near the periphery. Outcrops near Lambert Glacier are shown as black areas.

strong katabatic wind are directly comparable with those in the Lambert Glacier drainage basin. It is therefore possible that these very high rates of sublimation also occur in the catchment area of Lambert Glacier and are in part responsible for the exposed blue ice indicated by Landsat imagery.

The notion that the entire interior drainage basin of Lambert Glacier is an area of exceptionally low accumulation is also supported by an analysis of passive microwave radiometry (Zwally and Gloersen, 1977). Brightness temperatures of polar firn are closely although complexly related to mean annual temperatures and to accumulation. The anomalously low values found throughout the drainage basin were attributed by Zwally and Gloersen (1977) to particularly low accumulation rates, thereby supporting the suggestion that sublimation by katabatic winds across the regionally steep slopes may significantly reduce the mass input to the basin.

On the basis of the above observations, the distribution of accumulation rates was re-contoured as shown in Figure 3. Even though ablation rates of up to 60 kg $m^{-2}a^{-1}$ have been recorded for blue ice areas in the Queen Fabiola Mountains (Yokoyama, 1978), the present delimitation of bare ice includes intervening areas of firn. A mean net accumulation of zero has been used to account for this local variability. Accumulation rates in the rest of the drainage basin have been contoured at an interval of 25 kg $m^{-2}a^{-1}$ using brightness temperatures to provide an empirical extrapolation between the bare ice and the few known values at the periphery of the catchment area. The contouring attempts to show the regional patterns in accumulation and individual values have not been honoured in all cases. Local variability may, in part, be associated with the presence of areas of outcrop which significantly affect the heat balance and wind pattern at the ice-sheet surface (Allison, 1979).

RE-CALCULATION OF THE MASS BUDGET

Using the distribution of accumulation rates shown in Figure 3, the annual mass input to the interior drainage basin was found to be 32 Gt a^{-1}. This represents a 47% reduction from the figure of 60 Gt a^{-1} calculated by Allison (1979). There is only a 6% imbalance between input to the basin and discharge from it as opposed to the previous estimate of 100%, thereby allowing for a balanced mass budget. The mean rate of mass input across the drainage basin is 36 kg $m^{-2}a^{-1}$. Table I gives details of the mass budget which, for comparative purposes, has been extended to include the Lambert Glacier system and the Amery-Lambert system. The limits shown are for the worst possible combination of magnitude and sign of the estimated errors, as discussed by Allison (1979). Other than the much-reduced overall budget for the interior drainage basin (+2 rather than +30 Gt a^{-1}), it should be noted that the lower budget limit falls below zero by a significant amount. The errors for the change in surface elevation (-0.014 to +0.016 m a^{-1} water) allow for the ice sheet to be in balance or actually thinning; this was not the case in any previous budget calculations.

The mass budget for the whole Amery-Lambert drainage system is reduced by 67% to +14 Gt a^{-1}. This represents a mean surface increase of 0.015 m a^{-1} water. The lower limit indicates that the entire drainage basin may be in balance while the upper limit is significantly less than previous estimates.

TABLE I. RE-CALCULATION OF THE MASS BALANCE OF LAMBERT GLACIER ON THE BASIS OF THE REVISED AREA AND ACCUMULATION RATES SHOWN IN FIGURES 1 AND 3
(Bracketed values are those of Allison (1979).)

	Interior drainage basin	*Lambert Glacier system*	*Total drainage basin*
Inflow (Gt a^{-1})	- (-)	30 (30)	- (-)
Gain in basin (Gt a^{-1})	32 (60)	-7 (-7)	25 (53)
Outflow (Gt a^{-1})	30 (30)	11 (11)	11 (11)
Budget (Gt a^{-1})	+2 (+30)	+12 (+12)	+14 (+42)
Budget limits (Gt a^{-1})	-11, +16 (+3, +79)	-4.5, +28 (-4.5, +28)	0, +25 (+9, +89)
Area (thousand km^2)	902 (1090)	62 (62)	964 (1152)
Mean annual surface level change (m a^{-1} water)	+0.002 (+0.03)	+0.19 (+0.19)	+0.015 (+0.04)
Surface change limits (m a^{-1} water)	-0.014, +0.016 (+0.003, +0.07)	-0.07, +0.45 (-0.07, +0.45)	0, +0.024 (+0.01, +0.

DISCUSSION

The immediate conclusion of the downward revision of Lambert Glacier's mass balance is to question the possibility of the basin being in a post-surge build-up (Allison, 1979). This contention is supported both by the fact that the overall budget is significantly smaller than previous estimates and that the likely limits for the errors actually fall below zero. Although there is geomorphological evidence that ice levels in the Prince Charles Mountains may have fluctuated by several hundred metres in the recent past (Mellor, 1959; Tingey, 1974; Wellman, 1982) and although the results of modelling (Budd and McInnes, [c1978]) show that Lambert Glacier is likely to be subject to surging behaviour, the present data do not confirm these suggestions.

Identification of substantial areas of bare ice in the drainage basin of Lambert Glacier must also serve as a warning for the calculation of mass budgets, especially in regions of the Antarctic where data on elevations and accumulation rates are scarce. The possibility of significant local variations in mass balances, as have been found on Mizuho Plateau (Naruse, 1979), makes the extrapolation of accumulation rates over large distances difficult and uncertain. This is particularly true towards coastal regions where slopes are steeper and katabatic winds stronger. Errors in the estimation of discharge from these zones with high accumulation rates will be proportionately more important to calculations of the output of ice from the ice sheet.

Finally, it is possible that the areas of blue ice identified in the Lambert Glacier basin represent a zone of meteorite concentration. Whillans and Cassidy (1983) and Meier (quoted by Williams and others, 1983) identified regions with high vertical strain-rates and high ablation rates as the most likely areas for them to collect. It is possible that the presence of the very irregular subglacial Gamburtsev Mountains and the steep surface slopes resulting in strong katabatic winds may offer suitable conditions to warrant a meteorite collection expedition.

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