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MASS-BALANCE AND ICE-FLOW-LAW PARAMETERS FOR EAST ANTARCTICA

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ABSTRACT. A comprehensive set of ice-velocity and thickness data from traverses within the IAGP study area (bounded by long. 90°E. and 135°E., and north of lat. 80°S.) is compared with steady-state mass-flux calculations based on Scott Polar Research Institute (SPRI) map compilations.

The results of previous regional mass-budget estimates are reviewed and followed by a description of the new field measurements and the basis upon which a computer "grid-point" program is used to calculate balance fluxes.

A comparison of measured and balance fluxes indicates that the ice sheet in this region of East Antarctica is unlikely to be significantly out of balance.

The ratio of average column to surface velocity is discussed and calculated to be 0.89.

An analysis of the mean shear strain-rate (V_s/Z), versus down-slope basal shear stress ($\tau_b = \rho g \bar{\alpha} Z$), suggests that power flow-law parameters of n = 3.21 and k = 0.023 bar^{-n} m^{-1} are appropriate for the effective basal shear zone in this region of the Antarctic ice sheet.

RÉSUMÉ. *Bilan de masse et paramètres de la loi de fluage de la glace pour l'Antarctide Orientale.* On compare un ensemble important de données de vitesses et d'épaisseurs obtenus sur des profils de la zone étudiée par l'IAGP (limitée par les méridiens 90°E et 135°E, au Nord de 80°S) aux débits d'équilibre calculés à partir des cartes compilées par le Scott Polar Research Institute (SPRI).

Les résultats d'estimations antérieures du bilan de masse régional sont passés en revue et suivis d'une description des nouvelles données de terrain ainsi que de la base utilisée par le programme pour calculer les flux d'équilibre.

La comparaison des débits mesurés et des débits d'équilibre montre qu'il est peu probable que la calotte glaciaire soit, dans cette région de l'Antarctide Orientale, significativement déséquilibrée.

On a trouvé, pour le rapport entre la vitesse moyenne sur une verticale et la vitesse en surface la valeur de 0,89.

Les variations de la vitesse de déformation moyenne (V_s/Z) en fonction de la cission à la base ($\tau_b = \rho g \bar{\alpha} Z$) indiquent que, pour la glace de la couche basale, les paramètres de la loi de Glen pourraient être n = 3,21 et k = 0,023 bar^{-n} m^{-1}.

ZUSAMMENFASSUNG. *Parameter der Massenbilanz und des Fliessgesetzes für die Ost-Antarktis.* Ein umfasender Satz von Daten für die Eisgeschwindigkeit und -dicke aus Messprofilen innerhalb des AIGP-Untersuchungsgebietes (zwischen 90° und 135° östl. Länge und nördlich 80° südl. Breite) wird mit Berechnungen des stationären Massenflusses verglichen, die auf SPRI-Kartierungen des Scott Polar Research Institute beruhen.

Die Ergebnisse früherer regionaler Massenhaushaltsschätzungen werden überprüft; dann folgt eine Beschreibung der neuen Feldmessungen und der Grundlage für die Anwendung eines Netzpunkt-Rechenprogramms zur Berechnung des Gleichgewichtsflusses.

Ein Vergleich zwischen den Messungen und dem berechneten Gleichgewichtsfluss deutet darauf hin, dass der Eisschild in diesem Gebiet der Ost-Antarktis vermutlich nicht wesentlich vom Gleichgewichtszustand entfernt ist.

Das Verhältnis der mittleren Säulen- zur Oberflächengeschwindigkeit wird diskutiert; seine Berechnung ergibt den Wert 0,89.

Eine Analyse der mittleren Spannungsrate (V_s/Z) gegenüber der hangabwärts gerichteten Scherspannung am Untergrund ($\tau_b = \rho g \bar{\alpha} Z$) lässt vermuten, dass als Parameter für das Potenz-Fliessgesetz innerhalb der effektiven Scherzone am Untergrund dieser Region des antarktischen Eisschildes die Werte n = 3,21 und k = 0,023 bar^{-n} m^{-1} angemessen sind.

INTRODUCTION

The determination of the Antarctic ice-sheet mass budget has been one of the major aims of the International Antarctic Glaciology Project (IAGP) since its inception in 1969. However, collection of sufficient field data has been a slow task and the interpretation made difficult by results which often exhibit wide scatter and errors.

Many previous mass-flux calculations have begun by proposing a zero net mass budget as a first approximation. Two questions follow: how well does this assumed balance condition correlate with real measurements over a large section of East Antarctica? Secondly, is it possible to better estimate flow-law parameters appropriate for the ice sheet?

Budd and others (1971) compiled a comprehensive work aimed at calculating previously unknown physical characteristics of the Antarctic ice sheet, although it was recognized at the time that there were large gaps in the data coverage.

Budd and Smith (unpublished) and Morgan and Jacka (1979) also referred to the coarseness of mass-balance predictions when data are lacking. Many earlier studies (e.g. Loewe, 1960; Bardin and Suyetova, 1967) suggested that the net budget was difficult to estimate due to the character of errors but that accumulation probably exceeded ablation by an amount up to 100% (i.e. positive imbalance).

Recent Antarctic mass-balance studies have generally considered outlet glaciers or individual drainage basins. The variance reported illustrates that trends in particular coastal or inland regions may not be the same as each other, or as that of the Antarctic ice sheet as a whole. Morgan and Jacka (1979) and Meier (1980) summarized the studies to that time, reporting positive imbalances in all cases. These summaries included the studies of: Allison (1979), Lambert Glacier basin, imbalance +100%; Shimuzu and others (1978), Shirase Glacier and Soya Glacier, imbalance +40% and +100%, respectively; Bogorodskiy and others (1977), Hays

Glacier, Campbell Glacier, and Carnebreen Glacier, imbalance +13%; Young (1979), Pionerskaya to Dome C, imbalance +21%; Morgan and Jacka (1979), Kemp Land, imbalance +100%; Lorius (1962), Terre Adélie, imbalance +73%.

Brooks and others (1978) suggested that conventional surveys are an inadequate way of mapping the Antarctic ice sheet for dynamic studies and outlined a proposal for the use of repetitive satellite radar altimetry as a way of measuring directly the balance of ice sheets and monitoring possible surges.

Various authors have described computer models which seem to provide realistic assessments. However, computer models are usually limited by an inadequate coverage, smoothing of the input field data, and uncertainty about flow-law parameters derived from laboratory studies.

This paper draws on field measurements of ice velocity and other data from traverses within the IAGP study area bounded by long. 90°E. and 135°E., and north of lat. 80°S., to provide the most extensive direct check of the balance of the inland ice sheet so far available.

Measured surface velocity and ice thickness are multiplied to determine flux rates which are then compared to independently calculated balance fluxes. Balance fluxes were calculated using digitized surface elevations and accumulation rates for the entire Antarctic continent.

The sector of East Antarctica examined in this paper incorporates a number of drainage basins and was originally reported by Young (1979) to show a positive imbalance in the net mass budget of +21%. However, because of an estimated error of around 20%, this result was described as being "close-to-zero". Kotlyakov and others (1983) re-evaluated the sector inland of the Mirny to Dome C line, with more recent accumulation data and calculated the imbalance to be +28%.

The relationship between the mean strain-rate term and the expression for down-slope shear stress is then examined to determine empirical values of power-law flow parameters for comparison with the previous work of Budd and Smith (1981) and Cooper and others (1982).

FIELD MEASUREMENTS

The bulk of these measurements are from three major traverse lines within the IAGP study area (see Fig. 1). The three traverse lines are as follows. The eastern Wilkes Land route from lat. 68°36'S., long. 113°19'E. to lat. 68°59'S., long. 126°56'E., which crosses the general flow direction at an approximate elevation of 2000 m (Jones and Hendy, 1985); the southern Wilkes Land route from lat. 68°54'S., long. 112°02'E. to lat. 74°08'S., long. 109°50'E., which is approximately along a flow line (Young and others, 1982; Sheehy, unpublished); finally, the Soviet traverse route from Mirny (lat. 66°33'S., long. 93°00'E.) to Pionerskaya (lat. 69°44'S., long. 95°32'E.), which is approximately along a flow line, and then from Pionerskaya to Dome C (lat. 74°44'S., long. 124°22'E.), which crosses the general flow direction at an approximate elevation of 3000 m (Hamley, 1985). Other measurements are taken from Jones and Davis (1985), Medhurst (1985), and unpublished ANARE data.

Altogether, 55 ice-movement stations have been considered.

At each station, geodetic coordinates were computed from the results of satellite doppler surveys with a mean error range (for latitude, longitude, and height) assigned on the basis of the number of passes collected. After a suitable length of time, each station position was re-measured, requiring a simple calculation to determine surface-ice velocity. The error range in velocity measurements is therefore dependent on the quality of position "fixes" and the length of time between those measurements.

In Figure 2, the measured surface-ice velocity along sections of major traverse lines is shown by upper and lower bounds equivalent to the mean solution plus and minus the estimated error.

Ice thicknesses were obtained using a 100 MHz echo-sounding radar.

Measured flux rates were calculated from ice thicknesses (meaned over 20 km) and the measured surface velocities (see Fig. 3).

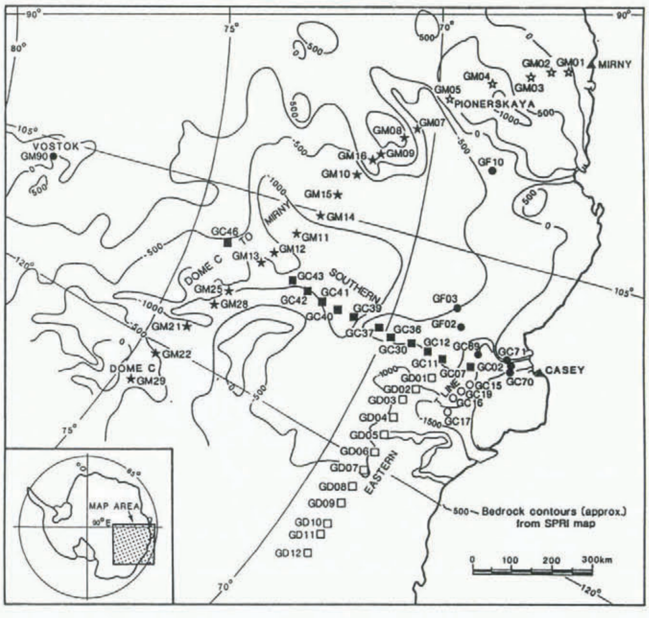

Fig. 1. Location of ice-movement stations.

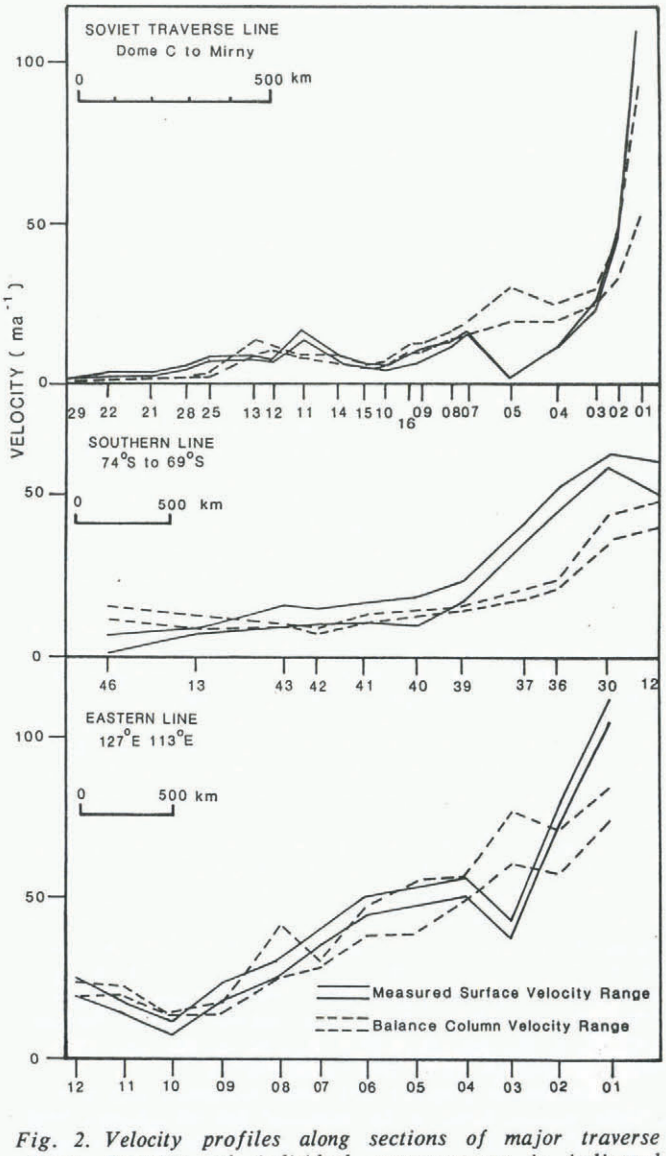

Fig. 2. Velocity profiles along sections of major traverse lines. Location of individual measurements is indicated along with station numbers.

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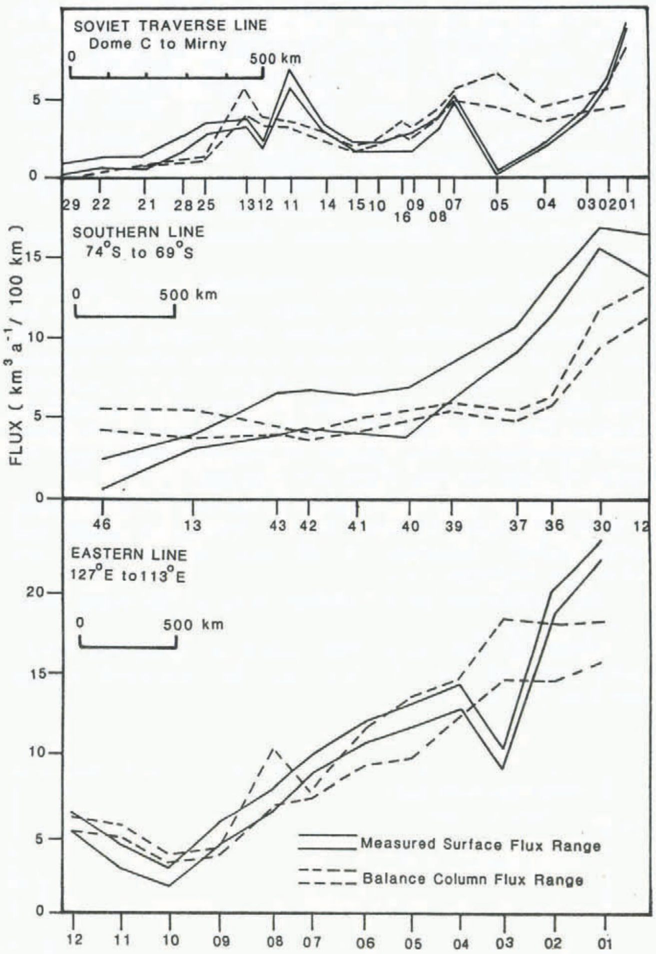

Fig. 3. Flux profiles along sections of major traverse lines. Location of individual measurements is indicated along with station numbers.

BALANCE CALCULATIONS

The calculation of balance fluxes for East Antarctica has been the result of a joint study between the Cooperative Institute for Research into Environmental Sciences (CIRES), University of Colorado at Boulder, Colorado, U.S.A., and the Meteorology Department, University of Melbourne, Australia. One of the primary aims was the determination of a variety of physical characteristics for the region in the manner of Budd and others (1971), updated by new techniques and recent data.

Surface-elevation data used in balance computations were digitized from the map series published by the Scott Polar Research Institute (Drewry, 1983). Accumulation data were based on a preliminary SPRI compilation supplied by Drewry and Radok (personal communications). These data and the results of various calculations consist of 281 x 281 grid points covering the entire Antarctic continent. Each grid point represents the mean value for the surrounding 20 km x 20 km square.

Balance fluxes have been calculated for the sector of East Antarctica covered by ANARE IAGP traverses.

Previous determinations of balance fluxes have been based on a method in which a series of flow lines is delineated to define a drainage basin. In a flow-line technique, accumulation rates are summed over the enclosed areas and at selected points the integral is divided by the flow-line separation (Budd and others, 1971). Manual methods of this type have been adopted in the mass-balance studies of Allison (1979) and Young (1979).

A computer program has been developed which now enables balance terms to be calculated for an arbitrary grid on which surface elevations and accumulation rates have been defined. The main advantages of a grid-point program are that it removes the subjective element of defining flow lines and provides a uniformly dense representation in a relatively short time.

The program treats each grid point in turn from the highest to the lowest surface elevation and calculates the rate of mass outflow required to balance mass inflow plus surface accumulation. Outflow is partitioned according to the relative magnitudes of the down-hill slope components.

The accuracy of the method has been verified by tests with analytic solutions (personal communication from D. Jenssen); however, several points need bearing in mind when making comparison with actual measurements. For example, it is assumed that surface slopes determine the flow direction which may not always be the case if longitudinal stresses are significant or other dynamic effects cause streaming. Streaming may introduce a bias in calculated balance fluxes down a flow line which would otherwise cancel out if similar comparisons are carried out along a contour of sufficient length. Therefore, the southern line may not provide the most reliable comparison (for mass balance), since it approximates a true flow line.

Another factor affecting balance calculations is the quality of surface-elevation data which is not uniformly reliable. Airborne profiling by the SPRI provides good coverage east of around long. 118°E. and the map-derived data show good agreement with the latest field results. However, there still remain relatively large areas where detailed surface-elevation data are lacking.

Accumulation data for the entire continent have been compared with those of Budd and Smith (1982) and are, on average, greater by about 10%. The accumulation map of Budd and Smith (1982) originates from Kotlyakov and others (1974) with updated modifications. Latest ANARE accumulation data along the eastern line, and Soviet accumulation data along the Mirny to Dome C line, correlate well on the large scale with values obtained from the preliminary SPRI compilations.

Figure 2 shows the maximum and minimum values of the measured and calculated balance velocities along the three traverse routes (i.e. the Mirny to Dome C, southern, and eastern lines, respectively). Note that the balance velocity has been obtained by dividing the calculated balance flux by the measured 20 km mean ice thickness (i.e. meaned over 20 km of the relevant traverse segment). Figure 3 shows the same comparison for balance fluxes.

Figure 4 shows the contour plot of balance fluxes. Major topographic features including Ridge B, Dome C, and Law Dome show up as areas of minimum flux. Major outflow areas correspond to Totten, Vanderford, and Denman Glaciers. Certain minor outflow areas are not associated with identifiable geographic features but reflect

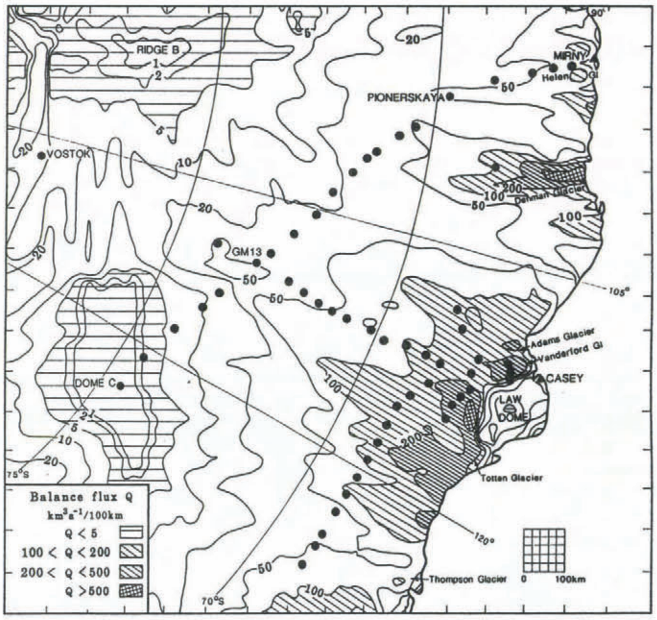

Fig. 4. Balance fluxes for East Antarctica from grid-point computer calculations.

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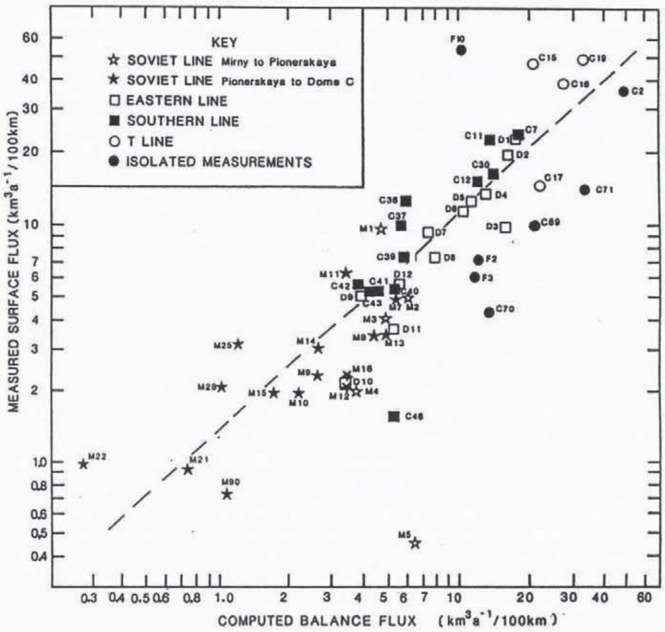

Fig. 5. Measured surface flux versus computed balance flux with line of best fit shown dotted. Station names GF10, GM05, etc. are labelled F10, M5, and so on.

slight patterns of convergence evident in surface-elevation contours.

For each ice-movement station, a maximum and minimum calculated balance flux is plotted, corresponding to the range of values occurring within a radius of 20 km (one grid spacing) of the point. Note that measured fluxes are based on surface velocities and are strictly comparable only if there is no vertical velocity gradient (i.e. the ice sheet flows as a block).

In Figure 5 the plot of measured versus balance flux shows that a linear relationship is evident within the limits of scatter.

DISCUSSION

In general terms, Figures 3 and 4 illustrate that flux rates are typically less than 20 km^3 a^{-1}/100 km at elevations above 2500 m (i.e. the majority of inland Antarctica). In coastal zones where the surface slope increases rapidly, so too do the flux rates. Between the 2000 m to 1000 m contours, flux rates typically increase by up to an order of magnitude.

In some areas local imbalance is suggested by a significant difference between the measured and balance fluxes (Fig. 3). Local thinning appears to be occurring in the area south of Casey between GC12 and GC40 on the southern line and GC01 and GC02 on the eastern line. There seems to be evidence of thickening at the end of the southern line near GM13; however, these conclusions may be unreliable for reasons discussed previously.

Between GM13 and Dome C on the Soviet traverse route there is evidence of local thinning which is supported by the recent model results of Alley and Whillans (1984). Elsewhere, both the Soviet and eastern lines indicate a state of balance apart from two points (GM05 and GF10), which are significantly at variance to the rest of the data.

Flow in the area of GM05 is known to be divergent, although this feature is not reflected by surface-elevation data. Likewise, GF10 lies at the head of Denman Glacier and, although convergence is apparent, the data may not define this effect in sufficient detail. The fact that these discrepancies are of opposite sign, yet occur in relative proximity, suggests that only the larger-scale features are represented in the data for this region of East Antarctica and that smaller-scale features remain to be resolved. The scatter of data along the eastern line in Figure 5 is significantly less than others which is probably a reflection of the better data coverage.

Budd and McInnes (1979) and Budd and others (1970) have stated that around major ice-shelf basins balance velocities tend to be higher (by about a factor of two) than measured values, thus indicating a slow build up in the interior. Similar evidence is apparent for several stations in the area of Vanderford Glacier (shown by solid black dots in Figure 1); however, the results indicate that this may only be a localized feature.

Analysis of the data in Figure 5 shows that the correlation between balance calculations and field measurements is on average very close after an allowance is made for the conversion from surface to column velocity. The value for the slope of the line of best fit (0.89) agrees favourably with suggested values of between 0.85 and 0.92 given by Budd and others (1971, p. 161) for a flow line in this region, and the value of 0.9 given by Young (1979). We therefore propose that this section of East Antarctica is generally in balance with local areas possibly subject to imbalance as previously described.

Figure 6 presents the relationship between the mean strain-rate term (V_s/Z) and the down-slope shear stress

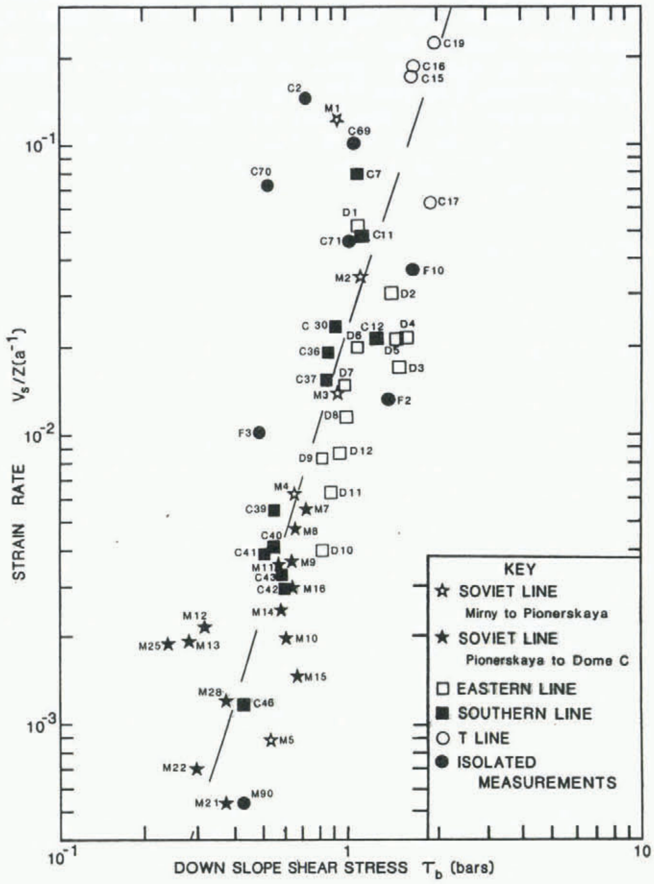

Fig. 6. Strain-rate versus down-slope shear stress with regression line shown dotted. Station names GF10, GM05, etc. are labelled F10, M5, and so on.

($\rho g \bar{\alpha} Z$) where V_s = measured surface velocity, Z = 20 km mean ice thickness, ρ = density of ice, g = acceleration of gravity, $\bar{\alpha}$ = surface slope averaged over the surrounding SPRI data grid points (approximately 20 km). A regression analysis of this relationship was used to determine empirical values for coefficients used in the general form of the power flow law of ice which may be expressed as follows:

$$V/Z = k\tau_b{}^n \quad (1)$$

where $\tau_b = \rho g Z \sin \alpha$.

Regression analysis of data shown in Figure 6 resulted in values for the flow-law parameters (Equation (1)), of n = 3.21 and k = 0.023 bar^{-n} m^{-1} with a coefficient of determination r = 0.79. This compares well with the results of Budd and Smith (1981) who, using data from a variety

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of other sources, obtained values for $n = 3.5$ and $k = 0.025$ bar^{-n} m^{-1} for polar ice. Cooper and others (1982) compared balance velocities from Wilkes Land with calculated shear stresses and found $n = 2.51$ and $k = 0.0085$ bar^{-n} m^{-1} with a correlation coefficient of 0.81.

For an isothermal ice mass with a power flow law, the theoretical value of the ratio of velocity at a depth z is given by

$$V_s - 2A(\rho g \sin \alpha)^n z^{n+1/n-1} \qquad (2)$$

which gives

$$\bar{V}/V_s = n + 1/n + 2 \qquad (3)$$

where $\bar{V}$ = average column velocity and V_s = surface velocity.

Therefore, if $n = 3.21$, then $\bar{V}/V_s = 0.81$.

For cold ice sheets, however, the increase in temperature towards the base tends to increase the effective value of n (cf. Budd, 1969). The change in ice crystallography can also greatly influence the ratio of averge to surface velocity (Russell-Head and Budd, 1979). If the increasing temperature towards the base is taken into account, then the ratio can be higher as given by Budd and others (1970). Values between 0.85 and 0.92 might be expected.

Therefore, the value obtained from data shown in Figure 5 for the ratio of balance velocity to surface velocity, of 0.89, is as close as could be expected for a balanced state.

CONCLUSIONS

A comparison between field measurements of velocity and ice thickness with calculated balance fluxes in East Antarctica suggests that the IAGP study area bounded by long. 90°E. and 135°E. and north of lat. 80°S. is unlikely to be significantly out of balance (i.e. more than ±10% of balance).

Indications are that the balance state applies in general over the entire region, except in some areas where local imbalance might be suggested.

The ratio of average column to surface-ice velocity for this section of East Antarctica is estimated to be 0.89.

Analysis of the mean shear strain-rate versus down-slope shear-stress relationship suggests the following approximate values of the power flow-law parameters are appropriate for the bulk flow of the ice sheet in this region:

$$n = 3.21, \text{ and } k = 0.023 \text{ bar}^{-n} \text{ m}^{-1}.$$

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