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MEASURED VELOCITIES OF INTERIOR EAST ANTARCTICA AND THE STATE OF MASS BALANCE WITHIN THE I.A.G.P. AREA

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Abstract. Recent measurements of accumulation and ice velocity made in the interior of East Antarctica indicate that a large sector between longitudes 80° E. and 135° E. and north of latitude 80° S. has close to a zero net mass budget. This sector is within the study area for the International Antarctic Glaciological Project (I.A.G.P.) and covers a major portion of the area indicated for projects of special emphasis. Velocity measurements were made at a number of points on a traverse route from Mirny (lat. 66° 33′ S., long. 93° 00′ E.) on the coast to Dome "C" (lat. 74° 40′ S., long. 124° 00′ E.), in the interior. Accumulation measurements were made along this and other traverse routes, extending as far as Vostok (lat. 78° 28′ S., long. 106° 50′ E.), by a number of methods. These included stake, stratigraphic, isotopic, and total β-decay observations. The better accumulation data have allowed a review of the total mass input to be made. The true mass budget has been estimated by comparing velocities, calculated assuming a zero net mass budget with measured velocities along the traverse routes and on a number of the outlet glaciers. For this purpose the area was divided into a number of drainage basins according to outlet at the coast. The area of about 10^6 km² and 150 Gt a⁻¹ flux input is drained primarily by three glacier systems of which the Totten accounts for 40% of the flux from 55% of the area; the Vanderford 20% from 15%; and the Scott/Denman 20% from 20%.

Résumé. *Vitesses mesurées de l'intérieur de l'Antarctique de l'Est et état du bilan de masse dans la zone du Projet Glaciologique Antarctique International.* De récentes mesures d'accumulation et de vitesse de la glace dans l'intérieur de l'Antarctique de l'Est indiquent qu'un vaste secteur entre les longitudes 80° E. et 135° E. et au nord de la latitude 80° S. ont un bilan de masse proche de zéro. Ce secteur est à l'intérieur de la zone d'étude du Projet Glaciologique Antarctique International (I.A.G.P.) et couvre la plus grande partie de la fraction de cette zone où sont recommandé de donner un développement spécial aux projets. Des mesures de vitesse ont été faites en de nombreux points sur un itinéraire transversal de Mirny (lat. 66° 33′ S., long. 93° 00′ E.) sur la côte au Dome "C" (lat. 74° 40′ S., long. 124° 00′ E.) dans l'intérieur. Des mesures d'accumulation ont été faites le long de cet itinéraire et d'autres transversales, s'étendant jusqu'à Vostok (lat. 78° 28′ S., long. 106° 50′ E.) par de nombreuses méthodes. Celles-ci comprennent des observations de perches, stratigraphiques, isotopiques et de l'attenuation de la radiation β totale. Les meilleures estimations de l'accumulation ont permis une vue générale de l'apport total en masse. Le bilan de masse vrai a été estimé en comparant les vitesses, le calcul admettant un bilan de masse net nul, avec des mesures de vitesses le long des itinéraires transversaux et sur un grand nombre de glaciers émissaires. Dans ce but, la zône a été divisée en un certain nombre de bassins hydrographiques découpés selon les embouchures sur la côte. La zone d'environ 10^6 km² et 150 Gt par an d'apport est divisée principalement par trois systèmes glaciaires parmi lesquels le Totten intervient pour 40% du débit recueilli sur 55% de la surface du bassin versant; le Vanderford pour 20% recueilli sur 15% et le Scott/Denman pour 20% sur 20%.

Zusammenfassung. *Geschwindigkeitsmessungen im Innern der Ostantarktis und Massenbilanz innerhalb des I.A.G.P.-Gebietes.* Neuere Messungen der Akkumulation und der Eisgeschwindigkeit im Innern der Ostantarktis zeigen, dass ein grosser Sektor zwischen 80° E. und 135° E. und nördlich des 80. Breitenkreises eine Netto-Massenbilanz von nahezu Null aufweist. Dieser Sektor liegt im Untersuchungsgebiet des International Antarctic Glaciological Project (I.A.G.P.) und nimmt einen Grossteil des Gebietes ein, für das Projekte mit besonderer Intensität vorgesehen sind. Geschwindigkeitsmessungen wurden auf einer Reihe von Punkten längs einer Traverse von Mirny (66° 33′ S., 93° 00′ E.) an Küste zum Dom "C" (74° 40′ S., 124° 00′ E.) im Innern durchgeführt. Akkumulationsmessungen wurden auf dieser und anderen Traversen, die sich sogar bis Vostok (78° 28′ S., 106° 50′ E.) erstrecken, nach verschiedenen Methoden vorgenommen. Dazu gehörten Pegelmessungen, stratigraphische, isotopische und Gesamt-β-Zerfallsbeobachtungen. Die genauen Akkumulationsdaten erlaubten eine neue Bestimmung des gesamten Massenauftrags. Die tatsächliche Massenbilanz wurde aus dem Vergleich von Geschwindigkeiten, die unter der Annahme einer Netto-Massenbilanz von Null berechnet wurden, mit längs der Traversen und an einigen Auslassgletschern gemessenen Geschwindigkeiten abgeschätzt. Zu diesem Zweck wurde das Gebiet in eine Reihe von Ausflussbecken nach Massgabe des Ausstosses an der Küste unterteilt. Das Gebiet von *c.* 10^6 km² mit einem Zufluss von etwa 150 Gt pro Jahr wird hauptsächlich durch die Gletschersysteme entwässert, wobei 40% des Abflusses aus 55% des Gebietes vom Totten-, 20% aus 15% vom Vanderford- und 20% aus 20% vom Scott/Denman-System getragen werden.

Introduction

The International Antarctic Glaciological Project (I.A.G.P.) is a cooperative venture linking Australia, France, the United Kingdom, the U.S.A., and the U.S.S.R. in a study of a large part of the East Antarctic ice sheet. The scientific programme is composed of several cooperative projects and a number of national programmes which are aligned, but not necessarily merged with one another; and, where each field operation is planned and carried out by one of the national expeditions but welcomes participants from other expeditions.

It is envisaged as a complete study covering the shape, dynamics, environment, and history of the ice mass and including elucidation of climatic and other information locked within the ice. Single-location studies such as core drilling into the ice, oversnow traverses to measure movement of the ice sheet and other parameters, and gridded aerial surveys for ice-thickness sounding and surface- and bedrock-elevation profiling, will be used to construct a complete picture of the ice sheet.

Areas for special study and traverse routes for greater emphasis have been defined (Anonymous, 1971). Three of these routes run from Vostok in the interior to Mirny, Casey, and Dumont d'Urville on the coast approximately paralleling "flow lines" or lines along the direction of ice flow, on the ice sheet. Other lines, "flux lines", running at right angles to the direction of flow lines, were also designated; one along an approximate 2 000 m contour and another further inland.

An area for special study, bounded by long. 90° E., the inland high ice-dome, the coast, and the Ross Ice Shelf includes the triangular area defined by Dumont d'Urville, Vostok, and Mirny. Apart from the re-supply route from Mirny to Vostok, this innermost area has been rarely crossed by oversnow traverses: Casey–Vostok, 1962; Dumont d'Urville to 800 km towards Vostok, 1972; and in recent years Casey to 2 000 m contour, 1973, 1975, 1976, 1978.

In 1976–77 and 1977–78, Australia participated in a Soviet traverse from Mirny to Pionerskaya (lat. 69° 45′ S., long. 95° 32′ E.) to Dome "C" and return, by providing a glaciologist, doppler satellite receiver, and other equipment. The traverse in 1976–77 reached only a point (lat. 73° 14′ S., long. 110° 27′ E.) 670 km from Pionerskaya; the remainder of the distance, 470 km to Dome "C", being covered on the repeat traverse during the following 1977–78 season.

Velocity measurements have been made on a number of outlet glaciers, along the route from Casey to the 2 000 m contour, and along the traverse route from Mirny to Dome "C". The only other velocity observations made in the deep interior of East Antarctica were at Vostok and South Pole. Many representative accumulation measurements have also been made along the traverse routes already mentioned.

Most of the area to the east of the Casey–Vostok line and the far southern areas near Vostok have been covered by aerial survey of ice thickness and surface and bedrock elevations. The area to the west has been covered only by the Mirny–Vostok and Mirny–Dome "C" traverses.

Past work

Work completed in the I.A.G.P. areas up to 1976 has been summarized by Radok (1977). Ice surface elevations, bedrock elevations, and ice thickness have been well defined by gridded aerial surveys and produced in map form (Drewry, 1975; Steed and Drewry, in press). The grid was surveyed at a spacing of either 100 km or 50 km, depending on detail required.

One traverse to Vostok and several shorter traverses have been made along the Casey–Vostok route. Surface elevation was measured barometrically; ice thickness by seismic and gravity techniques (Walker, [1966]) and accumulation by stake and stratigraphic methods (Black and Budd, 1964; Battye, unpublished; Budd, 1966). Also temperatures and temperature–depth gradients were measured down to 60 m depths at a number of locations (Battye, unpublished; Budd and Young, 1979).

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Intensive studies have been made by Soviet expeditions along the Mirny–Vostok route over many years, and further to the west and south. A number of bore holes have been drilled ranging in depths from 50 m to 900 m. Accumulation measurements have been made using long-term stake networks, stratigraphic studies, and isotope and total β-decay measurements (Kotlyakov and others, 1974). Surface elevations have been measured by geodetic levelling surveys, and ice thickness by seismic, gravity, and radio echo-sounding.

Earlier results have been summarized in the Soviet Antarctic Expedition Atlas of Antarctica (Tolstikov, 1966), and by Kapitsa (1968). Strain-rates were also determined at a number of "polygons" along the Mirny–Vostok route as a cooperative French–Soviet project (Vinogradov and Garelik, 1970), but no velocities were measured.

A French party made an 800 km traverse from Dumont d'Urville towards Vostok in 1971–72 (Lorius and Vaugelade, 1972, 1973; Raynaud and others, 1979). A number of shorter traverses have also been made along this route. Surface elevations were determined, surface temperatures and surface oxygen-isotope ratios measured, and accumulation-rate determined by total β-decay measurements at a number of sites. Ice thicknesses were inferred from gravity measurements and later confirmed by aerial echo-sounding. Recently special studies have been made at a Dome "C" site, where a good value of the accumulation-rate has been obtained from total β-decay measurements and a bore hole drilled to a depth of 900 m (personal communication from C. Lorius in 1978).

Measured velocities

Ice velocities have been measured on several outlet glaciers; notably Scott and Denman Glaciers (Toltstikov, 1966) and Vanderford Glacier (Budd, 1966). Other glaciers farther to the east and west have been surveyed but they are not relevant to the present study. Other estimates of glacier velocities derived from morphological considerations are also available (Tolstikov, 1966).

An extensive trilateration net was established stretching 250 km from the summit of the Law Dome, near Casey, inland to the 2 000 m contour (Budd and Young, 1979). Precise surface elevations, strains, and surface velocities were determined using tellurometer survey techniques and control obtained from geodetically determined positions. The geodetic positions were measured, using "Geoceiver" equipment provided by the U.S.G.S., by analysing the doppler shifts of signals received from satellites of the U.S. Navy Navigation Satellite System (U.S. NNSS) (i.e. geodetic doppler satellite position).

New work

The author participated on two extensive Soviet traverses in 1976–77 and 1977–78 along the route from Mirny to Dome "C" (Fig. 1) in response to invitations from the Arctic and Antarctic Research Institute, Leningrad. The route from Mirny to Pionerskaya (375 km) runs at a small angle to the flow lines in that region; and from Pionerskaya to Dome "C" (1 140 km) approximately parallels the 3 000 m contour for a greater portion of the distance.

A total of sixteen movement stations were established along the route to the point lat. 73° 14′ S., long. 110° 27′ E. in 1976–77. Geodetic doppler satellite positions were determined using "JMR-1" equipment receiving signals from satellites of the U.S. NNSS. Positions were determined with respect to an Earth-centred (geodetic) coordinate system (labelled "NWL 9D") independently of other fixed objects near the receiver. Provided a good data set is collected, which usually takes two days, coordinates are accurate in three dimensions to the 1–2 m level.

During 1977–78, fourteen of the original sixteen stations (Fig. 1) were resurveyed and a further seven established while completing the traverse to Dome "C". A good estimate of the

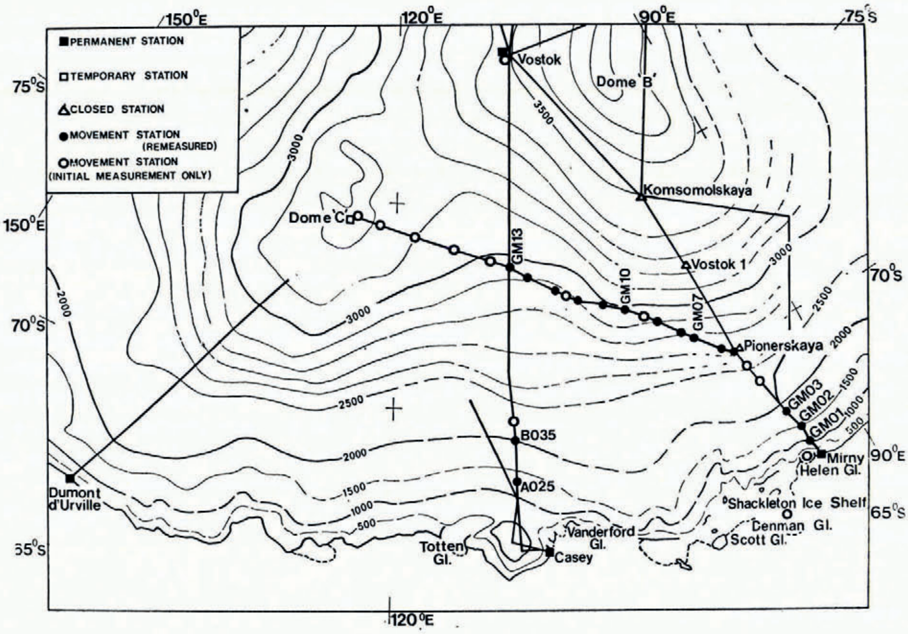

Fig. 1. Map of region of Antarctica including Dumont d'Urville, Vostok, and Mirny showing elevation contours in metres, ice movement stations, and traverse routes. Contours are broken where insufficient data are available to define detail (see text).

errors involved in the measurements can be gained by comparing the calculated elevations from the initial and second measurements. Where good data sets were obtained these values agree to within 2 m where a maximum difference of less than 0.5 m due to the vertical motion of the ice was expected. Because of the short time available at some of the stations, particularly during the 1977–78 season, not all of the stations will have the required accuracy. At the time of writing, only the first few of the remeasurement results were available. Further results will be available later. Improved positions will be able to be calculated by "translocation" doppler techniques, when data from a second receiver are returned by the wintering party at Casey, in 1979. The remainder of the discussion will evolve around these new findings.

Also along the Mirny–Dome "C" route, a precise elevation profile was obtained and ice-thickness measured continuously using a radio echo-sounder. Accumulation was measured using stake networks, stratigraphic studies, and oxygen isotope measurements (personal communication from P. A. Korolyov in 1978); 10 m temperature, surface hardness, and density were also measured. Detailed results of this work will be reported elsewhere.

Surface elevations and flow lines

A new surface-elevation map (Fig. 1) has been compiled from a composite of other maps and several traverses. The most comprehensive set of data is available from the radio echo-sounding map (1 : 5 000 000 scale) of Drewry (1975). These data supplemented by the (1 : 2 500 000 scale) map of Steed and Drewry (in press), effectively cover the eastern and southern parts of the study area. A discussion of errors associated with the compilation of the map shows that internal accuracy of the gridded data is about 30 m in elevation. A further error of up to 50 m may be included in this estimate due to inaccuracies in the ground control elevations, most of which have been determined barometrically. Barometric elevations in Antarctica can frequently be in error by 50 m and in the worst cases to the order of 100 m.

Drewry's map also indicated that there were three major centres (or domes) of outflow in East Antarctica known from highest to lowest as Dome "A" (lat. 81° S., long. 75° E.), Dome "B" (lat. 78° S., long. 95° E.), and Dome "C" (lat. 75° S., long. 125° E.). Elevation contours for the remainder of the area are obtained from the Soviet (1 : 5 000 000) map of Antarctica (U.S.S.R., 1976).

Precise elevations for control purposes are available along the Mirny–Vostok and Mirny–Dome "C" routes. These values have been obtained by geodetic levelling surveys (with an overall expected error of 10 m) or by geodetic doppler satellite survey, interpolated between stations by barometric survey. The overall expected error for the Mirny–Dome "C" line is 2 m–5 m with a maximum of 10 m for some of the barometrically levelled sections.

Barometric heights were obtained on the Casey–Vostok traverse, Dumont d'Urville traverse, and, using altimeter readings, from a number of aircraft flights over the area. Where accurate elevation control is now available, earlier elevation data has been adjusted to match the new values.

Large-scale smoothed surface-elevation contours (Fig. 1) for the area were drawn using all the available data. Contours have been depicted by broken lines where no surface elevation control is available and where insufficient data are available from aircraft flights to define the detailed contours accurately. Smooth flow lines (numbers 1–13) (Fig. 2) were then drawn as normals to these contours from the interior domes and ice divide to the coast.

Temperatures in the interior of the continent in the upper layers and for a greater part of the thickness of the ice are very cold. Temperatures within a column of ice moving along a typical flow line, from Dome "B" to Casey approximately parallel to flow line number 7 are considered by Budd and Young (1979). The variation of the average temperature through the whole column, and the average temperature for the upper 50% of the column are shown in Figure 3(a) against distance along the flow line from the summit. With an average temperature of −50°C, it can be seen that the upper 50% of the column has a dominant effect on the

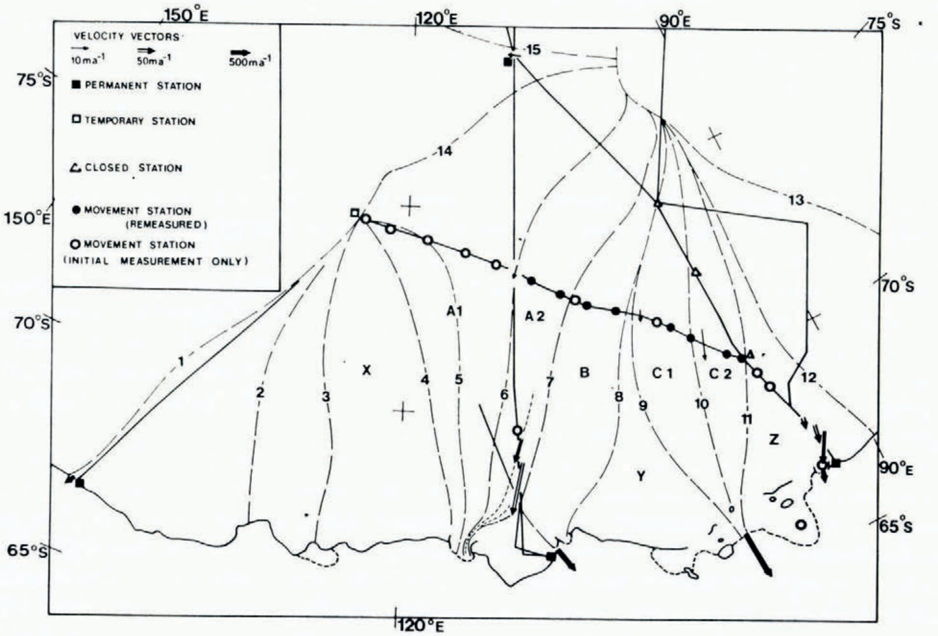

Fig. 2. Map showing smooth flow lines drawn from elevation data in Figure 1, the division of the area into drainage basins, and measured velocity vectors.

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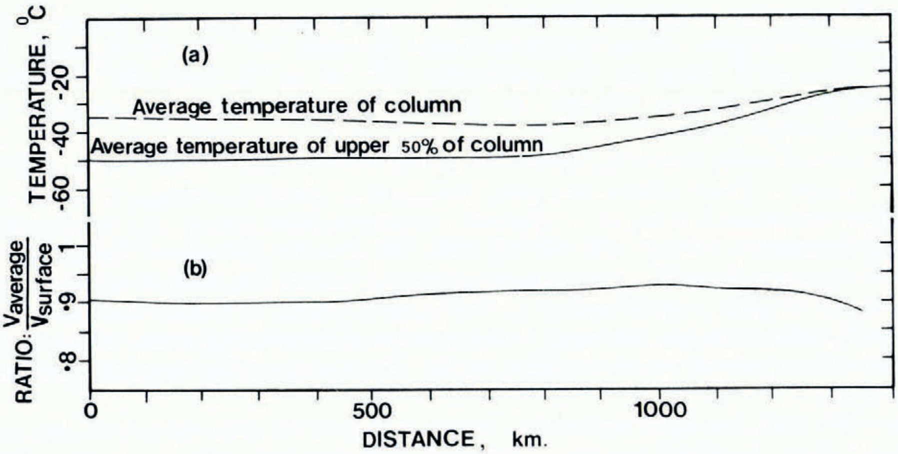

Fig. 3. (a) Average temperature of a column of ice and average temperature of the upper 50% of a column of ice plotted against distance from the summit (Dome "B") along a flow line to the coast at Vanderford Glacier. Flow line closely parallels flow line (7), see Figure 2. (b) Ratio of average column velocity to surface velocity for the same flow line as in (a) (see text).

average temperature of the column for the majority of the length of the line. This cold ice is very stiff, and plays a dominant role in the longitudinal and transverse motion of the ice. Hence longitudinal and transverse strains will be quite small and the velocities will vary smoothly and gradually over the ice sheet. This condition will not, however, be so strong near the coast where the increase of more than 25 deg in the average temperature of the upper 50% will allow an estimated 40-fold increase in the strain-rates for comparable stresses (Budd, 1969).

Thus in the interior, the magnitude and direction of the motion of the ice mass is controlled by the very large-scale stresses and hence the smooth large-scale changes in surface elevation, justifying the large-scale smooth contours used to draw smooth flow lines. In this process undulations in the form of ridges and domes on the surface, commonly of amplitude up to 20 m and more, are smoothed over. Nearer the coast stream flow can develop and the motion is controlled by smaller-scale features and stresses.

The section of the I.A.G.P. area crossed by the traverse is naturally divided into drainage basins by the flow lines. These basins are subdivided by other typical flow lines and the Pionerskaya–Dome "C" traverse route. Three of the drainage basins are classified according to their outlet in major glacier streams: the Totten Glacier, the Vanderford Glacier, and the Scott/Denman Glacier system. The Totten and Vanderford together account for the majority of the flux and drain the major portion of the central study area (between Totten and the Denman Glaciers). They flow in a substantial trench to the south of, and are otherwise separated by, the Law Dome. Three other areas: to the east of the Totten, between the Vanderford and the Scott, and to the west of the Denman, drain across the coast partly through ice shelves, without any distinct major streams.

As better elevation data become available with the extension of the aerial surveys to the west, it is expected that our knowledge of the shape and distribution of the drainage basins in the interior will remain unaltered. But more detailed data near the coast may change our view of the shapes of the basins there and particularly the distribution of discharge between stream-flow through the glaciers and sheet-flow across the coast. The ice streams themselves are well defined both by mapping and recent Landsat satellite imagery, where the Totten is visible as a glacier of major proportions. On present estimates it accounts for drainage from 55% of the central study area and 40% of the flux.

Ice thickness

The ice thickness is not considered specifically in this discussion except where it is required for the calculation of balance velocities. A complete profile of ice thickness is available along the Pionerskaya–Dome "C" line (Fig. 5(a)). Representative ice thicknesses for other areas can be extrapolated from the continuous profile along the Mirny–Pionerskaya line (to be published elsewhere) and from Budd and Young (1979), Kapitsa (1968), Drewry (1975), and Steed and Drewry (in press).

Accumulation

The most recent summary of accumulation data applicable to the I.A.G.P. study area is provided by Kotlyakov and others (1974). Other data are available from Raynaud and others (1979) and by personal communication from C. Lorius and P. A. Korolyov in 1978. Data from pit studies, reported by Black and Budd (1964) and Battye (unpublished), have been adjusted in the light of better accumulation measurements in the interior of East Antarctica, particularly at Vostok station, where various estimates have ranged between 20 kg m^{-2} a^{-1} and 30 kg m^{-2} a^{-1}. A study of the temperature–depth profile at Vostok has confirmed the validity of an accumulation-rate of this magnitude over a long period of time (Budd and others, 1975). Lorius (personal communication) reports apparent accumulation-rates of 36 kg m^{-2} a^{-1} and 28 kg m^{-2} a^{-1} at two different sites at Dome "C" only 1 km apart. The accumulation values along the Dumont d'Urville–Dome "C" line are those used in Raynaud and others (1979).

A map of accumulation-rate has been prepared from these data (Fig. 4). The greatest errors in the map are likely in regions nearest the coast where data are available on only three widely spaced traverse lines, and where rates can be highly variable, being very dependent on topography and prevailing winds. A possible extreme example is given by values measured on the Law Dome which vary from 100–200 kg m^{-2} a^{-1} in the west to 600–800 kg m^{-2} a^{-1} in the east (Budd, 1966).

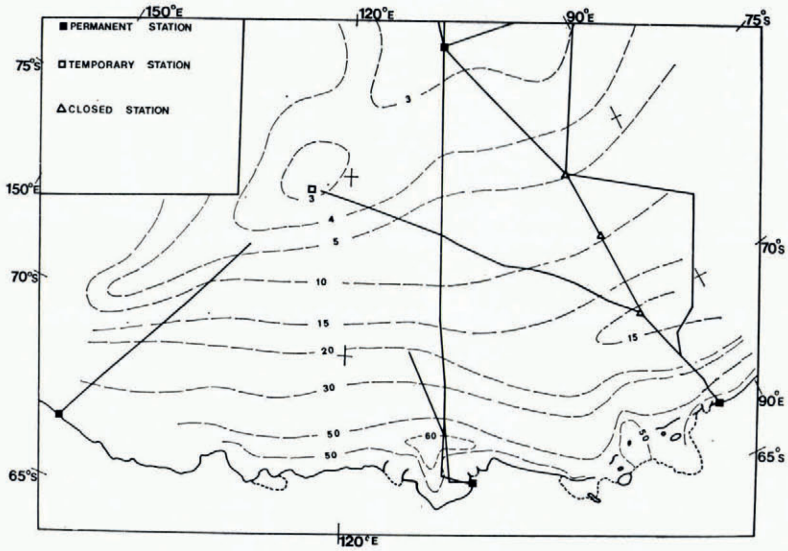

Fig. 4. Accumulation isopleths for the study area.

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Mass-budget calculations

The input mass flux was computed for each basin section by integrating the accumulation-rate over the section area, and adding inflow from other basin sections where applicable. The mass flux out of a section has been calculated assuming a zero net mass budget, i.e. mass flux out equal to input mass flux. All output or wastage from a section is taken to be by flow of the ice sheet without ablation at the surface or bottom-melting.

Balance velocities or flux-velocities have been calculated assuming a density of 0.90 Mg m^{-3} for the deep ice and measuring the cross-sectional width and average ice thickness across the section.

The ratio of the mean calculated velocity $\bar{V}$ of a column of ice to the calculated surface velocity V_s, where

$$\bar{V} = \frac{1}{Z}\int_0^Z V(z)\,\mathrm{d}z,$$

and Z is the ice thickness is shown in Figure 3(b) for a typical flow line from Dome "B" to Casey (Budd and Young, 1979). Generally the ratio fluctuates about a value of 0.9, but under different flow regimes may be as low as 0.8 or less and in extreme cases 0.65. A value of 0.9 will be assumed for the rest of the discussion.

The distribution of the ice velocities and their magnitudes and directions are shown in Figure 2. The values and other data are summarized in Table I. A mean column velocity $\bar{U}$ is calculated from the measured surface value U_s as $\bar{U} = 0.9U_s$. These mean velocities are compared with the balance velocities, calculated from the mass budget, for the Pionerskaya–Dome "C" line in Figure 5(b), and in Table II.

Table I. Ice-movement station data

Station	*Latitude** S.	*Longitude** E.	*Elevation** m	*Accumulation* kg m^{-2} a^{-1}	*Ice thickness* m	*Measured ice velocity* U_s m a^{-1}	*Error range* m a^{-1}	*Azimuth* °T	*Average column velocity* $\bar{U}$ m a^{-1}
GM01	67° 00′ 37.52″	93° 17′ 34.55″	912.4	420	890	123	115–130	25	110
GM02	67° 25′ 42.42″	93° 23′ 03.94″	1 452.4	270	1 320	50	45 – 55	10	45
GM03	67° 51′ 36.08″	93° 45′ 01.27″	1 782.1	230	1 700	32	25 – 40	15	29
GM07	70° 27′ 10.37″	97° 50′ 43.38″	2 757.5	138	3 067	17	15 – 20	20	15.3
GM10	71° 38′ 26.95″	101° 49′ 39.87″	2 977.0	118	3 127	6.5	4.5– 10	25	5.8
GM13	73° 14′ 27.14″	110° 27′ 22.77″	2 960.7	80	4 174	7.3	5 – 10	10	6.6
A025	68° 04′ 53.53″	112° 08′ 22.54″	1 399.2	500	1 918	155.2	154 –157	24±2	140
B035	69° 02′ 22.09″	111° 52′ 02.05″	1 942.4	300	2 636	67.3	66 – 69	23±2	60

* Coordinates are consistent with NWL-9D coordinate set and expressed on NWL-8E ellipsoid, Earth-centred with semi-major axis 6 378.145 km and reciprocal flattening of 298.25.

Table II. Summary of flow data across Pionerskaya–Dome "C" line

Basin	*Area* ×10^3 km^2	*Input flux* Gt a^{-1}	*x-section width* km	*Average ice thickness* m	*Calculated balance velocity* $\bar{V}$ m a^{-1}	*(Measured) average column velocity* $\bar{U}$ m a^{-1}
Totten 1 (A1)	190	7.0	230	4 000	7.6	6.6
Totten 2 (A2)	87	4.5	150	3 750	9	6.6
Vanderford (B)	42	2.9	150	3 500	6.1	(13.5)
Scott/Denman 1 (C1)	49	4.0	160	2 800	10	5.8
Scott/Denman 2 (C2)	53	4.8	140	2 700	13	15.3

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TABLE III. SUMMARY OF DATA FOR DRAINAGE BASINS

Basin	*Bounded by flow lines* number	*Total area* $\times 10^3$ km²	*Input flux* Gt a^{-1}	*Output width* km	*Estimated thickness* m	*Balance velocity* m a^{-1}
X	3, 4	203	51.4	350	400	370
Totten 1 (A1)	4, 6, 14	347	36.3	—	—	—
Totten 2 (A2)	6, 7	163	22.8	—	—	—
Totten (A)	4, 7, 14	510	59.1	50	900	1 300
Vanderford (B)	7, 8	140	27.2	—	—	refer text
Y	8, 9	87	32	450	400	180
Scott/Denman 1 (C1)	9, 10	118	18.5	—	—	—
Scott/Denman 2 (C2)	10, 11	92	14.0	—	—	—
Scott/Denman (C)	9, 11	210	32.5	—	—	refer text
Z	11, 12	100	28.4	420	400	170

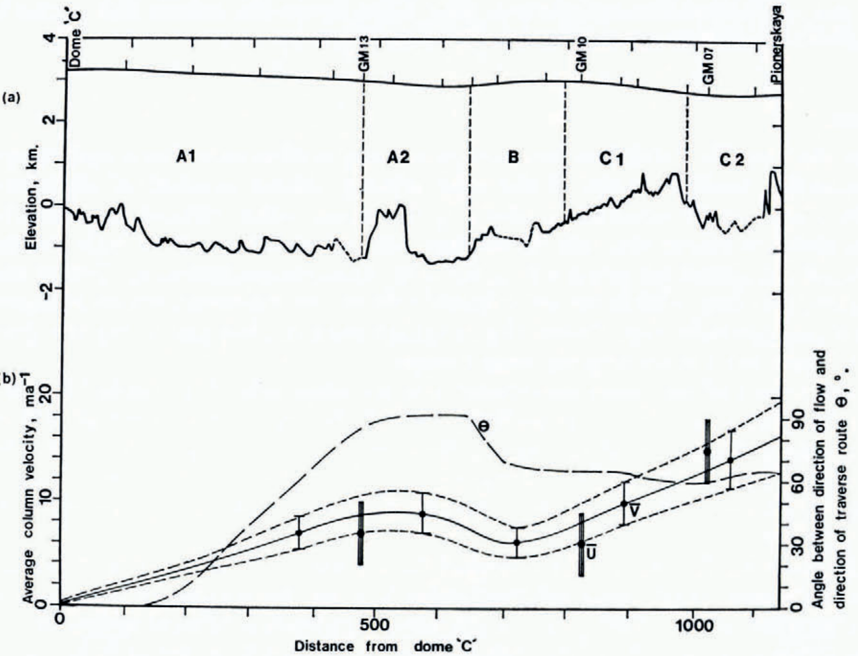

Fig. 5. (a) Profile of surface elevation and bedrock elevation for the traverse route from Dome "C" to Pionerskaya, also showing the cross-sections of various drainage basins and the location of ice-movement stations. (b) Plot of calculated balance velocities (see text) along the line from Dome "C" to Pionerskaya, indicated by circles with error bars assuming an error of ±20% in accumulation. Measured average column velocities (see text) together with errors are plotted as solid bars. Also shown is the angle between the direction of flow and the direction of the traverse line.

Other data for the whole sections of the drainage basins and their outlet are summarized in Table III. No balance velocity was calculated for Vanderford Glacier, because of the difficulty in defining the width of the outflow region and obtaining an estimate of the ice thickness on many separate streams. An output flux was calculated for the Scott/Denman system using data from Tolstikov (1966), for which a value of 23 to 28 Gt a^{-1} was obtained.

Balance velocities were also calculated for the flow across other flux lines passing through velocity measurement stations. These are given in Table IV. Two values are given for B035 which is close to the boundary between two basins, and where different average thicknesses are given for the two different basins. Calculations have been made for basin Z assuming that

Table IV. Summary of results at flux lines through other velocity stations

Basin	*Velocity station*	*Flux* Gt a^{-1}	*x-section width* km	*Estimated average thickness* m	*Balance velocity* $\bar{V}$ m a^{-1}	*(Measured) average column velocity* $\bar{U}$ m a^{-1}
Totten 2	B035	13.0	105	2 500	50	60
Totten 2	A025	17.6	95	1 700	110	140
Vanderford	B035	14.5	175	2 200	43	60
Z	GM03	7.8	240	1 750	19	29
Z	GM02	14.3	300	1 300	37	45
Z	GM01	19.5	350	600	93	110

flow conditions are uniform across the basin. Ice thickness data along the 1 000 m elevation contour are available from an echo-sounding flight across the eastern half of the basin. No further detailed calculations were made for basins X or Y.

Discussion

Velocities given in Table I in parentheses are only preliminary results and the error range is the expected possible range of the true velocity taking account of all known errors. Azimuths are generally accurate to about $\pm 10°$ except when enclosed in parentheses. The velocities given in Figure 5(b) are all average column velocities. Error bars for the balance velocities are calculated assuming a 20% error in the accumulation-rates. It can then be seen from Figure 5(b) that, within the error bounds given, the measured velocities agree with the calculated balance velocities. Hence the drainage basin discharging across the Pionerskaya–Dome "C" line has a near zero net mass budget.

For the results of the other movement stations summarized in Table IV, similar error considerations using velocity errors given in Table I and an expected error of 20% or more in the input mass-flux give a comparable result of zero net mass budget. It is notable however that all the calculated balance velocities are less than the measured average column velocities. This may be accounted for by an inaccuracy in the factor relating surface velocity to average column velocity.

Drainage basins X and Y were included for completeness. No measured velocities were available for comparison with calculations. Also no accumulation measurements were available in those basins. This prevents any direct application of error estimates to the input mass-flux because up to 70% of the flux estimate is derived from the 30% of the basin area nearest the coast where the accumulation-rate is large and most variable. Finally the calculated output through Scott and Denman Glaciers of 23–28 Gt a^{-1} is within the error bounds of the input flux of 32 Gt a^{-1}.

Conclusion

From the results given it is suggested that the central section of the I.A.G.P. study area has a zero net mass budget. Considering the relatively smooth and uniform shape of the area, it is further proposed that this condition would hold for that area draining across the coast from long. 80° E. to 135° E.

The distribution of balance velocities calculated are in general agreement with those given in Budd and others (1971). But the new values are uniformly smaller than the original reflecting the lower accumulation-rates used in the present study, but most noticeably near long. 90° E. where the flow is strongly divergent.

Doppler satellite survey techniques now existing allow the measurement of the movement rate of the ice sheet anywhere in Antarctica to an accuracy of 1–2 m a^{-1} over a period of one to a few years with individual measurement times of about 2 d. Better input mass-flux estimates can be obtained by a wider coverage of long-term accumulation measurements, e.g. by total β-decay determinations. By far the least-known part of the mass-budget equation is the relationship between surface and average column velocities. Better definition of velocity–depth profiles over a range of flow conditions is required before this problem can be resolved.

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