THINNING OF THE ICE SHEET IN MIZUHO PLATEAU, EAST ANTARCTICA

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ABSTRACT. Surveys of a triangulation chain 250 km in length were carried out in December 1969 and December 1973–January 1974 along the surface contour lines from 2 250 m to 2 600 m in Mizuho Plateau, East Antarctica. Horizontal velocities were obtained as small values near the Yamato Mountains, while they had maxima of more than 20 ± 0.7 m a^{-1} around long. 39° E., lat. 72° S. in the drainage of the Shirase Glacier. Submergence velocities showed large values, such as $(0.7$ to $1)\pm0.25$ m a^{-1}, in the region along lat. 72° S. from long. 39° E. eastward to long. 43° E. The amount of snow accumulation there, of average thickness 0.2 m a^{-1}, was not enough to compensate for the deficit of the ice mass caused by the submergence flow. It follows that the ice sheet was thinning there. It is suggested that the ice sheet of Mizuho Plateau is in an unstable condition as a whole.

RÉSUMÉ. *Amincissement de la calotte glaciaire du Mizuho Plateau, Est Antarctique.* On a réalisé la triangulation d'un cheminement de 250 km de long pendant l'été austral de 1969 et celui de 1973–74 le long des lignes de niveau 2 250 m à 2 600 m sur le Mizuho Plateau dans l'Est Antarctique. Les vitesses horizontales trouvées étaient faibles près des Yamato Mountains tandis qu'elles présentaient leur maximum de plus de 20 ± 0.7 m a^{-1} autour de 39° E., 72° S. Les vitesses verticales indiquent de forts affaissements tels que de 0,7 à 1 ± 0.25 m a^{-1} dans la région du parallèle de 72° S. entre 39° E. à 43° E. Le niveau d'accumulation de la neige en ce point 0,2 m a^{-1} de l'épaisseur moyenne, n'était pas suffisant pour compenser le déficit de la masse de glace causé par l'écoulement vers le fond. Il s'en suit que la calotte glaciaire est ici en voie d'amincissement. On émet l'hypothèse que la calotte glaciaire de Mizuho Plateau toute entière est dans l'ensemble dans un état instable.

ZUSAMMENFASSUNG. *Die Ausdünnung des Eisschildes auf dem Mizuho-Plateau, Ostantarktis.* In den Südsommern 1969 und 1973/74 wurde längs des 72 südl. Parallelkreises auf dem Mizuho-Plateau, Ostantarktis, eine Triangulationskette von 250 km Länge eingemessen. Nahe dem Yamato Mountains waren die Horizontalgeschwindigkeiten gering, während sie sum 39° E, 72° S Maximalwerte von über 20 ± 0.7 m pro Jahr erreichten. Die Vertikalgeschwindigkeiten deuteten auf ein beträchtliches Absinken, wie etwa 0,7 bis 1 ± 0.25 m pro Jahr im Gebiet längs des 72. südl. Parallelkreises von 39° E ostwärts bis 43° E. Die Menge der Schneeakkumulation in diesem Gebiet, die im Mittel 0,2 m pro Jahr beträgt, reicht nicht zum Ausgleich des Massendefizits, das durch die Abtauchbewegung entsteht. Als Folge ergibt sich eine Ausdünnung des Eises. Es ist anzunehmen, dass der Eisschild auf dem Mizuho Plateau sich in seiner Gesamtheit instationär verhält.

INTRODUCTION

Some studies have been carried out in regard to the recent growth or shrinkage of the Greenland and the Antarctic ice sheets on the basis of the measurements of the ice flow. Federer and others (1970) obtained a mass deficit amounting to 0.1 m a^{-1} (corrected later to 0.077 m a^{-1}: Federer and Sury, 1976) during the ten years from 1959 to 1968 at Jarl-Joset Station on the Greenland ice sheet. Using their data, Nye (1975) discussed the resultant lowering of the ice-sheet surface. Meanwhile, it was suggested that the West Antarctic ice sheet is currently thinning (Hughes, 1973; Weertman, 1976; Thomas, 1976) and is slightly thinning or stable (Whillans, 1973, 1976, 1977). Thomas (1976) estimated that the Ross Ice Shelf is growing thicker by almost 1 m a^{-1} in the vicinity of its grounding line. More detailed information is much sought on the flow of the Antarctic ice sheet in the study of such dynamical problems. Direct measurements of the flow have, however, been very few, and have only been made intensively in limited regions near the coast or on the ice shelf.

A study on ice-sheet flow was one of the main subjects of the Japanese Glaciological Research Program (Shimizu, 1978) conducted from 1969–75 over the ice sheet of Mizuho Plateau, East Antarctica. For this study, during a period from 24 November to 30 December 1969, the traverse party of the 10th Japanese Antarctic Research Expedition (JARE-10) set up (first survey) a triangulation chain over a distance of 250 km in the inland region of Mizuho Plateau (Naruse and others, 1972). The second survey was carried out four years later during a period from 20 December 1973 to 16 January 1974 by JARE-14 (Naruse,

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1975[b]). The triangulation chain composed of 164 stations stretched along the parallel of latitude 72° S., between A001 at the south-east end of the Yamato Mountains and A164 at long. 43° E. (see Fig. 1). The surface elevation of the ice sheet increased gradually along the chain from 2 250 m near A001 to 2 600 m near A164, so the chain was approximately parallel to a surface contour line. Obtained from the two surveys were horizontal and vertical
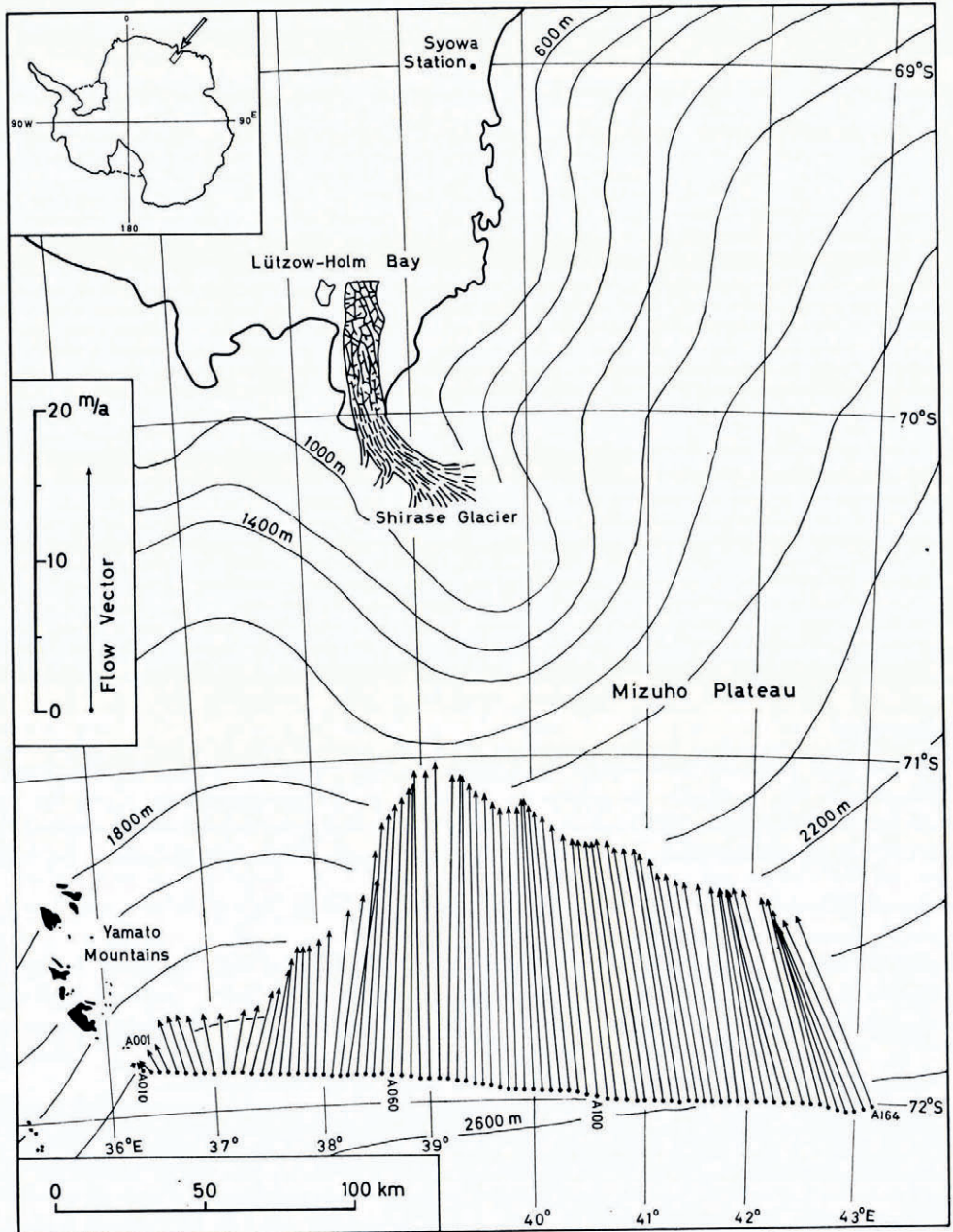

Fig. 1. *Distribution of horizontal vectors of ice flow (m a⁻¹) at every 5′ in longitude along the triangulation chain in Mizuho Plateau. Surface contours of the ice sheet are marked for every 200 m.*

components of surface velocities at 140 points and also various parameters of surface strains in 140 triangles of the chain. Some of these results were published in other articles (Naruse, 1978; Naruse and Shimizu, 1978; Mae and Naruse, 1978) with some discussions on the general flow and strain patterns and the dynamical features of the ice sheet in Mizuho Plateau. Measurements were also made along the chain of the surface slope (Naruse, 1975[b]), ice thickness (Shimizu and others, 1972; Naruse and Yokoyama, 1975), gravity (Yoshida and Yoshimura, 1972; Abe, 1975), and net accumulation (Yokoyama, 1975).

The present paper reports chiefly a thinning phenomenon of the ice sheet deduced from the measurements of the vertical component of the surface flow velocity in Mizuho Plateau. The method of triangulation survey and some results from it are also briefly described.

OUTLINE OF THE SURVEY OF A TRIANGULATION CHAIN AND DISTRIBUTION OF HORIZONTAL FLOW VECTORS

The datum point of a triangulation chain, A001, was selected upon a nunatak at lat. 71° 47′ 28″ S. and long. 36° 12′ 12″ E., which belongs to the Yamato Mountains. Positions and elevations of all the triangulation stations were determined relative to their values at the datum point. The adopted elevation of this point was 2 254 m obtained by the barometric method.

The triangulation chain was composed of 164 stations. Each station was marked by a metal pole 3 m long or a bamboo stake 2.5 m long, which were used also as snow stakes. Both the first and the second survey of the chain were conducted principally by angle measurements with Wild T2 theodolites. Measurements were made of the horizontal angles of the three interior angles of all the constituent triangles, and the vertical angles from each station to four neighbouring stations. With the aim of correcting the accumulation of errors, the distance was measured with a radiowave distance meter (Cubic DM-20) and an azimuth was observed by shooting the sun for one side of every 10 to 15 triangles.

The geodetic coordinates and their mean-square errors (standard errors) were obtained at all the triangulation stations in 1969 and 1973–74 respectively, from the calculations by applying the least-squares method to a number of observation equations based on measured angles, azimuths, and distances. Then, the horizontal vector of ice movement was determined at each station from the difference between two geodetic positions. The surface elevations of the stations were obtained in 1969 and 1973–74 respectively, by the measured values of vertical angles and the calculated distances from the above geodetic coordinates of the neighbouring two stations. Possible errors resulting from refraction due to the vertical gradient of air temperature and also from the curvature of the Earth can be counterbalanced, because measurements of vertical angles were carried out twice from both the stations in opposite directions and these were averaged. The "submergence or emergence velocity" V_z was, then, calculated on the basis of the above two surface elevations, as described in the following section.

The results obtained for the three components of the surface velocity (namely the magnitude of the horizontal velocity V_h, the azimuth α of V_h and the submergence or emergence velocity V_z) are shown in Table I, with calculated root-mean-square errors every ten stations along the chain. Since the surface flow is almost in a direction from south to north, the error in horizontal velocity was strongly controlled by the error involved in latitude, and not by the error in longitude. The absolute value of error in V_h showed a gradual increase from the datum point towards the end of the chain (A164); the relative error reached a minimum value of 3% at the middle part of the chain and 3 to 10% in other parts. Errors in azimuth are given as large values at places where the horizontal velocity is small. Relative errors in the submergence (emergence) velocity were considerably larger in the region from A003 to around A060 where the submergence (emergence) velocity was very small, while in the region eastward from A060 relative errors showed rather small values around 25%.

TABLE I. THREE COMPONENTS OF SURFACE VELOCITY OF ICE FLOW AND THEIR ROOT-MEAN-SQUARE ERRORS AT EVERY TEN STATIONS OF A TRIANGULATION CHAIN

α: clockwise from the north point
V_z: positive sign, submergence velocity; negative sign, emergence velocity

Station	Latitude S.	Longitude E.	Elevation m	Horizontal velocity		Azimuth of velocity		Submergence velocity	
				V_h m a⁻¹	Error m a⁻¹	α deg	Error deg	V_z m a⁻¹	Error m a⁻¹
A005	71° 48′ 24″	36° 16′ 13″	2 281	0.4	±0.03	342	±6.2	−0.09	±0.04
A015	71° 51′ 45″	36° 23′ 18″	2 353	1.1	±0.11	313	±5.8	−0.07	±0.06
A025	71° 50′ 31″	36° 47′ 42″	2 377	4.1	±0.25	347	±5.2	+0.02	±0.09
A035	71° 53′ 12″	37° 12′ 08″	2 423	4.5	±0.37	12	±6.4	+0.06	±0.11
A045	71° 53′ 23″	37° 46′ 02″	2 399	9.0	±0.55	6	±5.4	+0.15	±0.13
A055	71° 54′ 28″	38° 18′ 39″	2 404	15.1	±0.64	9	±3.8	+0.13	±0.15
A065	71° 54′ 16″	38° 56′ 57″	2 382	20.4	±0.67	1	±3.0	+0.71	±0.18
A075	71° 55′ 18″	39° 23′ 45″	2 411	20.7	±0.73	0	±3.2	+0.92	±0.20
A085	71° 56′ 55″	39° 51′ 54″	2 442	19.3	±0.76	359	±3.5	+0.78	±0.22
A095	71° 56′ 54″	40° 25′ 53″	2 452	18.5	±0.80	354	±3.7	+0.93	±0.23
A105	71° 58′ 16″	40° 57′ 46″	2 482	17.5	±0.85	352	±3.9	+1.03	±0.25
A115	72° 00′ 00″	41° 24′ 28″	2 510	16.6	±0.91	350	±4.3	+1.02	±0.26
A125	71° 59′ 51″	41° 43′ 07″	2 536	14.8	±0.92	349	±4.8	+0.78	±0.27
A135	71° 59′ 43″	42° 10′ 34″	2 524	14.4	±0.94	348	±5.1	+1.08	±0.28
A145	71° 57′ 59″	42° 33′ 56″	2 541	14.7	±0.97	343	±5.0	+0.82	±0.29
A155	72° 01′ 24″	42° 52′ 04″	2 588	13.3	±0.99	341	±5.5	+0.77	±0.30
A164	72° 00′ 07″	43° 09′ 48″	2 606	13.6	±1.01	336	±5.2	+0.64	±0.31

The distribution of horizontal flow vectors (m a⁻¹) across the triangulation chain every 5′ in longitude are shown by the thin arrows in Figure 1. It is clear that the flow is converging into the Shirase Glacier. Remarkable features noted of the horizontal flow along the parallel of latitude 72° S. in Mizuho Plateau are as follows:

The flow velocity had very small values less than 2 m a⁻¹ and the flow direction was north-westward in the vicinity of the Yamato Mountains, namely the region to the west of long. 36° 35′ E. The small value is considered to be caused by the effect of many nunataks lying down-stream. The direction of the flow was different on either side of long. 37° E. To the west of the boundary, the flow had a westward component, while to the east of it, the flow had an eastward component. The macro-scale surface contours of the ice sheet showed a ridge there (Shimizu and others, 1978[b]). It must follow, therefore, that the ice divide exists near long. 37° E. between the drainage of the Shirase Glacier and the drainage at its west side. The velocity increased gradually with the increase of distance from the datum point, that is from west to east. It was more than 20 m a⁻¹ in the region around long. 39° E. The velocity then decreased slightly and reached 13.6 m a⁻¹ at A164 which was located at the east end of the triangulation chain. The direction of the flow shifted gradually from northward to westward in the eastern part of the chain, and finally it was north-north-west at A164.

THINNING RATE OF THE ICE SHEET ALONG THE CHAIN

The submergence or emergence velocity V_z of the surface flow can be obtained from

$$V_z = V_z' - V_h \tan \theta,$$

where V_z' is the vertical velocity component of the top of a marker stake, V_h is the horizontal velocity and θ is the surface slope (positive sign) along the flow direction. As the value of V_z' is taken positive downward, a positive value of V_z indicates a submergence velocity and a negative value indicates an emergence velocity. The quantity, $V_z - A$, gives the rate of change of the surface elevation per year, where A is annual net accumulation in snow depth (positive value of A shows accumulation; negative value ablation). We call the quantity, $V_z - A$, the thinning-rate of the ice sheet.
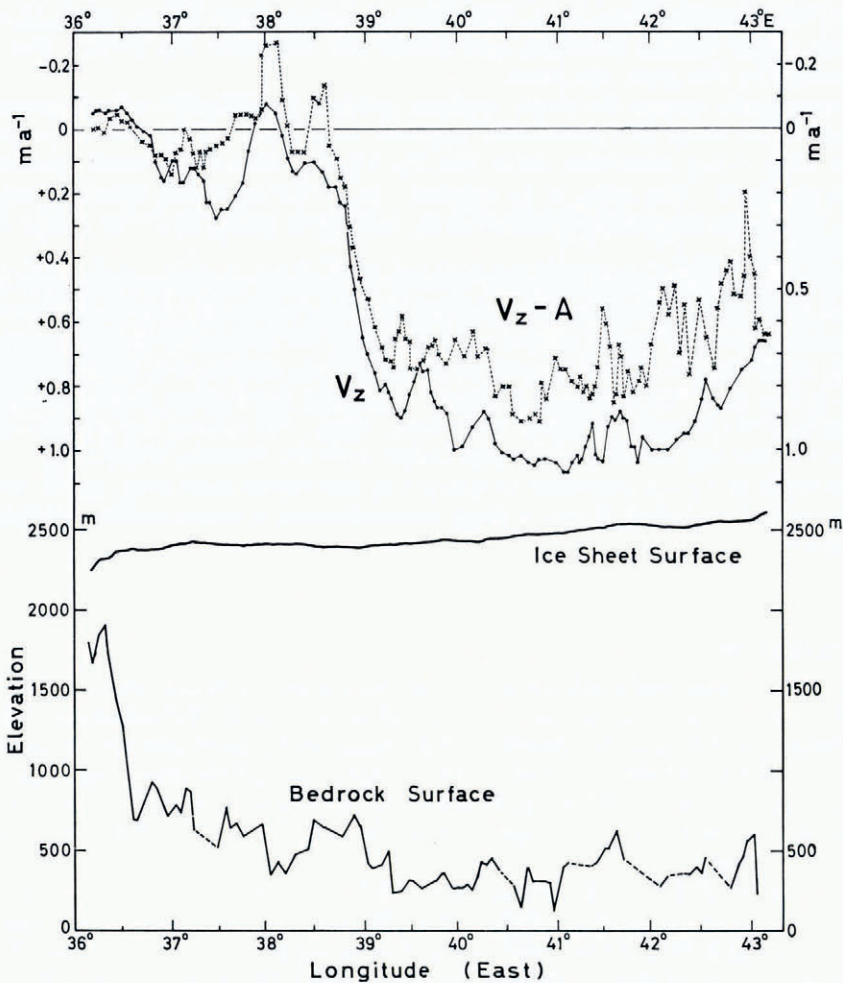
Fig. 2. Variations in submergence (emergence) velocity V_z (m a^{-1}), thinning-rate V_z-A (m a^{-1}), and profiles of the ice sheet and bedrock surfaces along the triangulation chain in 72° S. in Mizuho Plateau. Positive V_z indicates submergence velocity; negative V_z emergence velocity. Running mean over three stations was applied to V_z and V_z-A. The bedrock profile was obtained from the results of radio echo-soundings and gravity measurements as well.

Figure 2 shows the submergence (emergence) velocity V_z (m a^{-1}) at the surface, the thinning rate V_z-A (m a^{-1}), and the surface and the bedrock profiles along the chain plotted against the longitude from 36° 10′ E., the south-east end of the Yamato Mountains, to long. 43° 10′ E. Annual net accumulation A was obtained by averaging over four years from the measurements of snow stakes. The variations of V_z and V_z-A were slightly smoothed by using the running mean over three stations. The following results are characteristic in Figure 2:

(1) Negative velocities which signify emergence flow of ice were obtained in the limited regions around long. 36° 30′ E. and 38° E. The annual net accumulation was negative (mean value, -0.05 m a^{-1}) in the former region near the Yamato Mountains, which represents

ablation due mainly to sublimation of the exposed surface ice. A large number of meteorites were found (Yoshida and others, 1971; Shiraishi and others, 1976; Yanai, 1978; Matsumoto, 1978) in this region which, therefore, was named the Meteorite Ice Field. The bedrock profile is marked by the great rise there.

(2) In most parts except the above regions, positive V_z indicative of submergence flow was observed. The value of V_z·increased suddenly near long. 39° E. where the horizontal velocity was close to the maximum value (see Fig. 1), and then it decreased gradually from long. 42° E. eastward. The value of V_z reached 1 m a^{-1} in the region between long. 40° E. and 42° E., where the mean-square errors of V_z were from ± 0.25 m a^{-1} to ± 0.30 m a^{-1}, as shown in Table I.

(3) The amount of net accumulation A showed remarkable variations from place to place. Observation of the surface topography revealed a strong correlation between A and surface reliefs. Namely, the net accumulation was large in the depressed terrain (mean value, 0.47 m a^{-1}), small in the mounded terrain (mean value, 0.09 m a^{-1}), and average in the whole area is 0.20 m a^{-1} in thickness of snow. Assuming the average density of the surface snow as 450 kg m^{-3} (Naruse, 1975[a]; Watanabe, 1975), the annual net accumulation was 90 kg m^{-2} a^{-1} in the region along the chain except near the Yamato Mountains.

(4) The value of $V_z - A$ was close to 0 m a^{-1} in the region from long. 39° E. westward; while in the region eastward, it was a large value showing a considerable thinning-rate of about 0.7 m a^{-1}.

CONCLUDING REMARKS

Results of the present study indicated that the average submergence velocity was 0.9 ± 0.25 m a^{-1} in the region from long. 39° E. to 43° E. along lat. 72° S. Submergence flow is considered to have resulted from densification in the upper snow layer and also from outflow of ice from a vertical column with unit cross-sectional area through the thickness of the ice sheet. The rate of surface lowering due to densification of snow was estimated as about 0.1 to 0.2 m a^{-1} from the calculations of the equation on the non-Newtonian densification of snow derived by Bader (1963).

The distribution of $V_z - A$ shows that the supply of snow on the ice-sheet surface was insufficient to maintain a stable condition of the ice sheet in the region to the east of long. 39° E. It is concluded that the ice sheet was shrinking along a part of the chain during this observation period, as estimated using a similar method in the West Antarctic ice sheet (Hughes, 1973; Whillans, 1973; Thomas, 1976). However, surface lowering was not necessarily taking place over the entire area of Mizuho Plateau. As for the entire ice in the drainage basin of the Shirase Glacier in Mizuho Plateau, Shimizu and others (1978[a]) discussed the mass budget. The following estimates were made from the measurements in 1969–75: the drainage area: 20×10^{10} m^2; the stored ice: 32×10^{16} kg (Shimizu and others, 1978[b]); the total accumulation rate: $(13 \pm 8) \times 10^{12}$ kg a^{-1} (Yamada and Watanabe, 1978); the annual discharge of ice through the Shirase Glacier: $(7.4 \pm 1.9) \times 10^{12}$ kg a^{-1} (Nakawo and others, 1978). Then, we obtained the mass budget of $(6 \pm 8) \times 10^{12}$ kg a^{-1} by subtracting the discharge from the total accumulation, since the latter included the estimated amounts of melting at the coastal region and of the drifting snow. The mean value indicated a reasonably large positive budget. Therefore, it remains possible that the observed intense thinning of the ice sheet in the region from long. 39° E. to 43° E. along the parallel of latitude 72° S. might be a rather local or recent occurrence. To elucidate the causes and mechanisms of the instability of the ice sheet, more knowledge is urgently called for especially as to the flow-rates along a flow line and also along a vertical direction, together with the thermal regime of the ice sheet, in East Antarctica.

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DISCUSSION

I. M. WHILLANS: Is it possible that the surface lowering could be due to more rapid firn densification now than in the recent past?

R. NARUSE: I think not. The thinning rate $\dot{h}$ in Mae (1979) excluded the amount of the surface lowering due to the densification of the upper firn layers. I calculated the densification-rate by using the equation of non-Newtonian densification of snow derived by H. Bader. The amount of the surface lowering obtained was 0.1 to 0.2 m a^{-1}. But it is an approximate value because the data of the density profile used were those at Mizuho Station, which was located 150–200 km from the surveyed region of the triangulation chain.

T. J. HUGHES: A good companion study to your transverse strain network would be construction of a strain network along your central flow line. Do you plan to do that?

NARUSE: We think that a strain network study along the central flow line is important, and we want to carry out such a study in the future.

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