Proc. NIPR Symp. Polar Meteorol. Glaciol., 2, 97-104, 1989

DYNAMICAL BEHAVIOR OF THE ICE SHEET IN MIZUHO PLATEAU, EAST ANTARCTICA

Fumihiko NISHIO[1], Shinji MAE[2], Hirokazu OHMAE[3], Shuhei TAKAHASHI[4], Masayoshi NAKAWO[5] and Kunio KAWADA[6]

[1]*National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173*
[2]*Department of Applied Physics, Faculty of Engineering, Hokkaido University, Kita-13, Nishi-8, Kita-ku, Sapporo 060*
[3]*Institute of Low Temperature Science, Hokkaido University, Kita-19, Nishi-8, Kita-ku, Sapporo 060*
[4]*Kitami Institute of Technology, 165, Koen-cho, Kitami 090*
[5]*Nagaoka Institute of Snow and Ice Studies, National Research Center for Disaster Prevention, Science and Technology Agency, 187-16, Maeyama, Suyoshi-cho, Nagaoka 940*
[6]*Faculty of Science, Toyama University, 3190, Gofuku, Toyama 930*

Abstract: The Japanese Antarctic Research Expedition (JARE) has continued glaciological work in Mizuho Plateau, East Antarctica. We have already reported that the ice sheet on Mizuho Plateau which flows into Shirase Glacier, classified as a fast-moving outlet glacier, was thinning at a rate of about 70 $cm \cdot a^{-1}$ and the profile of basal shear stress along the central flow line derived from topographic map was similar to that of surging glaciers.

A new 5-year glaciological program in Mizuho Plateau and East Queen Maud Land which started in 1981 is now being carried out. We have obtained new results as follows:

(1) The ice sheet in the downstream region where ice elevation is lower than about 2800 m is thinning, based upon data on horizontal and vertical flow velocity, strain rate, inclination of ice surface, accumulation rate and densification of snow.

(2) The result of the radio-echo sounding on Mizuho Plateau suggests that the base of the ice sheet in the downstream region is wet. Based upon a two-dimensional numerical model, the calculated bottom temperature shows that the ice temperature at the base of the ice sheet in the glacier downstream is at the pressure melting point and the ice base is also wet. These results supports the result described in (1), since basal sliding due to the wet base causes the ice sheet thinning as proposed by our previous studies.

Summarizing these results, a possible explanation of ice sheet variation on Mizuho Plateau is as follows: the thinning of the ice sheet caused by the basal sliding due to melting of the ice base started at the mouth of the Shirase Glacier and has been expanding upstream to reach the present state. A simple calculation, using flow velocities, shows that the thinning started at Shirase Glacier about a few thousand years ago.

1. Introduction

The Japanese Antarctic Reseach Expedition (JARE) carried out its glaciological

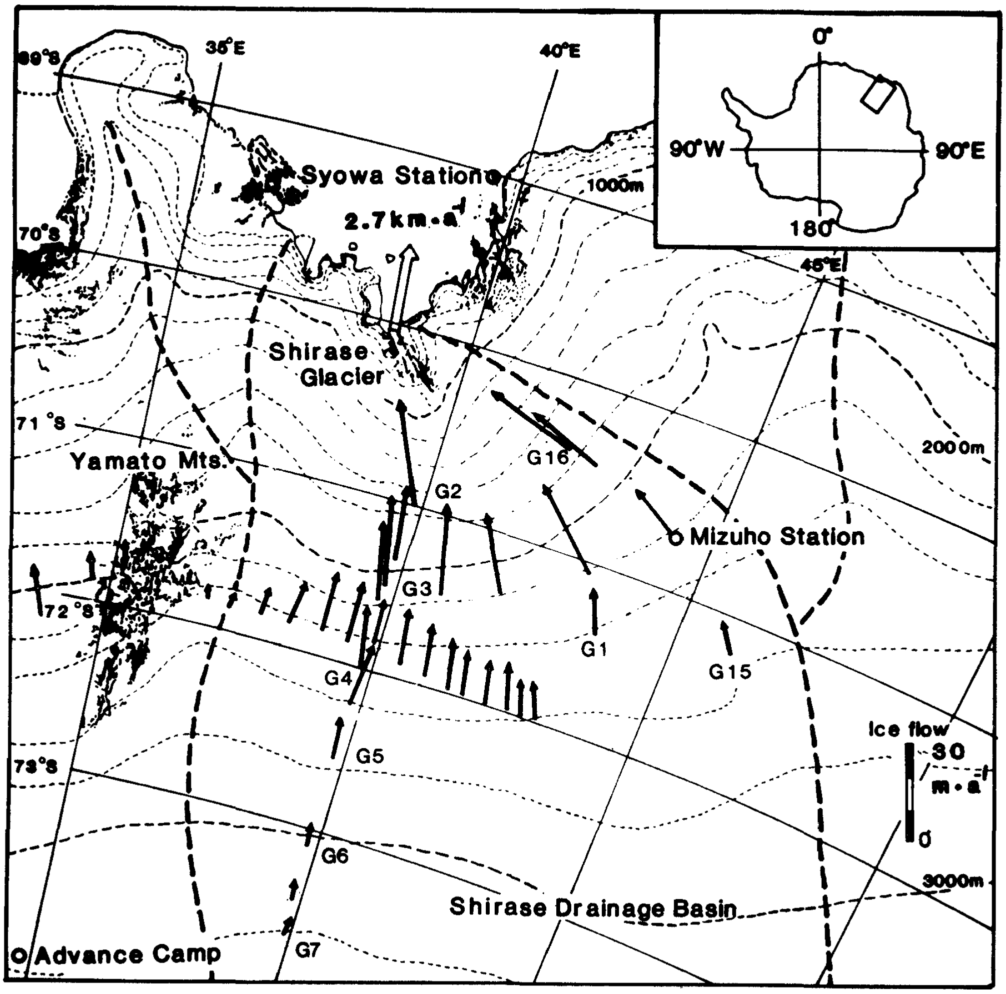

Fig. 1. Map of study area and distibution of horizontal vectors of ice flow ($m \cdot a^{-1}$) *obtained from satellite doppler positioning at the first grade grid points and from the triangulation chain along latitude 72°S (NARURE, 1978). Ice divides of the drainage basins are shown by dotted lines. Surface contours of the ice sheet are marked for every 200 m.*

research program on Mizuho Plateau from 1981 to 1987. As the primary program, we expended great effort on dynamical studies aiming at investigation of stability of the Shirase Glacier drainage basin and of the barrier effect of the Yamato and Belgica mountain chain against the flow of the ice sheet from the hinterland. Thus, the study area was expanded to the west of 25°E from Mizuho Station (about 40°E) on the Mizuho Plateau, as shown in Fig. 1, making flow-line studies upstream of Shirase Glacier and traversing approximately along the 2000 m contour. The main survey objects of the program were measurements of ice flow, surface and sub-glacial topography on Mizuho Plateau, and intermediate depth ice coring at Mizuho Station.

NARUSE (1978, 1979) analyzed the triangulation chain survey result. The starting point was fixed on a rock in the Yamato Mountains along latitude 72°S, and estimated the horizontal and vertical velocities of the ice surface and strain-rate at the surface. Taking into account the effects of the firn densification, he estimated the rate of change $\dot{h}$ of the ice thickness h. Results of this estimation revealed that ice on the main part of the route on Mizuho Plateau was thinning by 70 cm·a^{-1}. MAE (1977) and MAE and NARUSE (1978) investigated a possible cause of thinning of the ice sheet on Mizuho Plateau and reported their preliminary concludion that the thinning has not been caused by decrease of the accumulation-rate due to a change in climate but also by basal sliding of which the velocity was about 10 m·a^{-1}.

Thus, studies on ice-sheet flow have been carried out in order to determine the stability of the ice sheet on Mizuho Plateau. For this study, first grade grid points were established in 1982–1984 (first survey) for flow-line studies in the upstream area of Shirase Glacier along 39.5°E, and traverses approximatelly along the 2000 m contour between Mizuho Station and the Belgica and Yamato Mountains were carried out for topographic surveys of stations on the route. The second survey was carried out four or five years later in 1986–1987. Obtained from the difference between two survey results were horizontal and vertical components of surface velocities at 20 points and also various parameters of surface strains. Measurements were also made along the traverse route, on surface slope (OHMAE, 1984), surface elevation, ice thickness (NISHIO *et al.*, 1986), gravity and net accumulation. These results will be published in separate articles with some discussions on the general flow and the dynamical features of the ice sheet in Mizuho Plateau.

The present paper reports mainly on thinning of the ice sheet deduced from measurements of the vertical component of surface flow velocity, and characteristic features of the ice flow of Shirase Glacier drainage basin.

2. Outline of the Survey of First Grade Grid Points and Distribution of Horizontal Flow Vectors

The first grade glaciological grid points were established in 1982–84, and resurveyed after 4 to 5 years, determining positions and elevations of each point by a satellite doppler positioning system (JMR-4A). The surface elevation between these grid points was measured continuously with barometers; ground based radio-echo sounding along the routes was also carried out.

A first grade grid point consists of a five-stake strain grid. Its central station is used to determine position and elevation by satellite doppler positioning. Each central station was marked by an aluminum pole 3 m long; the poles were also used as snow stakes. Both the first and second surveys of the strain grid were conducted principally by angle measurements with Wild T2 theodolites. Measurements were made of the horizontal angles of the three interior angles of all constituent triangles, and the vertical angles from each station to four neighboring stations. Then, the geodetic coordinates were obtained for each stake, and the strain-rate was determined at each grid from the difference between the first and second geodetic positions.

The geodetic coordinates at the central station of each grid were obtained by satellite doppler positioning, applying more than 50 carefully selected satellite passes. SHIBUYA (1985) examined convergence of broadcast ephemeris positioning in the Antarctic, obtaining the result that the convergence process can be approximated by a curve which was inversely proportional to the square root of the accepted pass number (n) with a coefficient of 15 m. Then the distance of uncertaintly may be

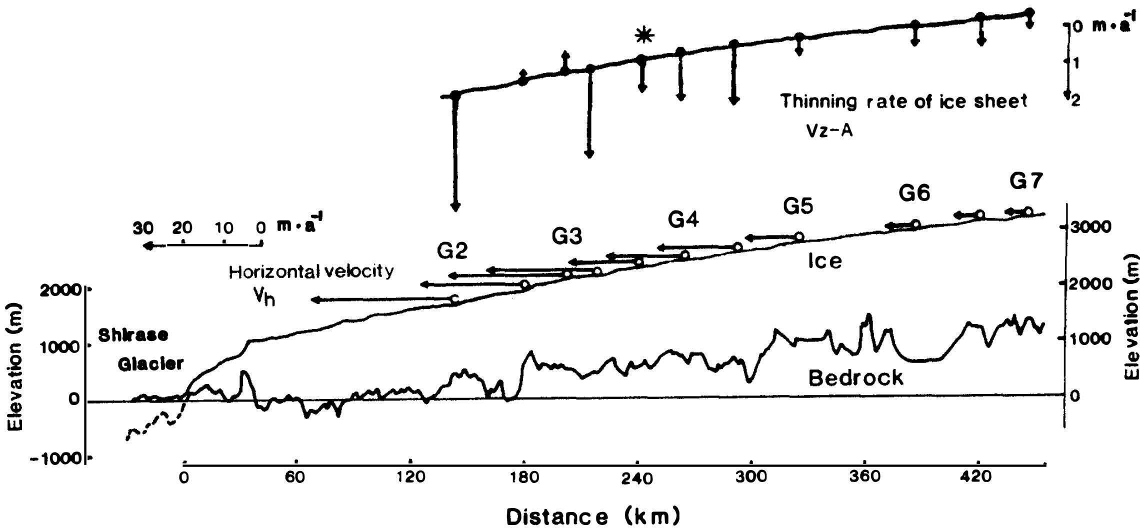

Fig. 2. Thinning-rate ($m \cdot a^{-1}$), horizontal velocity ($m \cdot a^{-1}$), and the surface and bedrock profiles along the Shirase Glacier flow line.

approximated by the following equation:

$$\Delta d \approx 15/\sqrt{n}\ . \qquad (1)$$

The equation may give an empirical criterion for convergence in the worst case, taking the pass number as a parameter. The above convergence cannot be improved to better than 0.6 m even in the final iteration, indicating a slowly varying undulation of Δd between 0 and 0.6 m. Thus, the uncertainty of the geodetic coordinates determined by more than 50 satellite passes can be estimated as between 0.6 and 2.5 m. Then, the horizontal and vertical ice movement vectors determined by the difference of positions and elevations over several years at each station have errors of magnitude Δd divided by years elapsed between the two measurements.

Results obtained for the two components of surface velocity (namely the magnitudes of the horizontal velocity V_h and the submergence or emergence velocity V_z) are shown in Fig. 2. They are comparable to previously obtained results from the triangulation chain along latitude 72°S (NARUSE, 1978) and the flow velocity of the outlet of Shirase Glacier (FUJII, 1981). Now, it is clear in this figure that ice flow is converging into the Shirase Glacier. Remarkable features of the horizontal flow along the flow line are as follows:

The flow velocity increases roughly in proportion to the reciprocal of distance between observed points and the outlet of the Shirase Glacier. The velocity of the glacier at the mouth is 2.7 $km \cdot a^{-1}$. Very small velocity less than 2 $m \cdot a^{-1}$ was obtained on the 2000 m contour near the Yamato Mountains; it is considered to be caused by the barrier effect of many nunataks lying down-stream.

3. Thinning Rate of the Ice Sheet along the Shirase Glacier Flow Line

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

$$V_z = V_z' - V_h \tan \alpha_s , \qquad (2)$$

where V_z' is the vertical velocity component of the top of a marker stake, V_h is the horizontal velocity and α_s 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 submergence and a negative value indicates emergence. The quantity $V_z - A$ gives the rate of change of the surface elevation per year, where A is the annual net accumulation in snow depth (positive value A shows accumulation; negative value for ablation). Herewith, we call the quantity $V_z - A$ the thinning-rate of the ice sheet.

Figure 2 shows the thinning-rate ($m \cdot a^{-1}$), horizontal velocity obtained from the surveys described in the preceeding section, and surface and bedrock profiles along the Shirase Glacier flow line (39°E). The value of $V_z - A$ is as small as 0.3 to 0.5 $m \cdot a^{-1}$ in the upstream area from G5 to G7, while in the region of downstream area, but it increases below G4 and reaches approximately 2.5 $m \cdot a^{-1}$ at point G2. The arrow marked by a star (*) between points G3 and G4 is a value obtained from triangulation chain measurements by NARUSE (1978). Negative values of thinning-rate shown around point G3, may be caused by a rise of the bedrock profile indicated in the bottom figure.

4. Basal Shear Stress

MAE and NARUSE (1978) suggested that the thinning was caused by basal sliding and that the Mizuho Plateau ice sheet may be unstable at present. The basal stress τ_b is an important parameter to examine the state of the ice sheet. It is given by

$$\tau_b = \rho g h \sin \alpha_s , \qquad (3)$$

where ρ is ice density, h ice thickness (depth), g garvitational acceleration and α_s the surface slope. Substituting the observed values of h and α_s along the Shirase Glacier flow line into the above equation, we obtain τ_b as shown in Fig. 3(d). A large solid circle indicates basal shear stress obtained from the observed surface slope of the ice sheet surrounding the station by measuring the vertical angle of the skyline at approximately several kilometers distance, while a small solid circle is the value obtained from the elevation difference along the flow line. It is seen from Fig. 3(d) that in the upstream area of point G3 τ_b is approximately 100 kPa. The deviation of τ_b from 100 kPa is mainly caused by the fluctuation of α_s due to the micromorphology of the ice sheet surface.

The basal shear stress along the flow line in the lower part of the basin increases with increasing distance from the outlet of Shirase Glacier, reaching a maximum value of 250 kPa around 100 km from the outlet, and then gradually decreases to an order of 100 kPa with fluctuations depending on the surface and bedrock profiles. This rise of τ_b at about 100 km from the outlet of Shirase Glacier resembles that in the trigger zone of several surging glaciers in their pre-surge state (ROBIN and WEERTMAN, 1973). Hence, we conclude that the ice sheet on Mizuho Plateau is unstable.

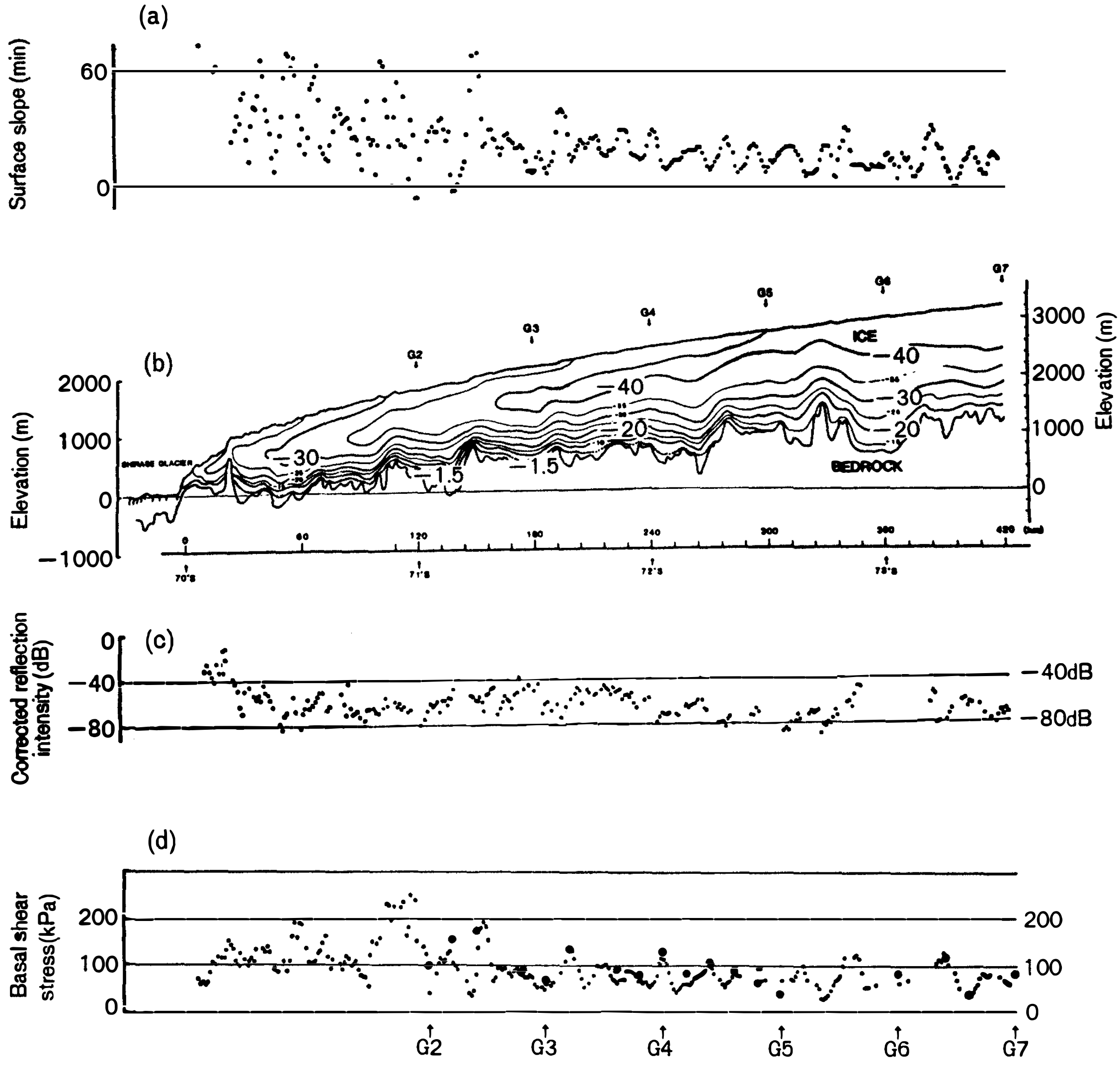

Fig. 3. Surface slope (a), temperature profile in the ice sheet (b), radio-echo reflection intensity (c) and basal shear stress profile (d) along the Shirase Glacier flow line (39.5°E).

5. Temperature at the Base

The temperature profile along the flow line is calculated based on a simple steady-state model of heat conduction (BUDD *et al.*, 1971). The calculated temperature profile is shown in Fig. 3(b). It indicates that the base temperature is at pressure melting point between 20 km and 260 km from the outlet of Shirase Glacier. In the upper part of the basin beyond 260 km from the coast, the basal ice is frozen. The temperature profile, therefore, is another proof of basal sliding occurring up to nearly 300 km from the outlet of Shirase Glacier, which causes the thinning shown in Fig. 2.

6. Radio-echo Reflection Intensity from the Bed

Radio-echo sounding along the same flow line was carried out by both air-borne (179 MHz) and ground-based (60 MHz) radio-echo sounders (OHMAE *et al.*

1988). Information concerning the nature of the basal interface from radar sounding alone is derived primarily from the strength of the bottom echo. Therefore, the corrected reflection intensity of the bottom echo was calculated by subtracting the total attenuation of transmitted power of radio waves in the ice sheet from the reflected power of the bottom echo. As shown in Fig. 3(c), there is a general tendency that the corrected reflection intensity from the bed is stronger in the downstream area than in the upstream area. There is a sharp rise of intensity at about 40 km distance from the outlet, and it becomes approximately constant around −60 dB upstream until 240 km, then a little change down to around −70 to −80 dB in the range of 260–320 km. The area of strong reflection of less than −60 dB roughly coincides with the area of pressure melting temperature, indicated by the −1.5°C isotherm in Fig. 3(b) as described in the preceeding section.

Signals reflected from the dry rock bottom in the upstream areas are reduced by 10–30 dB from those from the wet basal interface of the downstream area of Shirase Glacier. This fact coincides with the predicted reflection intensity from the base of the grounded ice from the attenuation of ice. The coincidence gives additional proof of the basal sliding described above.

7. Results and Discussion

Results of the present study indicate the following: The ice sheet in the downstream region where ice elevation is lower than 2800 m is thinning at present. Results of the radio-echo sounding on Mizuho Plateau indicate that the base of the ice sheet in the downstream region is wet. Calculations by a three-dimensional numerical model also show that the bottom temperature of the ice sheet in the downstream area is at the pressure melting point, hence the bottom should be wet (NAGAO *et al.*, 1983). δ^{18}O analyses of deep ice cores retrieved at Mizuho Station show that δ^{18}O increases significantly in the uppermost layer shallower than 150 m depth of the ice sheet (HIGASHI *et al.*, 1988). If thinning of the ice sheet is caused by basal sliding of the wet bottom, it should have commenced from the mouth of the Shirase Glacier and propagated upstream to a distance of 260 km on Mizuho Plateau during the last several thousand years. If we assume on the other hand that the increase of δ^{18}O above 150 m depth in the Mizuho ice core is an effect of the thinning of ice sheet, the ice age at 150 m depth could give the latest date on which the thinning reached the distance of 250 km from the mouth of the glacier. It is estimated to be approximately 1700 years B.P. (FUJII and WATANABE, 1988). Thus the thinning should have taken place for at least several thousand years. This approximate duration of thinning is also supported by the results of analyses of the total gas content of the Mizuho ice core (M. NAKAWO *et al.*, pers. commun.).

Estimations of the basal sliding velocity in various areas of the Shirase Basin indicated that the sliding is taking place over main parts of the Shirase Basin (MAE and NARUSE, 1978). This explains well the recent rapid motion of the Shirase Glacier terminus, about 2.7 km·a^{-1} (FUJII, 1981) and of Station G2, about 40 m·a^{-1}. However, we have no data to estimate how the velocity has changed in the last several thousand years.

The Shirase Glacier is conceivably a fast moving glacier at present, but it may transform to a surging glacier if the rise in the basal shear stress observed at about 100 km from the mouth is considered as a pre-surge phenomenon and the trend of expansion of wet bottom area continues.

Acknowledgments

The authors acknowledge help and encouragment given to this project from Prof. Y. NAITO, National Institute of Polar Research who was the leader of wintering party of JARE-27. We also wish to express our thanks to all members of the wintering party. This is contribution to the Glaciological Research Program in East Queen Maud Land, Antarctica (Prof. A. HIGASHI, the program chairman). Financial support by the Ministry of Education, Science and Culture, Japan is acknowledged.

References

BUDD, W. F., JENSSEN, D. and RADOK, U. (1971): Derived physical characteristics of the Antarctic ice sheet. ANARE Interim Rep., Ser. A (IV) Glaciol., **120**, 178.

FUJII, Y. (1981): Aerophotographic interpretation of surface features and estimation of ice discharge at the outlet of the Shirase drainage basin, Antarctica. Nankyoku Shiryô (Antarct. Rec.), **72**, 1–15.

FUJII, Y. and WATANABE, O. (1988): Microparticle concentration and electrical conductivity of a 700 m core from Mizuho Station, Antarctica. Ann. Glaciol., **10**, 38–42.

HIGASHI, A., NAKAWO, M., NARITA, H., FUJII, Y., NISHIO, F. and WATANABE, O. (1988): Preliminary results of analyses of 700 m ice cores retrieved at Mizuho Station, Antarctica. Ann. Glaciol., **10**, 52–56.

MAE, S. (1977): Hyôshô oyobi hyôga no hyôkô henka no genin ni tsuite (The variation of thickness of the Mizuho Plateau ice sheet, East Antarctica, and the Khumbu Glacier, Nepal Himalaya). Seppyo (J. Jpn. Soc. Snow Ice), **39**, 117–124.

MAE, S. and NARUSE, R. (1978): Possible causes of ice sheet thinning in the Mizuho Plateau. Nature, **273**, 291–292.

NAGAO, M., NAKAWO, M. and HIGASHI, A. (1983): Computer simulation of the ice sheet in the Shirase basin, Antarctica. Ann. Glaciol., **6**, 219–221.

NARUSE, R. (1978): Surface flow and strain of the ice sheet measured by a triangulation chain in Mizuho Plateau. Mem. Natl Inst. Polar Res., Spec. Issue, **7**, 198–226.

NARUSE, R. (1979): Thinning of the ice sheet in Mizuho Plateau, East Antarctica. J. Glaciol., **24**, 45–52.

NISHIO, F., OHMAE, H. and ISHIKAWA, M. (1986): Position, elevation and ice thickness of stations. JARE Data Rep., **110** (Glaciol. 12), 5–36.

OHMAE, H. (1984): Surface slopes of the ice sheet. JARE Data Rep., **94** (Glaciol., 10), 84–101.

OHMAE, H., NISHIO, F. and MAE, S. (1988): Distribution of reflected power from bed by radio echo-sounding in Shirase Glacier Drainage area, East Dronning Maud Land, Antarctica. Ann. Glaciol., **12**, 124–126.

ROBIN, G. de Q., and WEERTMAN, J. (1973): Cyclic surging of glaciers. J. Glaciol., **12**, 3–18.

SHIBUYA, K. (1985): Performance experiment of an NNSS positioning in and around Syowa Station, East Antarctica. J. Phys. Earth, **33**, 453–483.

(Received March 17, 1988; Revised manuscript received November 18, 1988)