DISCHARGE OF ICE ACROSS THE SÔYA COAST

Masayoshi NAKAWO,

The Institute of Low Temperature Science, Hokkaido University, Kita-ku, Sapporo 060

Yutaka AGETA

Faculty of Education, Yamaguchi University, Yoshida, Yamaguchi 753

and

Aiichirô YOSHIMURA

Geographical Survey Institute, Ministry of Construction, Meguro-ku, Tokyo 153

Abstract: The flow velocity of about 2500 m/year was obtained for the Shirase Glacier (70°S; 39°E), East Antarctica, by the analyses of aerophotographs taken in 1969 and 1975. Thicknesses of icebergs near the termini of the glaciers located along the Sôya Coast were also obtained from the shadows on aerophotographs. These data made it possible to estimate the amount of discharge of ice more accurately than ever made. The total discharge from the Mizuho Plateau area across the Sôya Coast is estimated at approximately 8.9×10^9 t/year, which comprises 7.4×10^9 t/year from the Shirase Glacier and 1.5×10^9 t/year from other glaciers and the ice sheet.

1. Introduction

The Glaciological Research Program in Mizuho Plateau has been carried out from 1969 to 1975. Principal purpose of the program was to estimate the local mass budget of the ice sheet in this area. Estimate of the amount of ice discharge by flow to the ocean across the coast was one of the important studies in this program.

MELLOR (1959a, b, 1961) classified the discharge of ice from the Antarctic Continent into three types; sheet flow, stream flow and ice-shelf movement. The present study was carried out along the Sôya Coast (from 68°50′S; 40°00′E to 70°00′S; 38°30′E), where the types of discharge of the ice mass of Mizuho Plateau are considered to belong to the first two. Six ice streams are located along the Sôya Coast, which are named from north to south Langhovde Glacier, Honnør Glacier, Telen Glacier, Skallen Glacier, Rundvåg Glacier (tentative name) and Shirase Glacier (Fig. 1).

AGETA (1971) gave a preliminary estimate of the discharge of ice from the

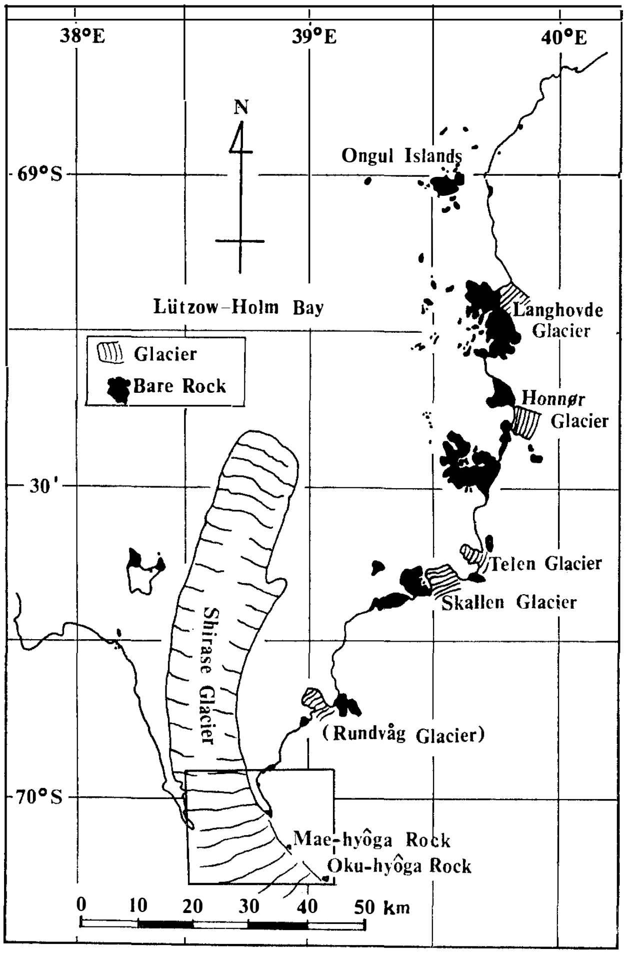

Fig. 1. Glaciers along the Sôya Coast. The squared section is enlarged and shown in Fig. 2.

ice sheet in Mizuho Plateau. He concluded that the Shirase Glacier plays the most important role in the discharge across the coast of this area; namely, 74% of the total discharge across the Sôya Coast is through the Shirase Glacier. This estimate was, however, very rough, because the data available at that time were very limited: 1) The flow velocity of the Shirase Glacier to be used was the one measured only once by a triangulation survey at an interval of about 5 months in the winter season (FUJIWARA and YOSHIDA, 1972). 2) Estimation was made of the thickness of ice only at a few glaciers along the Sôya Coast from the heights of icebergs floating near the terminus of each glacier, and the measurements of height on a course of traverse on the sea ice along the coast were so limited in numbers that the estimate of the average height was difficult. 3) The thickness of an iceberg was obtained by a triangulation survey only at one point of the iceberg.

In this paper, a more accurate estimate is given for the annual flow velocity of the Shirase Glacier and the thicknesses of many icebergs, both by the analyses of aerophotographs taken during the period of the program.

Combining aerophotographic analyses and ground surveys on the velocities of flow and thicknesses of small glaciers and the coastal ice sheet, amounts of discharge of ice from individual glaciers and the coastal ice sheet were calculated. The calculation of discharge was carried out by a simple multiplication of the velocity of flow, the width of glacier and the thickness of ice near the terminus of each glacier on an assumption that the area of the square shape of its cross section (surface width $\times$ thickness) equals approximately the real cross-sectional area. Obtained results are compared with the results of the previous study and the feasibility of the use of aerophotographs for the mass balance study is discussed.

2. Flow velocity of Shirase Glacier

The Shirase Glacier is the largest glacier on the coast of Lützow-Holm Bay. The approximate external margin of the glacier in the austral summer in 1975

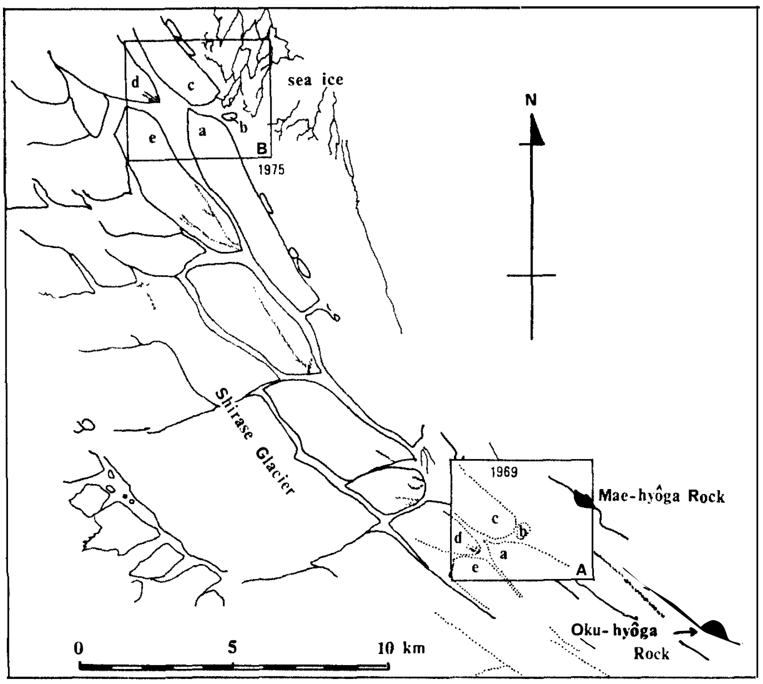

Fig. 2. Surface feature of the Shirase Glacier plotted by stereographic projection. Solid lines and dotted lines indicate the delineation of the glacier in 1975 and 1969, respectively, which are plotted relative to the Mae-hyôga Rock and the Oku-hyôga Rock. Portions a, b, c, d and e in a square A in 1969 flowed down to their counterpart positions in square B in 1975.

was as shown in Fig.1 (JARE-15, 1976). The glacier flows from south to north in a slightly curved path convex to the west. Observations made in the past several years indicate the advancement of the tongue during this period.

In 1960, the first attempt to measure the flow velocity of this glacier was made by FUJIWARA and YOSHIDA (1972), who measured the displacement of two stakes set on the floating ice tongue of the glacier near the Insteodden (about 12 km down-glacier from the Mae-hyôga Rock) in the period of 147 days from May to September 1960, and obtained values of 837 m and 855 m for each stake. These values give approximately 1800 m/year–2000 m/year for the flow velocity, if the seasonal variation is not considered. This velocity is one of the largest values among those reported hitherto for glaciers in Antarctica.

The method of determining the mean annual velocity of glacier flow in this paper is based on measuring the displacement of glacier ice which has a traceable

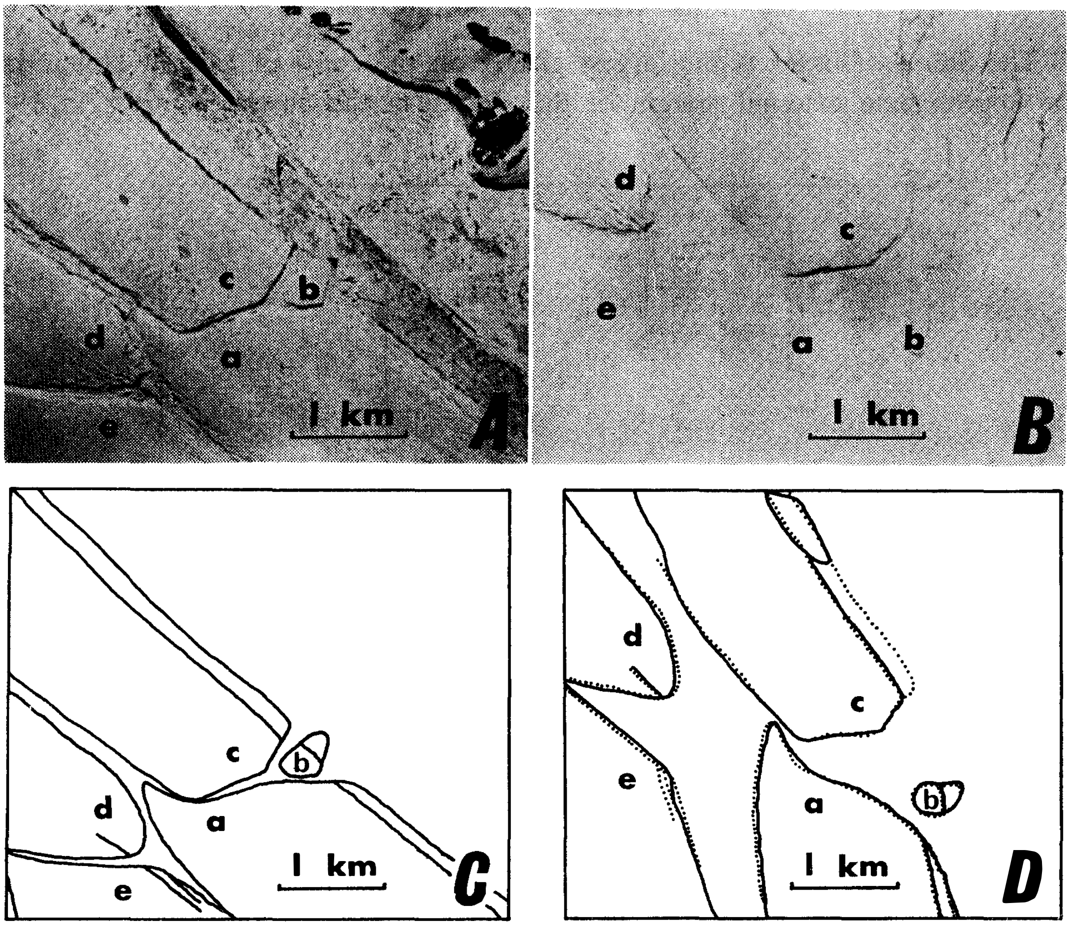

Fig. 3. Change of the shapes and dispositions of portions, a, b, c, d and e between 1969 and 1975 are shown in A and B, respectively. Solid lines in C and D show the delineation of the respective portions in A and B. Dotted lines in D represent the superposed delineation in 1969.

feature from aerophotographs taken at different times. Aerophotographs of the Shirase Glacier were taken in January 1969 and November 1975. From the photographs taken in 1975, Fig. 2 (the area in a small square in Fig. 1) is plotted by stereographic projection. Surface features in 1969 are superposed on Fig. 2 by the use of dotted lines. An aerophotograph of square A in Fig. 2, which was taken in 1969, is shown in Fig. 3A and that of square B taken in 1975 is shown in Fig. 3B. The similar features of cracked icebergs were found in both photographs.

Each of the external forms of icebergs or parts of the glacier designated by a, b, c, d and e in Fig. 3A taken in 1969 undoubtedly corresponds to each counterpart in Fig. 3B taken in 1975. They are delineated as shown by solid lines in Fig. 3C and 3D. The shape of each portion in Fig. 3C can be overlapped with dotted lines on that in Fig. 3D with appropriate rotations and translations. The fact that the width of portion c in 1975 became smaller than that in 1969 can be explained by disappearance of a marginal narrow part which was already crevassed longitudinally in 1969.

From the comparison of the features in areas A and B as stated above, it can be concluded that the ice in area A has flowed down to area B about 17 km during the period of about 7 years. Thus, the calculated mean annual velocity of the glacier during this 7 years is approximately 2400 m/year–2700 m/year. Since the value of velocity obtained by FUJIWARA and YOSHIDA was 1000 m per 6 months for the winter season, the velocity in the summer season is to be about 1500 m per 6 months if the mean annual velocity remained constant from 1960. It might be plausible that the summer velocity is 1.5 times the winter velocity.

3. Thicknesses of Icebergs near Terminus of a Glacier

Fig. 4 is an example of aerophotographs which shows shadows of icebergs allowing the measurement of their heights. Many icebergs shown in it indicate that they would have been calved at the terminus of the Honnør Glacier. When the solar azimuthal and zenithal angles are estimated for the time and location of aerophotographing, the height h of an iceberg can be calculated from the shadow length parallel to the solar direction for each tabular berg. A shadow length was measured at intervals of 20 m since an iceberg has different heights at different points and the mean value was calculated. The thickness d of the iceberg was then calculated by the following equation:

$$d=h\cdot\rho_w/(\rho_w-\rho_i),$$

where ρ_w and ρ_i are the density of sea water and glacier ice, respectively. It is, of course, assumed that the tabular bergs are not grounded. Values for ρ_w and ρ_i are taken to be 1.03 g/cm³ and 0.85 g/cm³ respectively. Calculated values

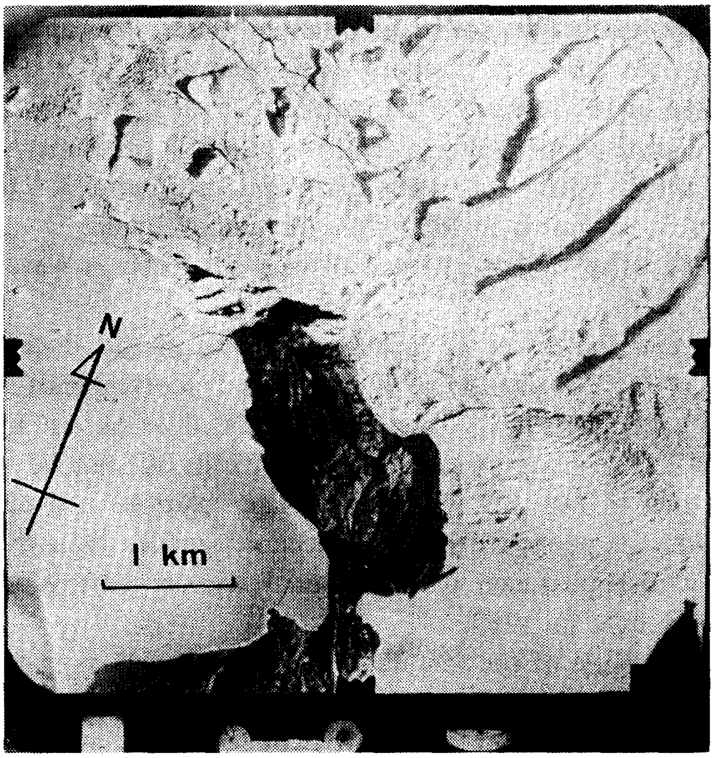

Fig. 4. An aerophotograph near the terminus of the Honnør Glacier.

Table 1. Thickness of iceberg near termini of glaciers (m). The mean value of measured thickness of each glacier is in parentheses.

Glaciers	Aerophotographic analysis	Ground survey
Shirase Glacier	228 263 293 294 (287) 272 364	275 (AGETA, 1971) 235 (WATANABE) 155 (〃) 172 ~ 401 (NAGATA and YOSHIDA, 1962)
Skallen Glacier	223 212 154 (192) 181	172 (WATANABE)
Honnør Glacier	281 236 259 199 (239) 217 238 245	206 (KIZAKI, 1962)

of thicknesses of icebergs from their shadows in aerophotographs taken in various areas in 1975 are tabulated in Table 1. The table also contains previous results obtained by the ground survey method in the same areas. The calculated values from the aerophotographs coincide well with those obtained by the ground surveys. The average values in Table 1 were used as the thickness of glacier ice at the terminus of each glacier.

4. Ice Discharge across the Sôya Coast

SHIMIZU *et al.* (1978) stated that the Mizuho Plateau area could be divided into two drainage basins, one with the outlet in the Shirase Glacier and the other in the remaining part of the Sôya Coast. Widths of the glaciers along the coast were measured on the map of Lützow-Holm Bay (GEOGRAPHICAL SURVEY INSTITUTE, JAPAN, 1963). The total length of the coast occupied by the ice sheet excluding the glaciers (but including Hamna Ice Fall because of its small flow rate) was also measured on the map. These values are tabulated on the second column in Table 2.

Thicknesses of the Shirase Glacier, the Skallen Glacier and the Honnør Glacier at their termini are assumed to be 280 m, 190 m and 230 m, respectively, based on the rounded numbers of average values in Table 1. For the Langhovde Glacier, its thickness is assumed to be 170 m from WATANABE's (private communication) measurements by the ground survey in 1970. The thicknesses of the other two glaciers have never actually been measured and no appropriate photographs were found to be used as stated in Section 3. Therefore, they are both assumed to be 200 m from the average of those of others in this area. The thickness of ice of the sheet flow type along the coast is estimated at 160 m as a

Table 2. Discharge of ice across the Sôya Coast (t/year) with its base data. Assumed values for the base data are in parentheses.

Place	Flow width (km)	Ice thickness (m)	Flow velocity (m/year)	Discharge (10^9 t/year)
Shirase Glacier	11.8	280	2500	7.4±1.9
Rundvåg Glacier	5.0	(200)	(300)	0.3±0.2
Skallen Glacier	7.3	190	400	0.5±0.2
Telen Glacier	4.5	(200)	400	0.3±0.1
Honnør Glacier	3.3	230	400	0.3±0.1
Langhovde Glacier	2.8	170	170	0.1±0.1
Others (Sheet flow)	65	100	5	0.03±0.03

result of the analysis of an aerophotograph of the icebergs adjacent to the ice sheet. However, AGETA's (1971) previous estimate of thickness based on the heights of small icebergs near Syowa Station was about 50 m. Therefore, it is now assumed to be 100 m. Values of the thickness are tabulated on the third column in Table 2.

As is mentioned in Section 2, the flow velocity of the Shirase Glacier is considered to be around 2500 m/year. FUJIWARA and YOSHIDA (1972) measured the flow velocity of the Langhovde Glacier near the terminus in 1961. They measured the movement of a stake from May to September 1961 and obtained the value of 172 m/year for the annual mean flow rate. SHIMIZU *et al.* (1975) surveyed the displacement of the Langhovde Glacier and got the value of 9 m–17 m during a 158-day period from September 1970 to March 1971. But these values are not suitable for the purpose of estimating the mass flux at the terminus since the location of the markers were fairly up-stream from the terminus. The horizontal displacement of fast ice along a shear crack off the tongues of the Telen and Skallen Glaciers was measured by FUJIWARA and YOSHIDA (1972), with an aim of estimating the flow velocity of the glaciers. The estimated flow velocity was about 400 m/year. The small flow velocity, 2 m/year–7 m/year, was obtained in the vicinity of the Skallen Glacier, but this small value may be attributed to the fact that the stakes were located close to Skallen Rock which retards the flow (AGETA and NARUSE, 1971). Then the flow velocity of the Skallen Glacier is assumed to be 400 m/year. FUJIWARA and YOSHIDA (1972) supposed the flow velocity of the Honnør Glacier to be 300 m/year–500 m/year from observations on the structure of the terminus of the glacier. For the Rundvåg Glacier, no data of velocity is available, but from the resemblance of its features to those of the glaciers in its vicinity, its flow velocity is assumed to be 300 m/year which is an approximation of averages of flow velocities of these glaciers. The velocity of sheet flow in this area was measured by several investigators; MURAUCHI (1960) obtained the velocity of 2 m/year–3 m/year, FUJIWARA and YOSHIDA (1972) 3 m/year–10 m/year, and SHIMIZU *et al.* (1975) 2 m/year–7 m/year. The flow velocity of Hamna Ice Fall was 3 m/year–5 m/year (NAGATA and YOSHIDA, 1962; FUJIWARA and YOSHIDA, 1972). On the basis of these results, the mean velocity of sheet flow is assumed to be 5 m/year. These estimated flow velocities are tabulated in the 4th column of Table 2.

Using these values of flow width, ice thickness and flow velocity in Table 2, the amount of discharge of ice at various outlets is calculated, on an assumption that the density of ice is 0.9 g/cm^3. As are shown in the 5th column of Table 2, the discharge of $(7.4\pm1.9)\times10^9$ t/year through the Shirase Glacier exceeds 80% of the total discharge of $(8.9\pm2.2)\times10^9$ t/year of the ice mass across the Sôya Coast.

The range of error of calculated value of discharge was estimated from the errors of the following. As for the flow width, an error of 10% of the observed value is considered to be sufficient in that the apparent flow width does not usually represent the real flow width of glacier ice, though the reading error is always negligible. As for the thickness, the standard deviation of the observed values of ice thickness was taken as its error, when a sufficient number of data were available. As for the flow velocity, in the case of the Shirase Glacier an error of 16% is estimated, as is mainly caused from stereographic projection of aerophotographs. Whereas, in the case of other glaciers, the error for the flow velocity of each glacier is considered to be in a range of differences of any measured values of the glacier, when many such data are available. For the glaciers where no real data of ice thickness and flow velocity were available, as exemplified by the values in parentheses in Table 2, the error was considered to be twice as large as those of the other glaciers.

5. Concluding Remarks

By the analyses of aerophotographs, more reliable data were obtained for both the flow velocity of the Shirase Glacier and the thicknesses of icebergs along the Sôya Coast in Lützow-Holm Bay. By combining these data with those of ground surveys previously made, the discharge of ice from Mizuho Plateau across the coast was estimated. The estimated total discharge across the Sôya Coast is larger than the previously estimated value by AGETA (1971) by nearly 50%. Percentage of the amount of discharge through the Shirase Glacier against the total discharge across the Sôya Coast also increased up to 83%, compared with his estimation. This difference is caused mainly by the increase of the estimate of flow velocity of the Shirase Glacier.

It is proved that the aerophotographs can be successfully used for the purpose of estimating the flow velocities of glaciers and the thicknesses of icebergs in such a wide area difficult of access as the area where the present study was carried out. It is feasible to apply the same method to any glacier if aerophotographing with an appropriate time interval is made. Should adequate markers be placed on a glacier surface, the results would become more reliable. Aerophotography could be used not only for measurements of the flow velocities of glaciers and of their thicknesses but also for measurements of their strain rates and for observations of such structures as crevasses or cracks. Continued systematic aerophotographing is strongly recommended for further studies of the mass balance of the Antarctic ice sheet.

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References

AGETA, Y. (1971): Nankyoku no shitsuryô shûshi to kongo no kadai (Mass budget in Antarctica and its future problem). Seppyo (J. Jap. Soc. Snow Ice), **33**, 4, 1–10.

AGETA, Y. and NARUSE, R. (1971): Measurements of ice flow around Skallen Rock, south of Syowa Station, Antarctica. Nankyoku Shiryo (Antarct. Rec.), **42**, 61–64.

FUJIWARA, K. and YOSHIDA, Y. (1972): Lützow-Holm wan tôgan no hyôga ryûdô sokutei (Ice flow measurements on the east coast of Lützow-Holm Bay, Antarctica). Nankyoku Shiryo (Antarct. Rec.), **44**, 79–92.

GEOGRAPHICAL SURVEY INSTITUTE, JAPAN (1963): Lützow-Holm Bay, 1:25000 series, ed. by Geographical Survey Institute, Japan.

KIZAKI, K. (1962): Ice fabric studies on Hamna Ice Fall and Honhörbrygga Glacier, Antarctica. Nankyoku Shiryo (Antarct. Rec.), **16**, 54–74.

MELLOR, M. (1959a): Ice flow in Antarctica. J. Glaciol., **3**, 377–386.

MELLER, M. (1959b): Mass balance studies in Antarctica. J. Glaciol., **3**, 522–533.

MELLOR, M. (1961): The Antarctic ice sheet. Hanover, U.S. Army Cold Regions Research and Engineering Laboratory, 50 p. (Monograph Series, Part 1, Sect. B1).

MURAUCHI, S. (1960): Kansoku hôkoku, chigaku bumon (Research report, geophysical section). Nankyoku kansoku dai-3-ji ettôtai hôkoku (Report of the Wintering Party of the 3rd Japanese Antarctic Research Expedition), 46–48.

NAGATA, T. and YOSHIDA, Y. (1962): Scientific programs for each discipline, IX Glaciology. Jap. Contrib. IGY and IGC, IV. Tokyo, Science Council of Japan, 138–141.

SHIMIZU, H., YOSHIMURA, A., NARUSE, R., WATANABE, O., NAKAWO, M. and OKUHIRA, F. (1975): Movement of ice sheet and glaciers in Sôya Coast in 1969–1972. JARE Data Rep., **27** (Glaciol.), 162–174.

SHIMIZU, H., YOSHIMURA, A., NARUSE, R. and YOKOYAMA, K. (1978): Morphological feature of the ice sheet in Mizuho Plateau. Mem. Natl Inst. Polar Res., Spec. Issue, **7**, 14–25.

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