# DISTRIBUTION OF ACCUMULATION MEASURED BY THE SNOW STAKE METHOD IN MIZUHO PLATEAU


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***Abstract:*** The seasonal and the annual variations of accumulation of snow and its regional distribution were measured by means of snow stakes distributed along the various traverse routes in Mizuho Plateau, East Antarctica, in 1968–1974. The deposition of snow occurs mainly in the winter season from February to September; on the contrary, the erosion of snow occurs in the summer season from November to January. Maximum values of accumulation rate were found at both the equinoxes. As for the coastal region between 1000 m and 1700 m a.s.l., the maximum annual accumulation during seven years from 1968 to 1974 was observed in 1970, which is about 2.5 times larger than the minimum which was observed in 1969. The firn line and the dry snow line are located in Mizuho Plateau, respectively at 400–500 m at 700–1000 m a.s.l. As for the region between 1700 m and 3500 m a.s.l., hiatuses in accumulation were usually found. The modes of regional distribution of annual accumulation differ sharply from each other among the five regions, which are divided at the boundaries located at 400–500 m, 700–1000 m, 1700–1900 m and 3400–3500 m a.s.l.


## 1. Introduction

Measurements of accumulation of snow on the surface of the ice sheet have been made at many locations in Antarctica by previous investigators in their studies of the mass budget of Antarctica. However, the previous measurements of accumulation were carried out mainly in West Antarctica as compared with East Antarctica. Especially, only a few measurements have been made in the two regions, namely the cold katabatic (DALRYMPLE, 1966) region and the region between it and the coastline, where most of our areas observed are located. In order to deepen the understanding of the mechanism of mass input to the continent from the sea, it will be essentially necessary to investigate the regional characteristics of accumulation process of snow depositing on the surface of the ice sheet, its seasonal and annual variations and topographical effects on the snow accumulation. This paper describes the results of measurements of accumulation of snow by the snow stake method along the traverse routes in Mizuho Plateau, East Antarctica, from the seacoast to the inland plateau at about 3700 m a.s.l.

The "accumulation of snow" used in this paper is defined by the thickness of snow which was deposited onto or removed from the surface of snow after the measurement made in the previous traverse, the sign being positive in the former case and negative in the latter case. The definition of the term has also been used in the literature on this subject (FUJIWARA and ENDO, 1971; AGETA and WATANABE, 1972; YAMADA *et al.,* 1975; YOKOYAMA, 1975; SATOW, 1977) from which the data used in this paper were obtained.

## 2. Observations

The accumulation of snow was measured by snow stakes installed along Routes S, H, Z, X and A, which are shown in Fig. 1 by thick solid lines on the map of Mizuho Plateau, East Antarctica. Snow stakes were set up on the snow surface at intervals of 2 km along Routes S, H, Z and X, and at intervals of 1 to 4 km along Route A. Snow stake measurements along Route S were carried out in 1968 from S16 (554 m) to Plateau Station (3673 m), in 1969 from S16 to S240 (2639 m), in 1970 from S16 to S169 (2083 m) and in the years from 1971 to 1974 from S16 to S122 (1910 m). The accumulation during four years from 1970 to 1973 was obtained in the areas from S170 to S240 and along Route A, and during three years from 1971 to 1973 along Route X. Stake measurements along Routes H and Z were performed for two years from 1973 to 1974, and three years from 1972 to 1974, respectively.

## 3. Results

### *3.1. Regional features of annual accumulation measured along traverse routes*

Fig. 2 indicates the annual accumulation of snow at each location where a snow stake was set up. Concerning the data of snow accumulation covering the entire areas traversed, the data obtained in 1968 along Route S are the only

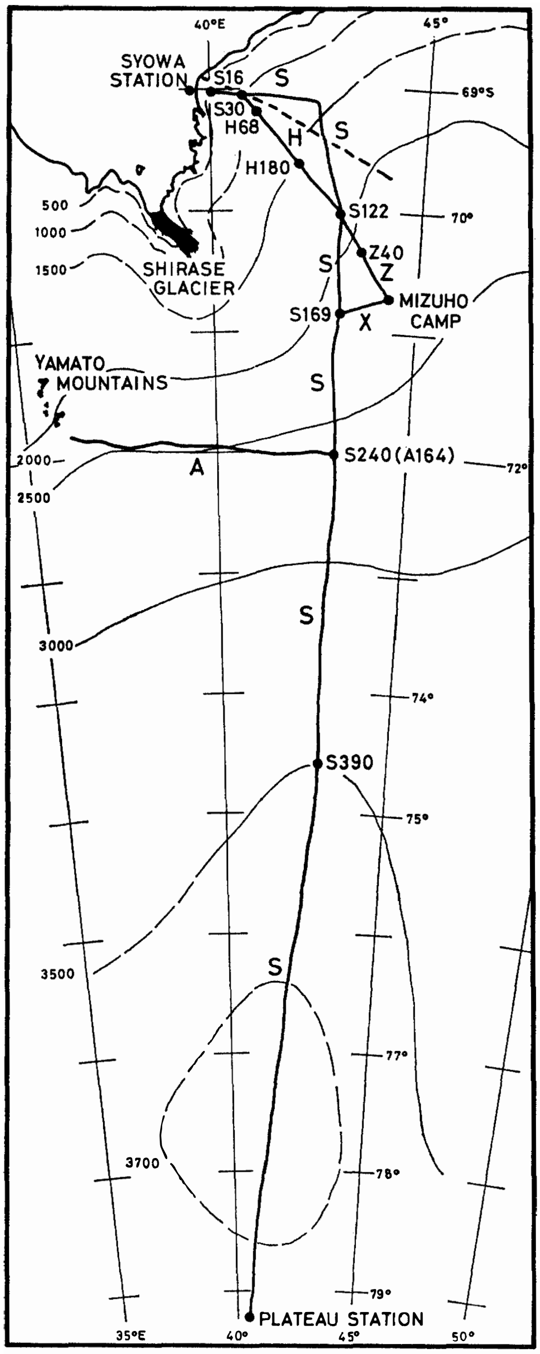



*Fig. 1. Contour map of observed area, Mizuho Plateau, East Antarctica and oversnow traverse routes. A broken line shows an obvious ridge.*

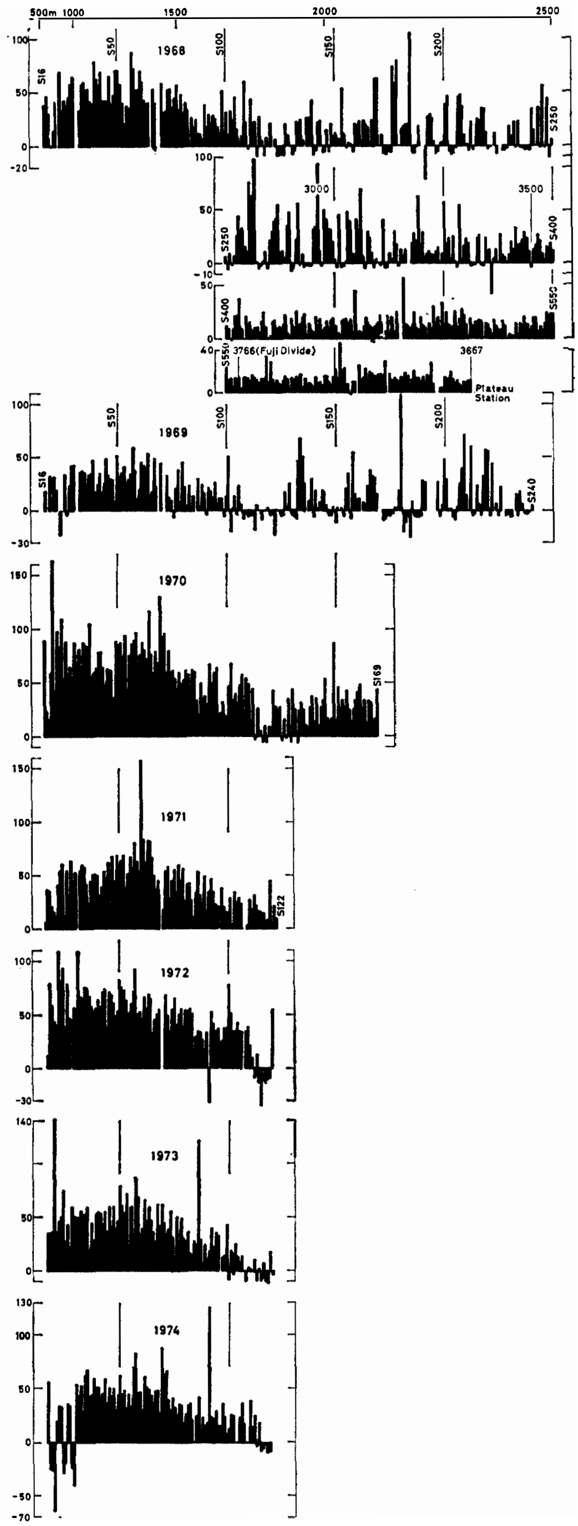



*Fig. 2. Distribution of annual accumulation of snow along Route S.*

available ones including those in the inland plateau (above 3000 m a.s.l.). From the distribution of annual accumulation of snow thus obtained, it can be found, as shown in Fig. 2, that there are three characteristic modes in the distribution.

The first one is the mound-like distribution of annual accumulation noticed in the section between S16 (554 m a.s.l.) and S110 (1749 m a.s.l.), having the peak around S60, as seen in Fig. 2, in which almost all the snow stakes indicate the occurrence of a positive and comparatively large accumulation of snow; it is then considered that an annual snow layer covers almost the whole snow surface in this section.

The second characteristic mode is seen in the section between S110 (1949 m a.s.l.) and S390 (3499 m a.s.l.), where the annual accumulation is small and fluctuates considerably from place to place. The distribution of annual accumulation along the route shows alternately negative and positive values. It means that an annual snow layer is missing at locations with negative values in this section. When average annual accumulation is to be estimated by a stratigraphic observation of pit walls or core samples, the missing of an annual layer or layers should be taken into account; otherwise it would cause the average to be overestimated.

The third characteristic mode is seen in the section from S390 to Plateau Station (3673 m a.s.l.). This section is featured by a small fluctuation and a further decrease, but not a negative one in values of annual accumulation. It has been pointed out by ENDO and FUJIWARA (1973) that a large areal fluctuation of accumulation was found in the area lower than 3500 m a.s.l., while a relatively constant accumulation in the area higher than this elevation.

The mound-like distribution in the positive annual accumulation is similarly found in the area below S100 (1680 m a.s.l.)–S120 (1901 m a.s.l.) in the data obtained in 1969–74 as indicated also in Fig. 2. This mode of distribution in the annual accumulation of snow may be understood if one recognizes that in the winter season moisture coming from the sea releases solid precipitation in the amount which decreases with increasing elevation or distance from the seacoast and that in the summer season the amount of snow or ice melting on the surface of the ice sheet in the coastal region below S30 (988 m a.s.l.) increases with lowering elevation, which will be discussed in a later section.

Figs. 3 and 4 show the distribution of annual accumulation of snow measured along Route H in 1973–74 and along Route Z in 1972–74, respectively, where Route H constitutes a shortcut of Route S from S30 to S122 and Route Z was established to reach Mizuho Camp from S122. Values of annual accumulation along Route H are positive at almost all the snow stakes, which coincides with the trend of the annual accumulation in the area between S30 and S100–S120, whereas values along Route Z fluctuate greatly and are negative at many locations,

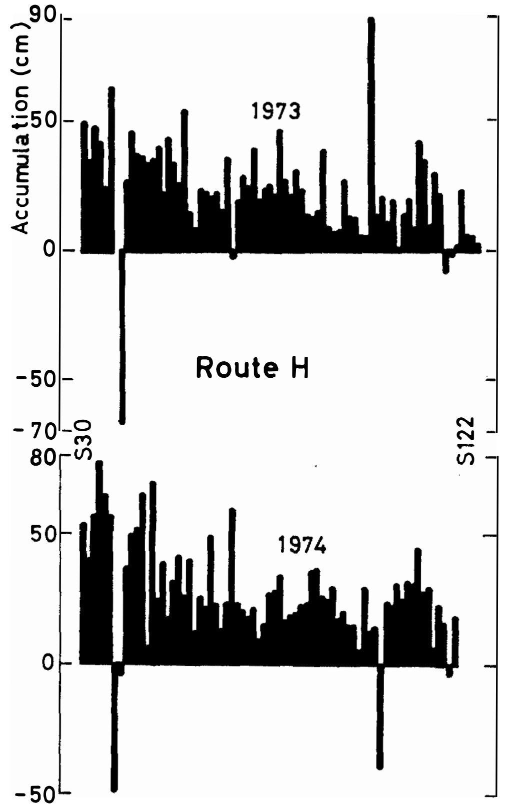



*Fig. 3. Distribution of annual accumulation of snow along Route H.*

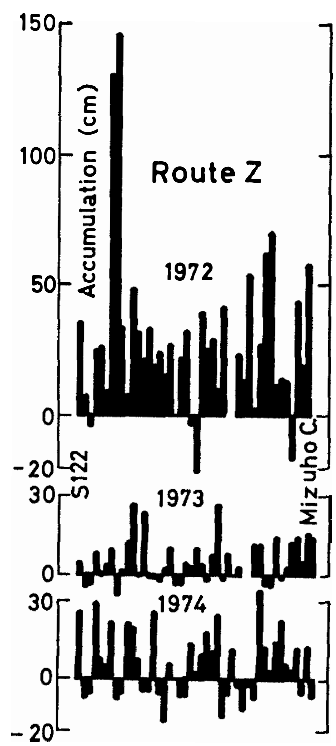
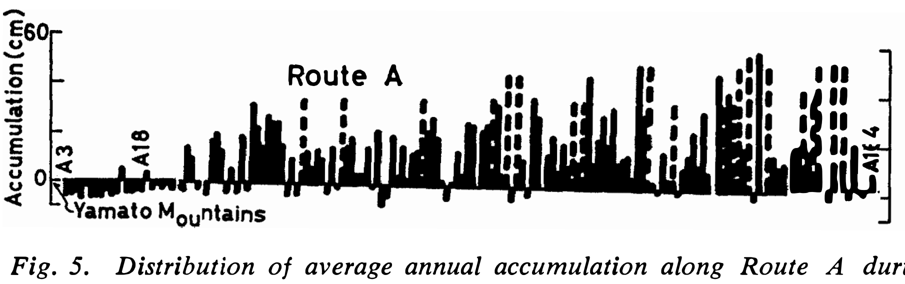



*Fig. 4. Distribution of annual accumulation of snow along Route Z.*

which follows practically the same tendency as values in the area from S100–S120 to S390, as indicated above.

Figs. 5 and 6 show the distribution of average annual accumulation measured along Routes A and X during four years from 1970 to 1973 for Route A and during three years from 1971 to 1973 for Route X, respectively. As seen in



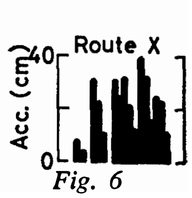




*Fig. 6*

*Fig. 5. Distribution of average annual accumulation along Route A during four years from 1970 to 1973. Broken lines show possible minimums, snow stakes having been buried when remeasured in January 1974.*

*Fig. 6. Distribution of average annual accumulation along Route X during three years from 1971 to 1973.*

Fig. 5, the stakes located from A3 to A18 near the Yamato Mountains show negative values, where bare ice was exposed on the surface and a snow layer could not be found out. Each of the snow stakes along Route A was also used as a marker for the triangulation survey aimed at studying the movement and deformation of the ice sheet and thus erected near the top of the surface rise of the undulation of the ice sheet for getting the longest unobstructed view to neighbouring markers. At the time of the last measurement made in January 1974, totally buried with deposited snow, 20 snow stakes were not found at the positions decided by the triangulation survey between A19 and A164 (identical with S240) where the stakes had been set up. The amount of snow accumulation during the four years at such a location is then larger than the original length of the stake. Each of the broken lines in Fig. 5 is given as a possible minimum of average annual accumulation, representing a quarter of the original length of a snow stake above the snow surface when set up during the first traverse in 1970, as it was buried under snow four years later. These facts suggest that the amount of annual accumulation in the area along Route A, except near the Yamato Mountains, is larger than those in the areas from S100 to S240 and along Routes Z and X. The mode of distribution of accumulation along Route A, although the data are averages over four years, shows also the same tendency, that is, the large fluctuation and hiatuses in accumulation, as in the areas from S100–S120 to S390 and along Route Z.

For estimating the ratio of the snow surface area where an annual layer is missing, to the total snow surface area, calculations were made and the results

*Table 1. Percentage ratio of number of stakes showing negative annual accumulation to total number of stakes set up in different areas along Routes S, H and Z.*

| Route | S16–S29 | S30–S100 | Route H | S101–S169 | Route Z | S170–S240 | S241–S390 | S391–P.S.* |
|---|---|---|---|---|---|---|---|---|
| Elevation (m) | 554–962 | 988–1680 | 988–1910 | 1681–2083 | 1910–2230 | 2082–2639 | 2647–3499 | 3502–3673 |
| Distance (km) | 28 | 142 | 150 | 136 | 90 | 142 | 300 | 544 |
| 1968 | 0 | 0 | | 16/67=24 | | 29/65=45 | 32/145=22 | 4/263=2 |
| 1969 | 2/9=22 | 3/65=5 | | 23/65=35 | | 30/59=51 | | |
| 1970 | 0 | 0 | | 7/69=10 | | | | |
| 1971 | 0 | 1/68=1 | | | | | | |
| 1972 | 0 | 1/68=1 | | | 5/39=13 | | | |
| 1973 | 0 | 1/70=1 | 4/74=5 | | 14/39=36 | | | |
| 1974 | 7/13=54 | 1/71=1 | 5/72=7 | | 19/42=45 | | | |

* Plateau Station

are given in Table 1 showing the ratio of the number of stakes which showed negative values of annual accumulation to the total number of stakes set up in the various locations along Routes S, H and Z. The areas observed were divided into eight areas depending on the characteristics of accumulation mode mentioned earlier and the availability of data consistently obtained during the years when measurements were made. The ratio does not have the same statistical weight, because the number of snow stakes is different in each area. It can be seen that in the areas between S30 and S100, along Route H and between S391 and Plateau Station, the ratios indicate very small values ranging from 0 to 7% and there are practically no hiatuses in accumulation. But in the areas between S101 and S390 and along Route Z, the ratio ranges from 10 to 51%. Fig. 7 shows the relationship between the ratio and the area-mean annual accumulation

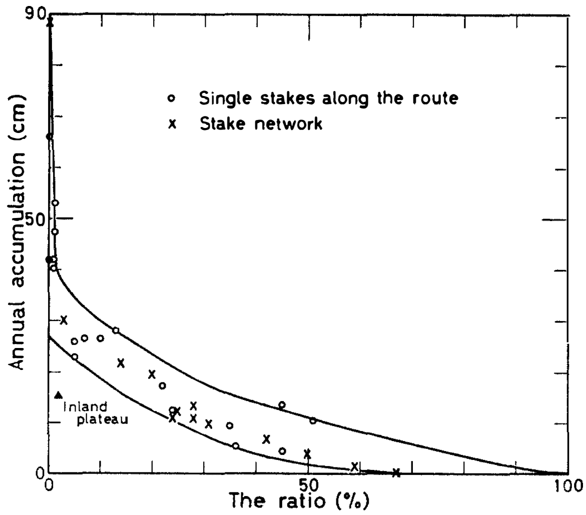



*Fig. 7. Relationship between area-mean annual accumulation and ratio of number of stakes showing negative annual accumulation to total number of stakes.*

obtained in these areas along the routes and in a limited area of 100×100 m each at S16, S30, H68, H180, S122, Z40 and Mizuho Camp, where snow stake networks were set up. A solid triangle in Fig. 7 which indicates the relationship in the inland plateau between S391 and Plateau Station is out of the belt enclosed by an upper and a lower boundaries of the plots representing the relationship in the area below the elevation of S390 (3499 m). It means that in the inland plateau, hiatuses in accumulation occur scarcely in spite of a relatively small value of area-mean annual accumulation. It is found out in Fig. 7 that in the area from S390 toward the coast, with the elevation below 3500 m a.s.l. throughout, the ratio increases with decreasing area-mean annual accumulation, whereby, when the latter decreases to less than 10–20 cm/year, the former increases to more than

25%. At a location where the ratio is more than 25% an annual layer of snow may cover the previous year's surface in the patch-like form. This value, 10–20 cm/year, is consequently considered as the critical one, below which a hiatus may occur practically in accumulation and above which it may not. In the areas from S30 to S100 and along Route H, hiatuses in accumulation are not observed practically, because the area-mean annual accumulation is more than 20 cm/year and the ratio is less than 25%.

Concerning the areal fluctuation of annual accumulation along the routes, Figs. 2, 3, 4, 5 and 6 can show that it is much higher in the area below 3400 m a.s.l. than in the area above this elevation. The standard deviations of annual accumulation computed over every ten neighbouring values obtained by stakes along the routes are in the range between 10 and 40 cm/year in the area below 3400 m, whereas the standard deviations decrease to the range between 4 and 14 cm/year in the inland plateau above this elevation. The large areal fluctuation of accumulation in the area below this elevation is caused by deviative deposition of snow resulting from the interaction between the air and the surface features.

The accumulation of snow significantly depends on the topographical feature of the ice sheet. A comparison is made between two records of the annual accumulation measured along two Routes S(S30–S122) and H. Though the length of Route H is shorter than that of Route S, the relative location of both routes against the seacoast is approximately the same as shown in Fig. 1. Fig. 8 shows the distribution of annual accumulation obtained in 1973 (solid lines) and 1974 (broken lines) along the two routes as a function of elevation. The values of annual accumulation are moving averages over ten values. A comparison of the amount of annual accumulation between the two routes shows a significant

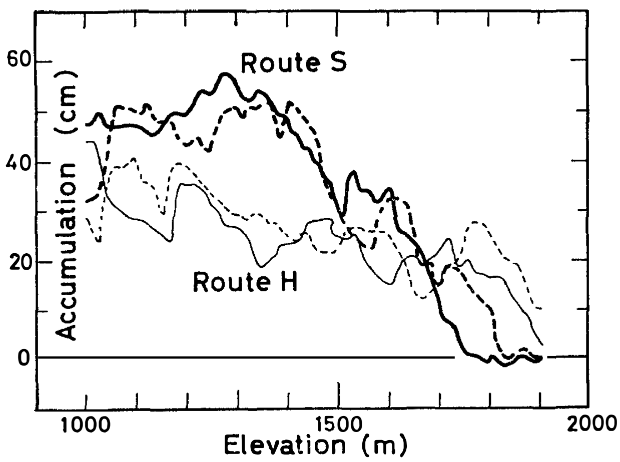



*Fig. 8. Distribution of annual accumulation alonng Routes S and H in 1973 (solid lines) and 1974 (broken lines).*

difference, as seen in Fig. 8, in the area between 1000 and 1500 m a.s.l. According to the contour map of Mizuho Plateau (SHIMIZU *et al.,* 1978), there is an obvious ridge running down between Routes S and H, as shown by a broken line in Fig. 1. Since the prevailing wind directions in this area are NNE–ENE (WATANABE, 1978a), Routes S and H are situated respectively in the windward and the leeward, producing much more accumulation of snow along Route S than along Route H. It could be considered that the annual accumulation in the windward slope of the obvious ridge of the ice sheet, where strong katabatic wind blows stationarily, is remarkably larger than that in the leeward slope of it. This fact suggests that the amount of snow accumulation is dependent not only on meteorological conditions but also the surface topography of the ice sheet.

### *3.2. Ablation in the coastal melting region*

According to snow temperature measurements in a 2 m depth (SATOW *et al.*, 1974) and stratigraphic observations (WATANABE, 1972), the elevation of the dry snow line (BENSON, 1962; MÜLLER, 1962) in Mizuho Plateau in summer of 1971–72 is regarded to be 800 m a.s.l., although the elevation or location of it may change every summer. From the observations for seven years, the minimum and the maximum elevations of the dry snow line are respectively considered to be about 700 m and 1000 m. The firn line is located at about 400 m a.s.l., below which the surface of the ice sheet constitutes a steep slope with a blue ice surface. In the area below the firn line snow particles contained in the blowing or the drifting snow are mainly transported throughout the year toward the sea by the strong katabatic wind or the violent wind caused by a cyclonic disturbance, then few snow deposits remain on the blue ice slope. Fig. 9 shows the amount of melting snow or ice in the summer season as a function of elevation, which is also measured by the stake method. In the area below the dry snow line, the annual accumulation may tend to decrease gradually with lowering elevation as a result of melting in the summer months. In the area above the firn line, meltwater produced at the surface does not run off to the sea but percolates into snow and refreezes there to form superimposed ice. Therefore, the value obtained as the difference of the present and the previous readings by the snow stake method in the area between the firn line and the dry snow line is an apparent one, not providing a real value of either accumulation or ablation; hence this value is of no significance in obtaining a real surface mass balance, in principle. The accumulation of snow in winter in this area may have almost the same value as that in the large accumulation area from S30 to S70 (988–1428 m a.s.l.). On the blue ice slope below the firn line, almost the entire amount of meltwater may be drained away toward the sea through water channels in the ice body and streams formed on the surface of the blue ice slope, resulting in ablation. The amount of meltwater in the summer season on the blue ice slope below the firn line is

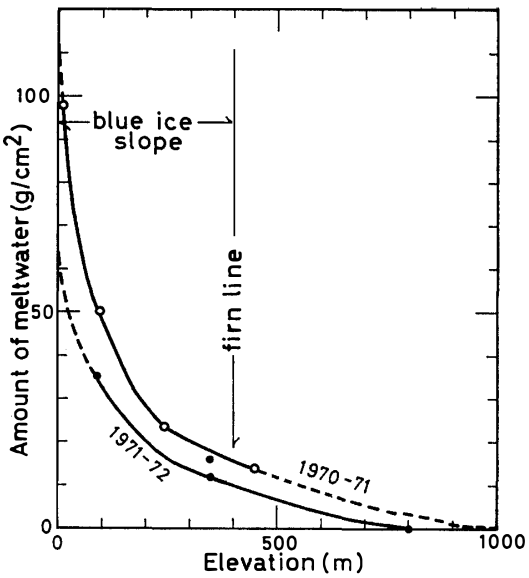



*Fig. 9. Total amount of meltwater (g/cm²) measured by stakes during summers in 1970–71 and 1971–72 in the coastal region.*

evaluated as the amount of annual ablation, because there are few snow covers throughout the year. From Fig. 9, the average mass of net annual ablation in the coastal area below the firn line which is lost out to the sea from the continent is 34 g/cm$^2$ in 1970–71 and 22 g/cm$^2$ in 1971–72 in rough estimation.

### *3.3. Seasonal variation of snow accumulation*

Stake measurements were made along the route (S16—S30—Route H—Route Z—Mizuho Camp) in different seasons in 1973 and 1974, during which logistical reasons caused the measurements to be made in periods that were not the same in the two years. In Fig. 10, five curves delineate the values of accumulation, which are moving averages over ten values measured in different periods in 1974. The distribution of accumulation differs largely in each period. The value of accumulation in summer months from October to February was negative for almost all the areas observed. Fig. 11 shows the seasonal variation of the rate of accumulation (cm/day) which was obtained in 1973 (solid line) and 1974 (broken line) averaging over the area from S30 to Mizuho Camp. The data obtained in the coastal melting area from S16 to S30 is omitted because of snow melting in the summer months. As seen in Figs. 10 and 11, the accumulation of snow primarily occurred in the period from February to September, and the ablation in the summer season from November to January. As seen in Fig. 11, the increment in the rate of accumulation seems to occur around the autumnal (April) and the vernal (September) equinox rather than during the winter season. This tendency is also supported by the data obtained by seven 36-stake networks

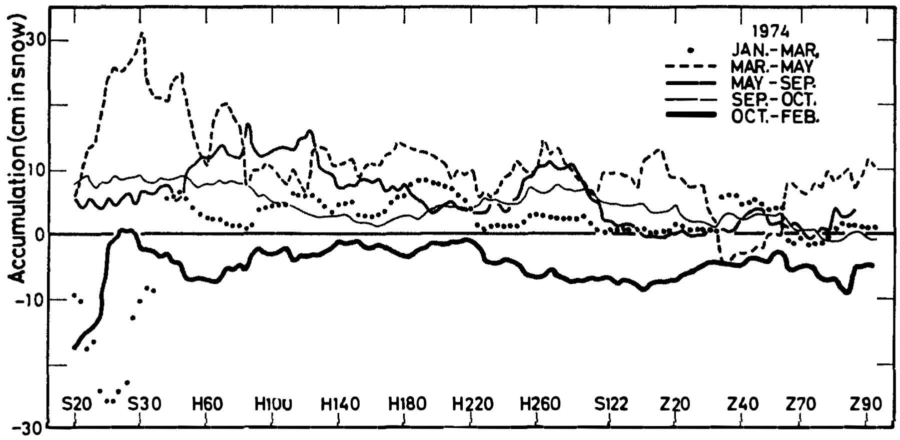



*Fig. 10. Accumulation along Routes S, H and Z in 5 subdivisional periods of 1974.*

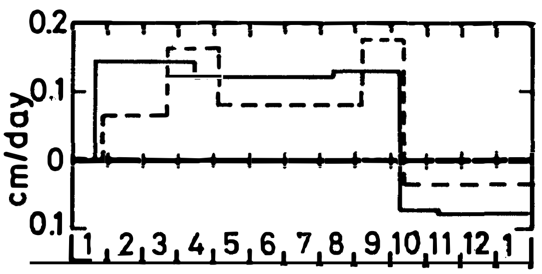



*Fig. 11. Monthly variations of area-mean accumulation rate in 5 subdivisional periods in 1973 (solid line), as shown in Fig. 10 and in 1974 (dashed line).*

and three 200-stake networks installed in the area between S16 and Mizuho Camp, each with a limited area of 100×100 m (YAMADA *et al.*, 1975; YOKOYAMA, 1975; SATOW, 1977). This maximum of accumulation rate agrees with the extreme minimum of atmospheric pressure at Syowa Station, which also occurs around both the autumnal and the vernal equinox. This agreement suggests that the seasonal variation of accumulation results from the seasonal variation of the activity of synoptic disturbance between the sea and the continent (INOUE *et al.*, 1978).

### *3.4. Annual variation of snow accumulation*

Table 2 shows the area mean annual accumulation in the areas which indicate characteristic modes of accumulation for the years when the measurements were made for more than two years. The second column in Table 2 shows the area-mean annual accumulation of snow in the area between S30 (988 m a.s.l.) and S100 (1680 m.a.s.l.) for seven years from 1968 to 1974. For other areas indicated in other columns in the table, the measurements of snow accumulation were not made continuously during the seven years. The area between S30 and

*Table 2. Area-mean annual accumulation of snow.*

| Route | S30–S100 | Route H | S101–S169 | Route Z | S170–S240 |
|---|---|---|---|---|---|
| Elevation (m) | 988–1680 | 988–1910 | 1681–2083 | 1910–2230 | 2082–2639 |
| Distance (km) | 142 | 150 | 136 | 90 | 142 |
| 1968 | 42.0 | | 12.4 | | 13.6 |
| 1969 | 26.0 | | 9.5 | | 10.7 |
| 1970 | 65.9 | | 26.5 | | |
| 1971 | 47.5 | | | | |
| 1972 | 53.1 | | | 28.2 | |
| 1973 | 42.1 | 22.9 | | 5.3 | |
| 1974 | 40.3 | 26.6 | | 4.6 | |
| Mean | 45.3 | 27.2* | 16.4* | 12.7* | 16.2* |

*: 7-year mean value estimated on the assumption that the annual variation of accumulation in the areas along Route H, S101–S169, along Route Z and S170–240 shows the same tendency as that in the area S30–S100.

S100 had the large area-mean annual accumulation in the area observed in Mizuho Plateau. As seen in the first column, the annual accumulation varied from 26.0 to 65.9 cm, which ranges about ±45% of the seven years' average value of 45.3 cm. The maximum annual accumulation during these seven years was observed in 1970, which was approximately 2.5 times larger than the minimum which took place in 1969. In Table 2, as the value in the area between S30 and S100 shown in the second column is compared with those in the areas between S101 and S169, along Route Z and between S170 and S240 shown from the fourth to sixth columns, one can recognize the positive correlation between them. That is, as for the values of area-mean annual accumulation, those observed in the inland above the elevation of S100 (1680 m) are large/small correspondingly at those observed in the coastward areas below this elevation are large/small. The seven years' average values of area-mean annual accumulation in each area are also shown in Table 2. The seven years' average values shown from the third to sixth columns are estimated on the assumption that the annual variation of accumulation in the areas along Route H, from S101 to S169, along Route Z and from S170 to S240 shows the same tendency as that in the area between S30 and S100.

## 4. Concluding Remarks

From the discussions concerning the rate of accumulation, hiatuses in accumulation and its areal fluctuation mentioned in the preceding sections, the series of data obtained along the traverse routes seem to differentiate Mizuho

Plateau into five divisions (one: ablation; four: accumulation). One of the four boundary lines is located at 400–500 m a.s.l., which divides Mizuho Plateau into an ablation area and an accumulation area. One of the remaining three boundaries for the four divisions in the accumulation area is located at 3400–3500 m a.s.l., which draws a line between the coastward region and the inland plateau region characterized respectively by a high fluctuation and a comparatively low fluctuation in accumulation of snow. The coastward region can be divided into the upper and the lower subregions at the boundary situated at 1700–1900 m a.s.l. in consideration of differences in the amount of annual accumulation and the hiatuses in accumulation. As for the lower limit of this lower subregion, there is a dry snow line below which snow melting takes place in summer, the elevation ranging from 700 m to 1000 m depending on the condition of an individual year.

According to the glacio-meteorological data obtained in Mizuho Plateau, East Antarctica, including 10-m snow temperatures (SATOW, 1978), oxygen isotope contents ($\delta^{18}$0) (KATO *et al.,* 1978) and stratigraphic data of the snow cover (WATANABE, 1978b), Mizuho Plateau is divided into three regions. The boundaries between these regions may be drawn at the elevations of about 1000 m and 3000–3200 m. One can recognize a disagreement between the boundary of 3000–3200 m in elevation derived from the glacio-meteorological data and the boundary of 3400–3500 m in elevation estimated from the regional characteristics in annual accumulation along the routes. The disagreement should be reexamined by making further observations in future.

The following conclusion may be drawn: The relatively large amount of accumulation obtained in the lower subregion between 700–1000 m and 1700–1900 m must be primarily attributable to the direct influence of the moisture carried by a cyclonic disturbance passing eastward along the seacoast near Syowa Station. As for the inland plateau region above 3400–3500 m, the accumulation of snow may be produced mainly by the moisture conveyed by a large-scale air circulation which comes up from the sea to the continent, because the disturbance originated by cyclones may scarcely reach the inland plateau region; after the release of moisture in this region, the air mass blows down from the inner continent to the sea as the katabatic wind. In the upper subregion between 1700–1900 m and 3400–3500 m, the direct influence of the cyclonic disturbance decreases and the influence of the water vapour transported by a large-scale air circulation increases, as the elevation increases.

## Acknowledgments

The authors would like to express their gratitude to Prof. D. KUROIWA and Prof. G. WAKAHAMA of the Institute of Low Temperature Science, Hokkaido

University, and to Prof. K. HIGUCHI, Water Research Institute, Nagoya University, for offering useful criticism.

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(*Received June 3, 1977*)