THE REGIONAL DISTRIBUTION OF SURFACE MASS BALANCE IN MIZUHO PLATEAU, ANTARCTICA*

Tomomi YAMADA and Gorow WAKAHAMA

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

Abstract: Mizuho Plateau is classified into an ablation zone and three different accumulation zones from the regional distribution of thickness of the annual layer accumulated snow measured during ten years beginning in 1968 using the snow stake method, and from the locations of the ablation area provided by images of ERTS satellite. A snow stake along a traverse route gave the thickness of the annual layer at a given place in a given year; the thickness there in another year in which measurements were not made was obtained by extrapolation, using a value of annual variation in areal average in each of the zones; then, the thickness was averaged over the ten years. In addition, stratigraphic data provided thicknesses and the density profile of the surface layers at a given place. Consequently, contours indicating the surface mass balance averaged over the ten years were obtained and delineated on the topographical map of Mizuho Plateau. It was then derived from the contour map that the total mass inputs in the Shirase and the Sôya drainage basin are respectively 15.5 and 1.2 Gt/yr. Moreover, from the result of discussions of the general role concerning the characteristics of the distribution of the mass balance related to the topography, the emergence/submergence flow of the ice sheet and the action of katabatic winds, it is suggested that the positive and the negative balance take place on the surface of the ice sheet in such a direction that the unilateral changes due to the perturbation deposition of solid precipitation and the vertical flow of the ice sheet cancel out, resulting in the maintenance of the morphological features of the ice sheet.

1. Introduction

A study was made of the regional distribution of the surface mass balance on Mizuho Plateau for the ten years from 1968 to 1977, mainly by measuring the thickness of the annual layer, and partly obtaining a density profile of the surface snow layers along oversnow traverse routes and by using images of bare ice areas provided by ERTS satellite. The data thus obtained lead to the contours of the surface mass balance, which are delineated on the topographical map of Mizuho Plateau. The mass inputs in the Shirase and the Sôya drainage basin are estimated from the contour map, whereby a discussion is given of the general role concerning the charac-

* Contribution No. 2362 from the Institute of Low Temperature Science, Hokkaido University.

teristics of the regional distribution of surface mass balance on this plateau.

2. Observational Data

Traverse routes investigated during the ten years from 1968 to 1977 are shown by thick solid lines in Fig. 1. Snow stakes were set up at intervals of 2 km along Routes S, H, Z and X, and intervals of 1 to 4 km along Route A. The snow stake measurements were made along each route in the years shown in Table 1. Only the

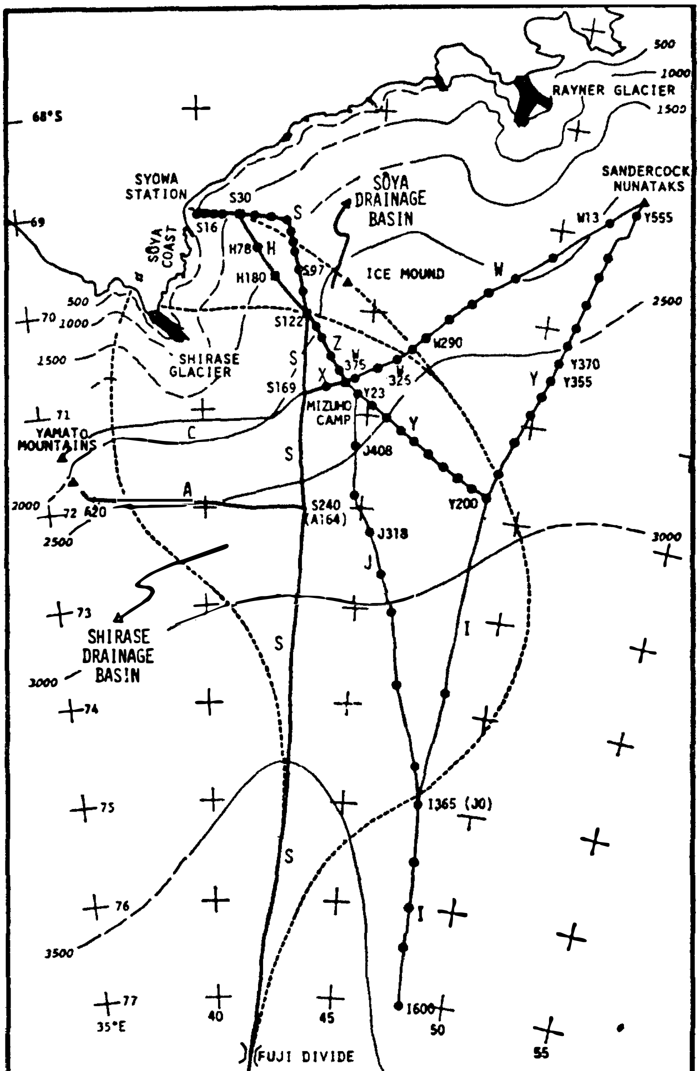

Fig. 1. Traverse routes and boundaries of the Shirase and the Sôya drainage basin on a topographical map of the Mizuho Plateau.

Table 1. Years of survey in each route.

Route	Altitude (m a. s. l.)	Observation year										
		1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978
Route S												
S16–S122	(554–1910)	|—	-|—	-|—	—|—	—|—	—|—	-|—	-|			
S122–S169	(1910–2035)	|—	-|—	-|—	-|							
S169–S240	(2035–2606)	|—	-|—	-|—	—	—	—	-|				
S240–P.S.*1	(2606–3624)	|—	-|									
Route H (S30–S122)	(988–1910)						|—	-|—	-|—	-|—	-|—	-|
Route Z (S122–M.S.*2)	(1910–2230)					|—	-|—	—|—	—|—	-|—	-|—	-|
Route X (M.S.–S169)	(2230–2035)				|—	—	—	-|				
Route A (Y.M.*3–S240)	(2254–2606)			|—	—	—	—	-|			
		*4	*5		*6		*7	*8	*9		*10	

*1 Plateau Station (U.S.A.).
*2 Mizuho Station (Japan).
*3 Yamato Mountains.
*4 FUJIWARA and ENDO, 1971.
*5 AGETA and WATANABE, 1972.
*6 YAMADA *et al.*, 1975.
*7 YOKOYAMA, 1975.
*8 SATOW, 1977.
*9 NISHIO, 1978.
*10 FUJII, 1979.

measurement carried out along Route S in 1968 covered the inland plateau above 2600 m a.s.l. The budget year of surface mass balance was taken to start and end in summer, generally in January. The mass balance is not thought to be affected much by a variation of a month or two in the length of a "year", because the austral summer is a season of no layer formation in the present study area (WATANABE, 1978a).

In addition to the stake measurements, the thicknesses of several annual layers at a given place were investigated by WATANABE (1972, 1977, 1978a) in terms of a number of stratigraphic observations, using walls of pits 1 to 2 m deep, and cores 2 and 10 m deep along the routes, as indicated by solid circles on Routes S, H, Z, Y, W, I and J in Fig. 1.

Judging from the density measurements of surface snow layers made by ENDO and FUJIWARA (1973), WATANABE (1975) and NARUSE (1975a, b) in the area from 500 to 3000 m a.s.l., the average density is 0.43 ± 0.05 g cm^{-3}, which is fairly constant regardless of altitude, whereas the average density in the inland plateau above 3000 m a.s.l. decreases to 0.35 ± 0.03 g cm^{-3}.

3. Procedure for Obtaining a Contour Map of the Mass Balance

Snow stake measurements were not simultaneously conducted along all the routes; *i.e.*, the site and the route surveyed varied with the year, as shown in Table 1. Moreover, the distribution of the routes was not uniform in areal density on

Mizuho Plateau, as seen in Fig. 1. A map showing contours of the mass balance averaged over the ten years 1968–1977 has been prepared, using data which are not necessarily uniform in time and area. To make a mass balance map, the following procedures were employed: First of all, Mizuho Plateau was differentiated into several accumulation zones based on the characteristics of areal variability in the thickness of the annual layer. Then, the annual variation in the area-mean thickness of the annual layer in an individual zone was obtained for the ten years from 1968 to 1977. For clarifying whether or not the trend of the regional distribution of mass balance was similar every year, the distribution was obtained for each year along the routes by adopting running averages over ten values (ten sites) of the stake data with a wide fluctuation in thickness from site to site. Finally, from the annual variations and the trend of the regional distribution of thickness of the annual layer along the routes, the distribution of the ten-year mean thickness was derived, from which the trend of the surface mass balance *versus* altitude or continentality is evaluated along each route. As for the regions with no data, the mass balances are estimated by either interpolation or extrapolation by considering the altitude or continentality of a given region, as well as by determining the locations of the ablation areas.

4. Zoning of Mizuho Plateau

The terrain observed along the routes is divided into an ablation zone below 400–500 m a.s.l. and an accumulation zone above this altitude. The coastal area below 700–1000 m a.s.l. is characterized by the occurrence of summer melting. Consequently, it is reasonable to draw the firn line and the dry snow line at 400–500 and 700–1000 m a.s.l. respectively (YAMADA *et al.,* 1978; WATANABE, 1978b). As special cases, there are two other ablation areas, one consisting of bare ice in the vicinity of the Yamato Mountains and the other in the Ice Mound located at some 100 km northward from Mizuho Station. The surface snow of the Ice Mound consists of firn with a high density greater than 0.7 g cm^{-3}, which implies the absence of successive formation of surface layers.

The general trend in the distribution of thickness of the annual layer in the accumulation zone above 400–500 m a.s.l. was demonstrated in Fig. 2 by the stake data along Route S obtained in 1968 as an example of abundant stake data along the routes. The thickness of the annual layer at each stake site is illustrated in Fig. 2a; the moving averages of ten values, M, and the coefficient of variation defined by S/M, in which S is the standard deviation of the ten values, are presented in Fig. 2b. The large and the small value of S/M imply that the variation in thickness is respectively large and small compared to the mean value over ten stake sites. It is shown in Fig. 2 that there are three characteristic modes in the distribution of thickness of the annual layer along Route S.

In the accumulation zone below 1700 m a.s.l., S/M is relatively small and al-

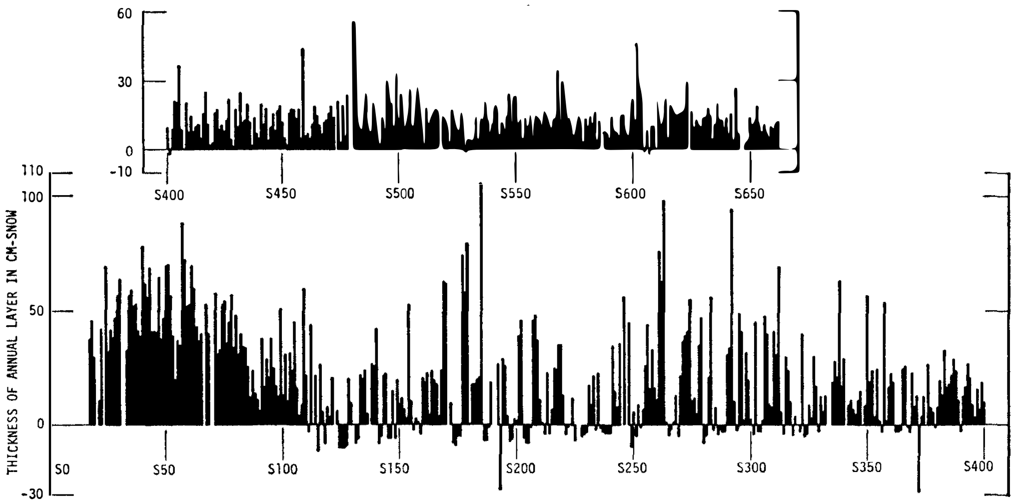

Fig. 2a. Thickness of the annual layer at each stake site along Route S.

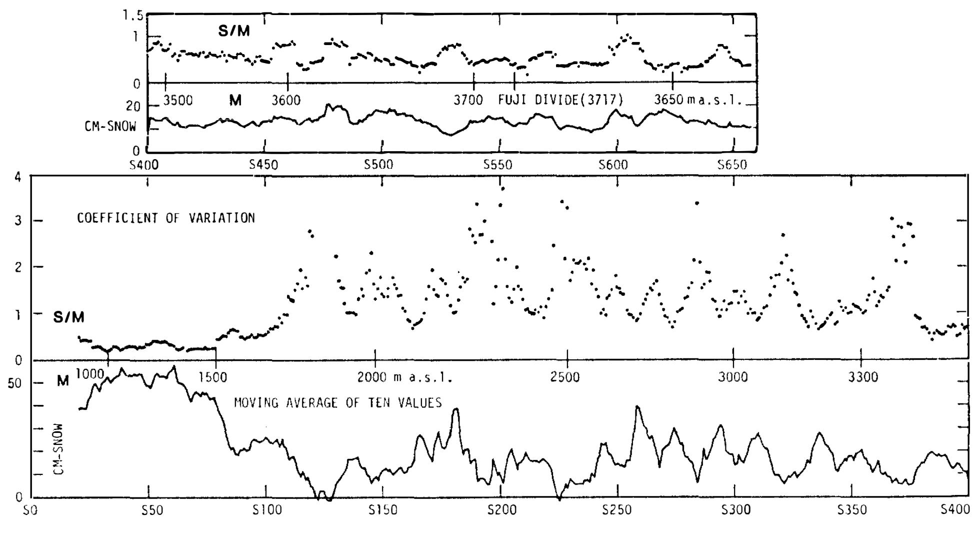

Fig. 2b. Running averages of thickness over ten stake sites, M, and coefficient of variation, M/S where S is the standard deviation of the ten values.

most all the stake data indicate the occurrence of a positive and comparatively thick deposition of snow; that is, the annual layer covers all the snow surface without gaps. Thus the area shall be called a "continuous accumulation zone", since one can find the formation of a horizontally continuous annual layer over this area.

As for the area above this zone up to 3350 m a.s.l., the thickness of the annual layer relatively decreases and shows alternately negative and positive values at stake sites along the route, which results in greater values of S/M as seen in Fig. 2b; the annual layer is deposited in a patch-like pattern and may not cover the entire surface of this area during one or several years; therefore, the area is designated as a "sporadic accumulation zone" because of the sporadic formation of an annual layer.

The farther inland area above the sporadic accumulation zone (above 3350 m a.s.l.) is featured by less fluctuation and a farther decrease but not a negative value in the thickness of the annual layer; the values of S/W decrease again and an annual layer covers the entire surface of this area similarly to the continuous accumulation zone; hence the area is named a "calm accumulation zone" because the deposition-erosion process (defined by WATANABE, 1978b) is not active, *i.e.,* relatively calm, resulting in a small areal fluctuation in the thickness of the annual layer as against a tiny area-mean thickness of it.

From the trends of distribution and areal variability in the thickness of the annual layer measured along the other Routes H, Z, X and A in various years, it is detected that these other routes are located in the continuous accumulation zone and/or the sporadic accumulation zone, although the altitudes of the boundary between two zones shift a few hundred meters up or down, namely, in the range of 1600 to 2200 m a.s.l., depending on the topography along the routes and the observation year. As for the calm accumulation zone, the data were only obtained in a single year, 1968. For confirming that above facts are a special case in 1968 or not, successive investigations must be continued in the calm accumulation zone.

As a result, Mizuho Plateau can be divided into a coastal ablation zone below 400–500 m a.s.l. and three accumulation zones (continuous, sporadic and calm) above that altitude as summarized in Fig. 3. This zoning of the accumulation zone obtained from the viewpoint of accumulation phenomena agrees fairly well with the zoning derived from the other viewpoints such as surface conditions and wind systems on the Mizuho Plateau (WATANABE, 1978b). In addition to the coastal ablation zone, two ablation areas are found in the vicinity of the Yamato Mountains and in the Ice Mound to the north of Mizuho Station, as will be discussed later.

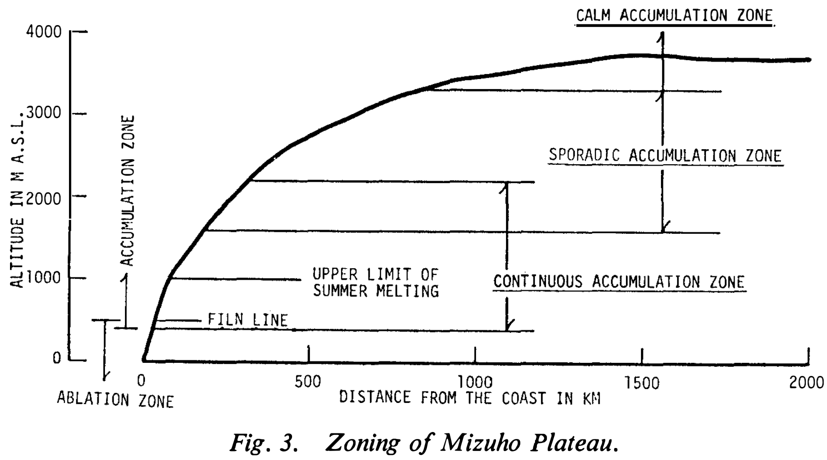

Fig. 3. Zoning of Mizuho Plateau.

5. Annual Variation in Thickness of the Annual Layer

From the stake data obtained along Routes S, H and Z over many years, as shown in Table 1, it is confirmed that two areas from S30 to S100 (Route S) and from S30 to H264 (Route H) belong to the continuous accumulation zone every year, as well as one area from Z6 to Z100 (Route Z) in the sporadic accumulation zone. These areas are respectively named Areas 1, 2 (the continuous accumulation zone) and 3 (the sporadic accumulation zone) for convenience in this section.

For clarifying the annual variation in thickness of the annual layer in each zone, the area-mean thickness was computed for each year as shown in Fig. 4. The years 1973 and 1974 are common years when the stake measurements were made in Areas 1 and 2 belonging to the same continuous accumulation zone. In a comparison of the area-mean thickness between the two areas in each of two years, the thickness in Area 1 is recognized to be about 1.6 times larger than that in Area 2 (1.7 times in 1973 and 1.5 times in 1974). Although the multiplier is derived from only two years data, if we assume that the multiplier is applicable to other years, the area-mean thickness is obtainable for any year lacking data in one area, should the value be known for the same year in the other area.

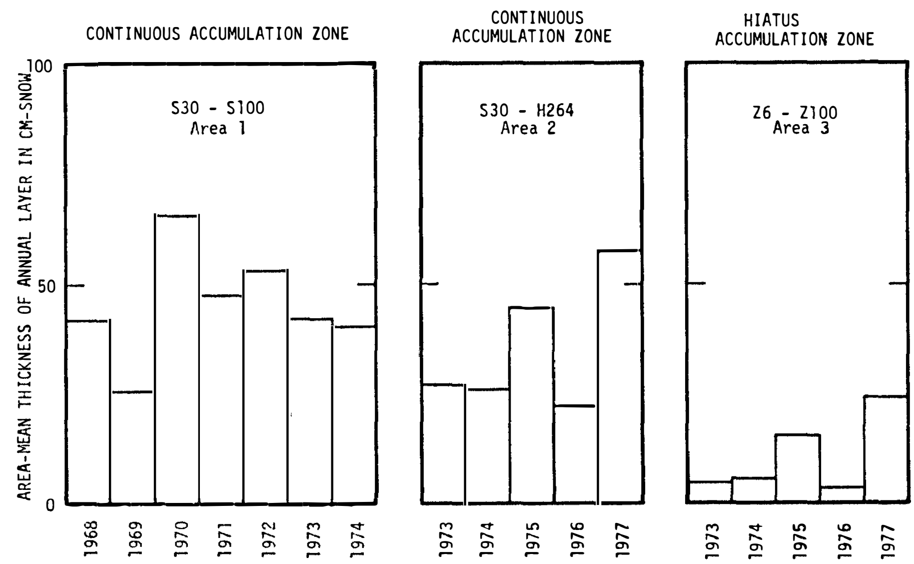

Fig. 4. Annual variation in area-mean thickness of the annual layer in the continuous accumulation zone (S30–S100 and S30–H264) and in the sporadic accumulation zone (Z6–Z100).

In the meantime, it is found that the area-mean thickness in Area 3 (sporadic accumulation zone) increases in proportion to the second power of that in Area 2 (continuous accumulation zone) as shown in Fig. 5. Using this relation, area-mean

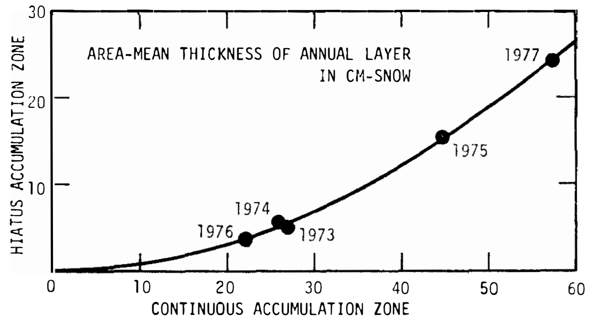

Fig. 5. Relationship of area-mean thickness of the annual layer between the continuous accumulation zone (S30–H264) and the sporadic accumulation zone (Z6–Z100).

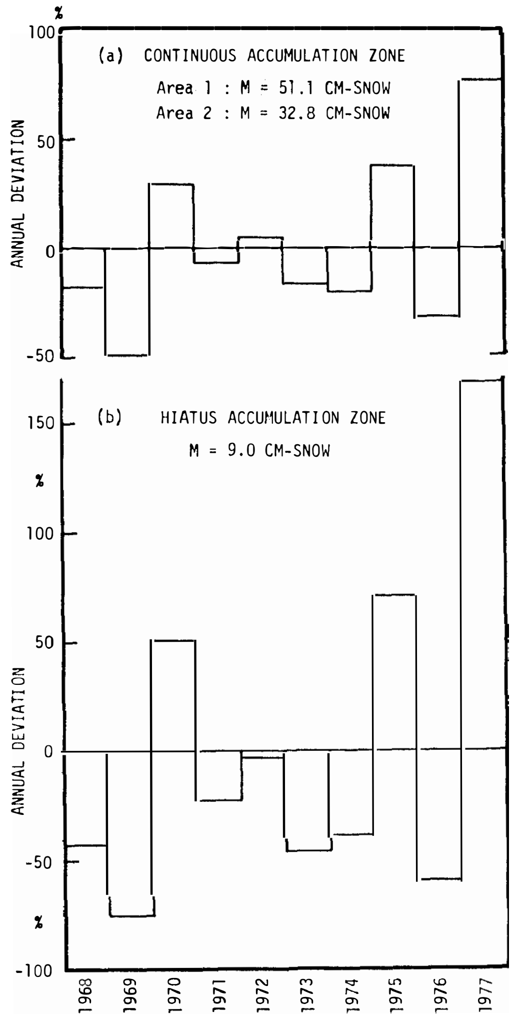

Fig. 6. Deviation from ten-year mean thickness of the annual layer in the continuous accumulation zone(a) and in the sporadic accumulation zone(b).

thickness in Area 3 can be estimated each year from values in Area 2, some of which are derived from values in Area 1 as mentioned above.

Thus, we obtained area-mean values during the ten years from 1968 to 1977. The annual deviations are shown in Fig. 6a and b respectively corresponding to Areas 1 or 2 (continuous accumulation zone) and 3 (sporadic accumulation zone). It is seen from the figure that the annual deviation changes harmonically between the continuous and the sporadic accumulation zone. The degree of variation in the latter is approximately two times of that in the former, and 1972 is close to the average because of smallest deviation.

The stake data obtained in 1968 along Route S are the only available data covering the area from the coast to the inland plateau as previously stated. They deviate about 20% less in the continuous accumulation zone and about 40% less in the sporadic accumulation zone in comparison with the ten-year mean value as shown in Fig. 6. The ten-year mean value in the calm accumulation zone was derived as a first approximation on the assumption that the deviation in 1968 in this zone is coincidental with that in the sporadic accumulation zone.

6. Distribution of Surface Mass Balance on Mizuho Plateau

In the previous sections, the discussions were based on the thickness of annual layers. In this section, the surface mass balance is introduced by converting the thickness into a water equivalent, using density data as discribed in Section 2.

An attempt was made to roughly estimate contour lines of the ten-year mean surface mass balance on Mizuho Plateau from the characteristics of the regional distribution and the annual variation of balance obtained in previous sections by the use of snow stake data along the routes, as well as the data of the thickness of annual layers at given sites along Routes W, Y, I and J derived by stratigraphic observations (WATANABE, 1978a), where stake data are not available.

The negative balance in the coastal ablation zone decreases rapidly with altitude, the mean value being estimated to be some $-30\,\mathrm{g\,cm^{-2}}$ from the results of investigations in 1970 and 1971 (YAMADA *et al.*, 1978). As for the ablation area near the Yamato Mountains, the ablation rate is approximately $-6\,\mathrm{g\,cm^{-2}a^{-1}}$ (YOKOYAMA, 1975); the negative balance in the remaining ablation area of the Ice Mound is also regarded to be almost equal to this value, though there are no observation data.

A tentative map of the ten-year mean balance is given in Fig. 7 with a contour interval of $5\,\mathrm{g\,cm^{-2}a^{-1}}$, only the positive sign of the balance being given to avoid complicating the figure. In practice, the contour lines are determined from synthetic estimations consistent with the locations of ablation areas and the trend of the amount of mass balance with the topography, altitude and distance from the coast, which are found from the actual data obtained along the many routes surveyed. The relatively uncertain lines are shown by dotted lines in the figure.

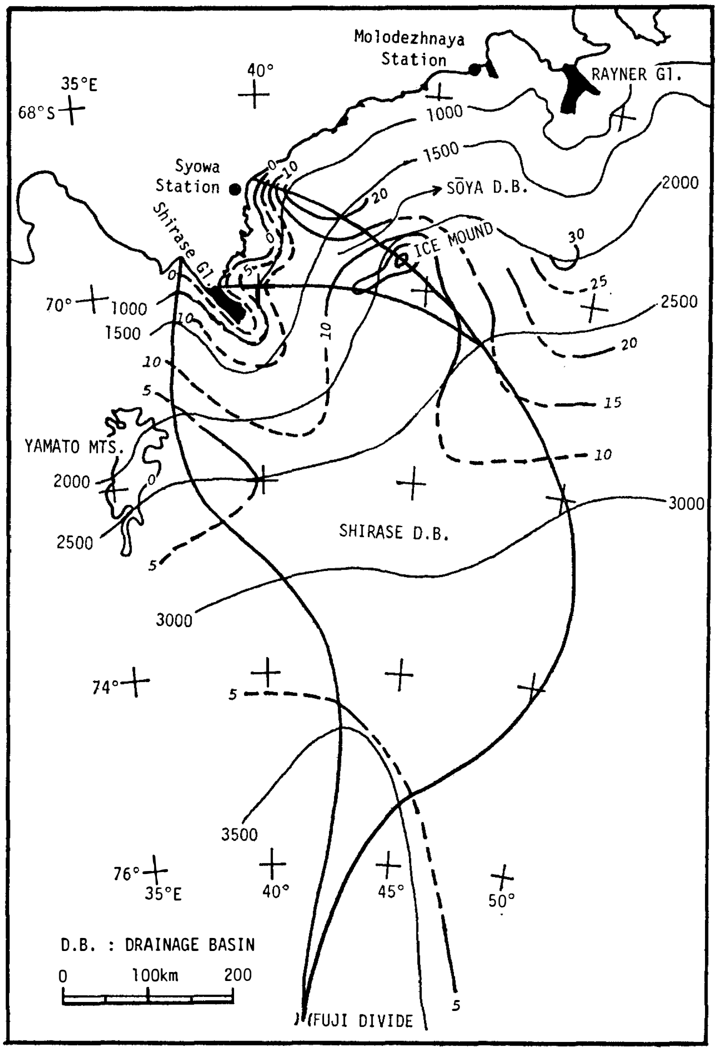

Fig. 7. Tentative map of ten-year mean surface mass balance ($g\,cm^{-2}\,a^{-1}$) *on Mizuho Plateau.*

Computations of the ten-year mean balance were done on the basis of the several assumptions as discussed in Section 5; moreover, the contour lines are drawn by means of extrapolating data obtained in a limited area over the whole area of Mizuho Plateau. Therefore, the map is considered to show one of the possible distributions of balance in Mizuho Plateau as of 1981. Successive measurements of surface mass balance will modify the map in more detail and with more precision.

On the basis of the tentative map given in Fig. 7, the mass input is estimated in the Shirase and the Sôya drainage basin, having the areas of 200 and 22×10^3 km^2 respectively (SHIMIZU *et al.*, 1978). As shown in Table 2, the estimated mass inputs in the former and the latter are 15.5 and 1.2 Gta^{-1}, corresponding to the area-mean

Table 2. Estimated mass inputs (Gta^{-1}) in the Shirase and the Sôya drainage basin.

	Shirase	Sôya
Accumulation area	16.2	2.0
Ablation area	−0.7	−0.8
Mass input	15.5	1.2

annual mass balances of 7.8 and 5.5 $g\,cm^{-2}a^{-1}$, respectively. The result of a comparison of the mass inputs shown in Table 2 with those previously obtained using another method by YAMADA and WATANABE (1978) shows that the mass inputs newly estimated are greater for the Shirase drainage basin and smaller for the Sôya drainage basin than the values previously estimated. The mass inputs in the Shirase and the Sôya drainage basin of 15.5 and 1.2 Gta^{-1} are in fairly good agreement with the 14 and 1.5 Gta^{-1} for mass discharge obtained by FUJII (1981) and NAKAWO (1978), respectively, in a range of errors in both estimations of input and discharge.

7. Discussion

An annual surface mass balance means water equivalent of a newly formed snow layer during a year. Solid precipitation reaching over the ice sheet is removed leeward as blowing snow by strong and stationary katabatic winds, and finally destined to be deposited on the surface of the ice sheet as a newly formed snow layer after repeating processes of deposition and erosion (OKUHIRA and NARITA, 1978; WATANABE, 1978b). Thus, the original distribution of solid precipitation is changed into the actual distribution of the surface mass balance.

As mentioned in Section 5, the annual deviation in area-mean thickness changes harmonically between the continuous and the sporadic accumulation zone as seen in Fig. 6. If blowing snow disturbs the original distribution of solid precipitation completely, this phenomenon is difficult to explain. That is, blowing snow may not have enough ability to change, as a whole, the original distribution of solid precipitation into a completely different distribution of balance. As a result, the area-mean mass balance is considered to be fairly equal to the original area-mean amount of solid precipitation. Then the map of the ten-year mean mass balance given in Fig. 7 can be considered to express the general trend of the distribution of solid precipitation, which decreases gradually with increasing altitude and continentality. This decrease may be due to a successive loss of moisture as solid precipitation as it travels inland from the coast. The same precipitation mechanism is likely to control annual variations of balance on a synoptical scale in the continuous and the sporadic accumulation zone because they are harmonical between two zones.

The area-mean thickness in the sporadic accumulation zone increases in proportion to the second power of that in the continuous accumulation zone, as seen in Fig. 5; so the former shows a greater increase in annual variation than the latter, as seen in Fig. 6. These facts mean that the rate of decrease of precipitation with the altitude and the continentality becomes small (or large) with increase (or decrease) of the total amount of moisture penetrating from the sea to the continent.

It is recognized from Fig. 7 that there are several deviations from the general trend in the distribution of the mass balance discussed above. For example, the mass balance deviates considerably to high values of 30 $g\,cm^{-2}a^{-1}$ in the valley-shaped area developed as a result of the flow of the Rayner Glacier (WATANABE, 1978a), the maximum balance of 20 $g\,cm^{-2}a^{-1}$ appearing on the north slope facing the sea in the coastal area (YAMADA *et al.*, 1978). These deviations suggest that the amount of moisture transported from the sea is remarkably controlled by the topography of the ice sheet.

Another appreciable deviation is noted in two ablation areas, one in the Yamato Mountains bare ice area and the other on the Ice Mound, both located in the sporadic accumulation zone where the surface does not melt at all. In the ablation area in the vicinity of the Yamato Mountains, as a result of the effect of damming up of the flow of the ice sheet due to the mountains, the emergence flow of 6 to 8 cm a^{-1} of ice (NARUSE, 1978) is comparable to the negative balance of approximately -6 $g\,cm^{-2}a^{-1}$ (YOKOYAMA, 1975), which is lost by sublimation from the surface of the bare ice; then the surface level is nearly in equilibrium. On the Ice Mound, as the formation of the annual snow layer cannot be found, emergence flow and negative balance may occur and the surface level may also be kept in equilibrium, as in the Yamato Mountains bare ice area. On the contrary, a submergence flow of about 70 cm a^{-1} was surveyed in the area east of 30°E along Route A (NARUSE, 1975a, b), where a relatively large positive balance was observed (YOKOYAMA, 1975), though not so much as to compensate the amount of the submergence flow.

As mentioned before, fallen snow is commonly transported as blowing snow due to the action of katabatic winds in the continuous and the sporadic accumulation zone. The rate of mass transportation by blowing snow is proportional to the third power of the wind speed (KOBAYASHI *et al.*, 1969). Therefore, snow is deposited mostly in the lee of rises and in depressions where the wind speed is relatively low, while a little or no deposition or erosion takes place windward and along the tops of rises where the wind speed is relatively high. A patch-like distribution of snow deposition changes the surface features of the ice sheet, which prepares a new base for successive deposition. Long-term repetition of this process results in the surface of the ice sheet being covered entirely with newly formed snow layers; thus, the ice sheet is maintained.

The conclusion reached from the observations of the positive or the negative mass balance as well as the flow of the ice sheet is that these factors work out and lead to such a direction as maintains the morphological feature of the ice sheet by cancelling out the changes developed unilaterally by the deviatory depositions of solid precipitation and the vertical flow of the ice sheet.

Acknowledgment

This work was supported financially in part as a cooperative research project with the National Institute of Polar Research.

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(*Received May 11, 1981*; *Revised manuscript received June 8, 1981*)