VARIABILITY OF SURFACE MASS BALANCE IN THE MIZUHO PLATEAU, ANTARCTICA

Kazuhide SATOW

Nagaoka College of Technology, 888, Nishi-katakai-machi, Nagaoka 940

Abstract: On the basis of the data of surface mass balance along the traverse routes in 1968–1983, mean and variation of the annual balance were obtained in the Mizuho Plateau, Antarctica. A year-to-year variation of the surface mass balance showed a general increase during the period of the measurement. The climatic effect and the effect of surface microrelief, such as sastrugi and dunes, on the mass balance variability were assessed. The former prevailed in a high accumulation zone of the coastal region, and the latter became larger inland.

1. Introduction

In order to get accurate information of surface mass balance on ice sheets, it is necessary to understand the variability of net snow accumulation so that snow core stratigraphy can be properly interpreted, and the limits of confidence can be placed on the annual surface mass balance values that are used in snow densification models or glacier flow models. The variability can be caused mainly by long- or short-time climatic changes and by the effects of surface relief such as sastrugi and dunes. One method to investigate these influences is to use the surface net accumulation data obtained from stake height measurements.

RUBIN and GIOVINETTO (1962) discussed snow accumulation in terms of meteorological factors and topographic influences in central West Antarctica. Besides, analyzing surface mass balance obtained from bamboo pole height measurements for nine years, WHILLANS (1978) reported that the local variability of surface mass balance near Byrd Station was due to the combined effects of drifts and sastrugi, and climatic changes.

The author presents the annual variation of surface mass balance in a high accumulation zone obtained by using the data of the Japanese Antarctic Research Expedition 1968 through 1983 which measured surface mass balance (by the stake method) along the oversnow traverse routes in the Mizuho Plateau. He also examines the variability mentioned above to evaluate the effects of climatic changes and surface relief.

The row of stakes placed at the intervals of about 2 km ran 260 km inland from the coast near Syowa Station to Mizuho Station. Figure 1 shows the traverse routes S, H and Z, and the position of 36-stake farms; Stations S16, H68, H180, S122, Z40 and Mizuho Station. In Fig. 2, which shows the snow density at the surface in 1976 (NISHIO, 1978a), the regional difference of the density cannot be seen. The uniform value is 377 kg m^{-3} and its standard deviation is 37 kg m^{-3}. Other reports (ENDO and FUJIWARA, 1973; YAMADA and WATANABE, 1978) noted also that the average den-

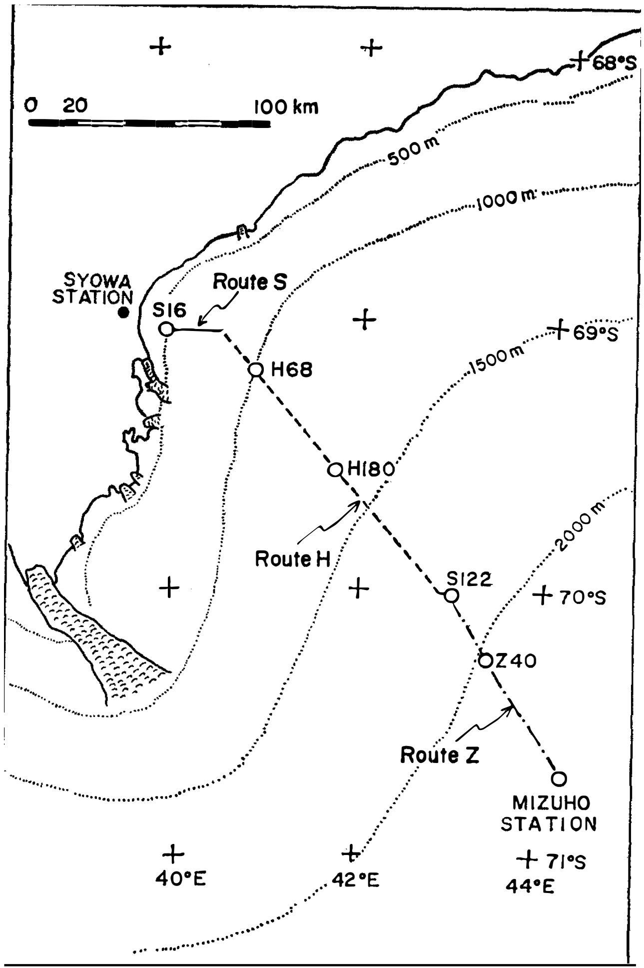

Fig. 1. Map of Mizuho Plateau showing the study area along traverse routes S, H and Z, leading to Mizuho Station. White circles denote the positions of 36-stake farms.

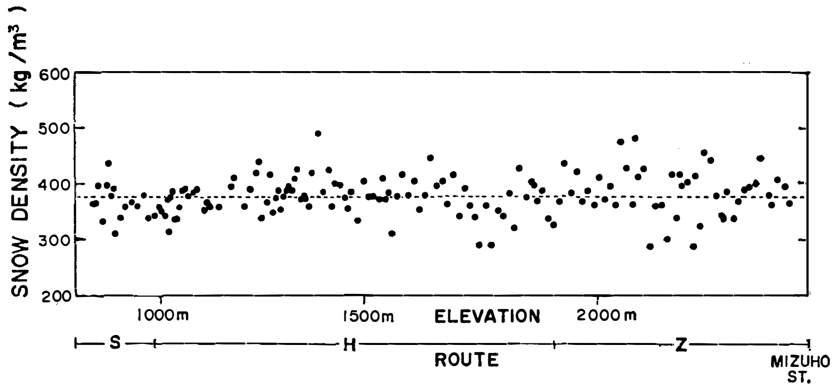

Fig. 2. Density (kg m^{-3}) of surface snow cover in April 1976 (NISHIO, 1978a) along Routes S, H and Z. A dotted line shows the mean density to be 377 kg m^{-3}.

sities from the surface to the depth of 1 to 2 m were fairly constant in this region. So, for convenience, in this paper, snow mass balance is expressed by snow depth in meters.

The data of stake measurements along traverse route S in 1968–1971 are quoted from the reports of FUJIWARA and ENDO (1971), AGETA and WATANABE (1972) and

YAMADA *et al.* (1975), and those along traverse routes S, H and Z in 1972–1983 are quoted from the reports of YAMADA *et al.* (1975), YOKOYAMA (1975), SATOW (1977), NISHIO (1978b), FUJII (1979), WADA *et al.* (1981), KOBAYASHI *et al.* (1982), SATOW *et al.* (1983), TAKAHASHI (1984) and NAKAWO *et al.* (1984).

2. Year-to-year Variations of Surface Mass Balance

Though there are many factors to form surface mass balance regimes, three probable factors are examined here. These are the long-term mean surface mass balance, the short-term climatic change (which is related to such factors as the storms or blizzard and the strength of katabatic winds affecting the region), and the local surface features (such as sastrugi, dunes and glazed surfaces) of the position where the stake is placed.

Therefore, the annual surface mass balance at any site can be expressed in the following equation:

$$M = {}^{t}\bar{M} + M_c + M_r, \quad (1)$$

where M is the annual surface mass balance, ${}^{t}\bar{M}$ is the time mean for the site, M_c is the variation due to the climate, and M_r is the variation due to the surface relief such as sastrugi and dunes. The annual surface mass balance in this study is the net accumulation for one year from January to the next January.

The annual mean mass balance ${}^{t}\bar{M}$ for a period from 1968 or 1972 to 1983 was obtained at 129 sites along the traverse routes (Fig. 3). The value of ${}^{t}\bar{M}$ is larger near in the coast area, and decreases farther inland. Judging from the annual mean mass balance, the region is divided into three areas, *i.e.*,

Area I (between 600 and 1300 m a.s.l.): the average of ${}^{t}\bar{M}$ is 0.52 m in snow depth,

Area II (between 1300 and 1900 m a.s.l.): the ${}^{t}\bar{M}$ is 0.30 m and

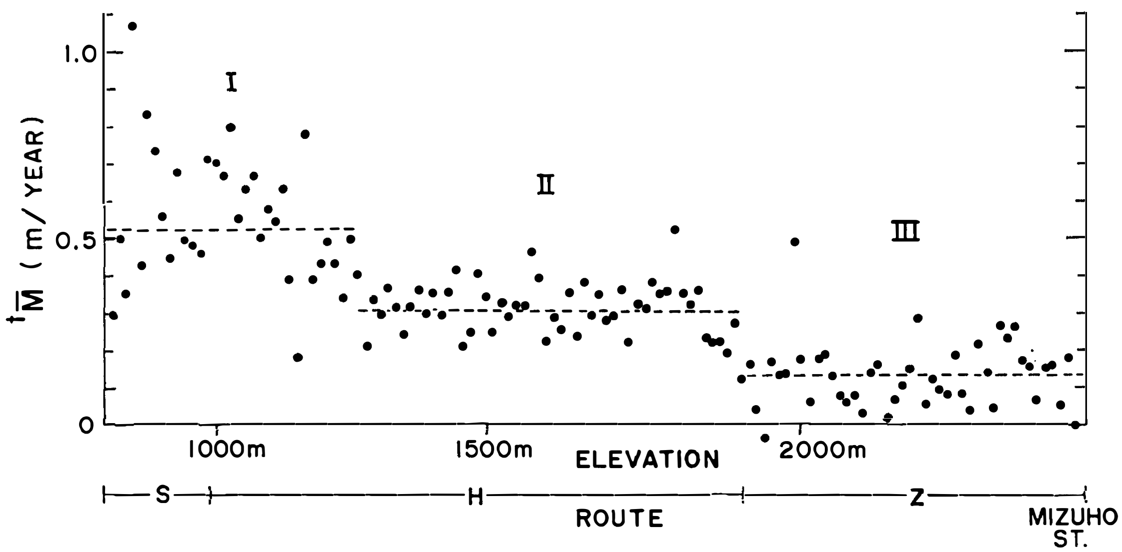

Fig. 3. Annual mean mass balance ${}^{t}\bar{M}$ (snow depth in meters) in 1968/1972–1983 along Routes S, H and Z in the Mizuho Plateau. Three horizontal dotted lines show the averages of ${}^{t}\bar{M}$ in Areas I, II and III, i.e. 0.52, 0.30 and 0.13 m/year, respectively.

Area III (between 1900 and 2230 m a.s.l.): the ${}^t\bar{M}$ is 0.13 m.
By multiplying these values by 377 kg m^{-3} (the uniform value), the water equivalent of the annual mean mass balance can be obtained. Areas I and II coincide with a high accumulation zone, and Area III with an irregular accumulation zone (WATANABE, 1978; YAMADA and WAKAHAMA, 1981; SATOW and WATANABE, 1984).

If the width of secular variations in surface mass balance, (M_c+M_r) in eq. (1), is given as ΔM;

$$\Delta M = M - {}^t\bar{M}.$$

The standard deviation S_M of the secular variation of the surface mass balance is given by

$$S_M = \sqrt{\frac{1}{N}\sum(\Delta M)^2},$$

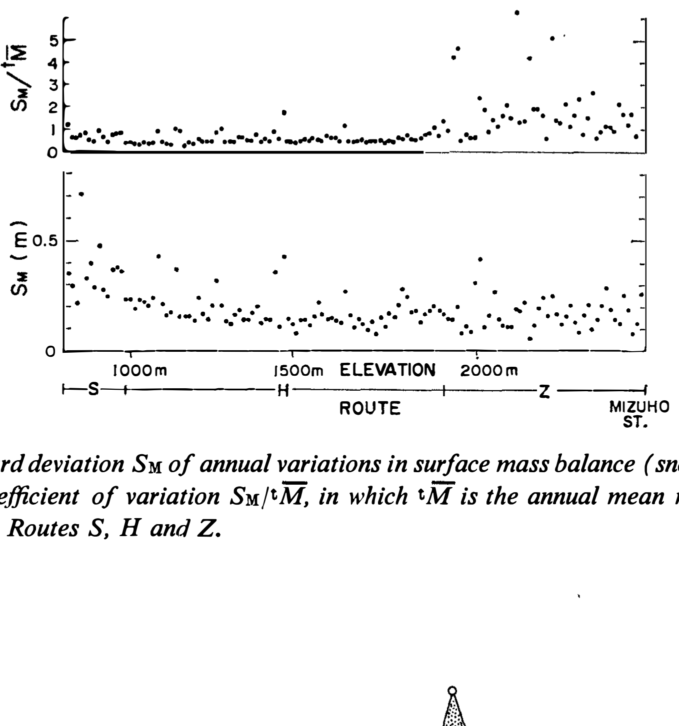

Fig. 4. The standard deviation S_M of annual variations in surface mass balance (snow depth in meters) and the coefficient of variation $S_M/{}^t\bar{M}$, in which ${}^t\bar{M}$ is the annual mean mass balance at the sites along Routes S, H and Z.

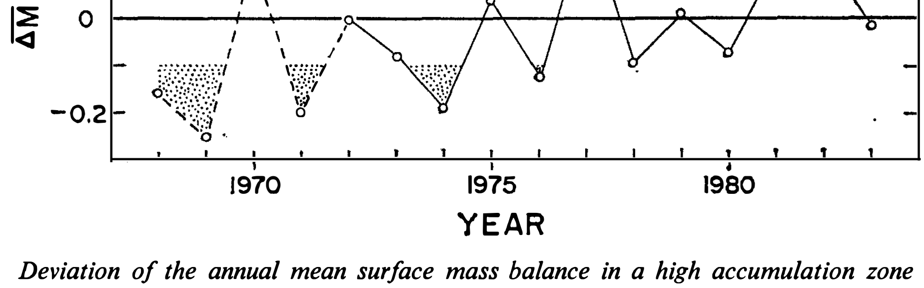

Fig. 5. Deviation of the annual mean surface mass balance in a high accumulation zone (Areas I and II) of the Mizuho Plateau. ΔM is the deviation of the annual mean surface mass balance at a site. $\overline{\Delta M}$ means the averages of the deviations ΔM at about 80 sites in Areas I and II (Routes S and H). The values in 1968–1971 are those along Route S only.

where $\sum$ signifies the summation over measurement years, and N is the number of years. The values of S_M at all stake sites are plotted along the routes in Fig. 4, and the coefficient of variation $S_M/{}^{t}\bar{M}$ is also shown. In Areas I and II (Routes S and H), ${}^{t}\bar{M}$ is larger and $S_M/{}^{t}\bar{M}$ is smaller, and in Area III (Route Z), conversely, ${}^{t}\bar{M}$ is smaller and $S_M/{}^{t}\bar{M}$ is larger. Therefore, it is likely that the value of the annual mass balance only at one site in Area III lacks the reliability as the representative value.

A tendency of secular variations in surface mass balance was thus obtained in Areas I and II for a period between 1968 or 1972 and 1983 (Fig. 5). $\overline{\Delta M}$ in Fig. 5 means the areal average of the deviation ΔM $(=M-{}^{t}\bar{M})$ at about 80 sites in Areas I and II. The values from 1968 to 1971 in Fig. 5 were obtained from the data along Route S only. Figure 5 shows that $\overline{\Delta M}$ values are higher in 1970, 1977, 1981 and 1982, and are lower in 1969, 1971, 1974 and 1976. And it can be seen that the annual mass balance generally has an increasing tendency in a high accumulation zone of the Mizuho Plateau.

3. Evaluation of the Effects on the Variations due to Climate M_c and due to Surface Relief M_r

3.1. Climatic change

It is not easy to strictly tell how M_c and M_r contribute respectively to the variation of surface mass balance. But, the variability due to the climate during the years 1968/1972–1983 can be assessed by taking the areal mean as follows:

$$
\begin{aligned}
&{}^{a}\bar{M} = {}^{t,a}\bar{M} + {}^{a}\overline{M_c}, \\
\therefore\ &{}^{a}\overline{M_c} = {}^{a}\bar{M} - {}^{t,a}\bar{M},
\end{aligned} \tag{2}
$$

where ${}^{a-}$ signifies the areal mean, *i.e.*, the mean of the data from the 15 consecutive sites at intervals of 2 km along the traverse routes. The middle of the 15 consecutive sites is located at the same site as the 36-stake farm, and the 100-stake row comprises

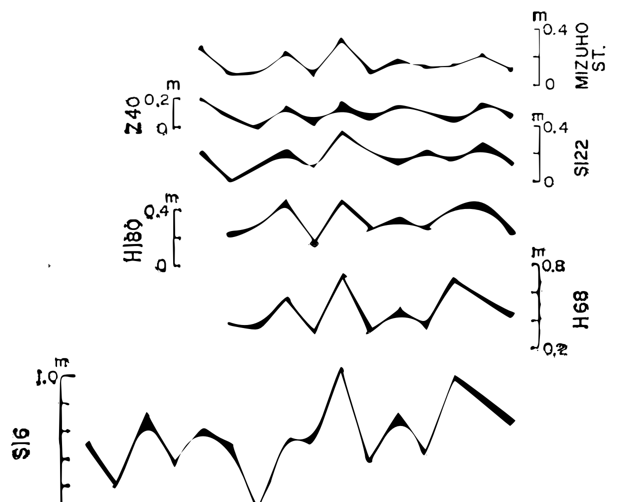

Fig. 6. Variation of areal mean ${}^{a}\bar{M}$ of the surface mass balance (snow depth in meters) in six regions S16, H68, H180, S122, Z40 and Mizuho Station.

S16, H68, H180, S122, Z40 and Mizuho Station. Figure 6 shows the secular variation of areal mean ${}^{a}\bar{M}$ of the annual surface mass balance in six places. S16 and H68 belong to Area I, H180 to Area II, and S122, Z40 and Mizuho Station belong to Area III. The variation features are very similar in all the areas. The variation due to sastrugi and dunes, M_r, does not appear in these equations (2) because this variability is due to the features having a horizontal extent of the order of a few tens of meters or less, which does not significantly affect the average of many stakes whose spacing is 2 km. The variance due to climate effects S_c^2 in any area is given by

$$S_c^2 = \frac{1}{N} \sum ({}^{a}\overline{M_c})^2 ,$$

where the summation $\sum$ is taken over years and N is the number of years. The standard deviations for climate effects S_c were thus calculated in six places (Table 2).

3.2. *Effect of surface relief*

The effect of surface relief can also be assessed in another manner. The surface of the ice sheet is usually rough and the relief has a horizontal scale of one meter to a few tens of meters. To estimate the effect, we can utilize the data of a 36-stake farm and a 100-stake row. The farms were installed at six places (see Fig. 1), in each of which 36 bamboo stakes in a square of side 100 m were arranged in a rectangular lattice with spacings of 20 m. Every stake farm was prepared in the same pattern in regard

Table 1. Assessment of surface relief effect on the annual mass balance.

Site	Stake farm (N)	Year	$\bar{M}$ ($\times 10^{-2}$ m)	S_r ($\times 10^{-2}$ m)	Average of S_r ($\times 10^{-2}$ m)
S16	36	1977	53.2	16.1	
	36	1981	59.8	9.2	12.7
H68	36	1977	46.4	12.1	
	36	1981	28.6	8.6	10.4
H180	36	1977	39.9	11.6	
	36	1981	39.3	6.8	9.2
S122	36	1977	35.2	15.9	
	36	1981	14.9	11.6	
	100	1973	4.8	11.6	
	100	1974	16.1	11.5	
	100	1975	15 9	21.2	
	100	1977	28.5	13.2	
	100	1981	11.3	14.5	14.2
Z40	36	1977	22.1	21.2	
	36	1981	5.2	9.0	15.1
Mizuho Station	100	1973	7.3	10.1	
	100	1974	0.9	8.2	
	100	1977	5.3	8.1	
	100	1979	12.2	11.9	
	100	1980	6.4	9.7	
	100	1981	8.6	13.9	
	100	1982	−1.8	7.2	
	100	1983	12.8	8.6	9.7

$\bar{M}$: Mean annual net accumulation measured with a stake farm (snow depth in meters) ($\therefore \bar{M} = {}^{t}\bar{M} + M_c$).

S_r: Its standard deviation (snow depth in meters).

to the prevailing wind direction. Another stake row of 100 bamboo stakes with 1 m spacing was set up at S122 and Mizuho Station, and every stake row was perpendicular to the direction of the prevailing wind.

Equation (1) can be used to describe the variations of the surface mass ba'ance due to the remaining effects of the surface relief:

$$M_r = M - ({}^t\bar{M} + M_c).$$

The standard deviation for relief effects S_r is thus given by

$$S_r = \sqrt{\frac{1}{N}\Sigma(M_r)^2},$$

where the summation Σ is taken over the stake sites and N is the number of stakes (36 or 100). The results at six sites are shown in Table 1. Though each measurement year was different, the averages of the standard deviation for relief S_r were obtained at the respective sites as shown in Table 1.

3.3. The regional difference between the effects of climatic change and surface relief on the mass balance variability

The results as calculated above are summarized in Table 2. Every region is taken as an area of about 30 km along traverse routes, as mentioned earlier, and the mean annual mass balance ${}^{t,a}\bar{M}$ and the standard deviation for climate effects S_c were obtained within the measurements period from 1968 or 1972 to 1983. And the standard deviation for the surface relief effect S_r was calculated using the measurement data of 36-stake farms and 100-stake rows. In region S16, for example, the annual surface mass balance M is generally to be examined as follows:

$M = 0.57\ ({}^{t,a}M) \pm 0.25\ (S_c) \pm 0.13\ (S_r)$ m (in snow depth). It can be said in Table 2 that

(S16) : $|S_c| > |S_r|$ $(S_c : S_r = 2:1)$
(H68 and H180) : $|S_c| \geqq |S_r|$
(S122, Z40 and Mizuho St.) : $|S_c| < |S_r|$.

If the contribution rate of M_c to the total variation of the surface mass balance can be defined as

Table 2. Regional difference between the effects of climatic change and surface relief on the mass balance variability (unit: m in snow depth).

Region		${}^{t,a}\bar{M}$ ($\times 10^{-2}$ m)	S_c ($\times 10^{-2}$ m)	S_r ($\times 10^{-2}$ m)
Area I	S16	56.8	25.4	12.7
	H68	47.5	13.2	10.4
Area II	H180	31.8	10.0	9.2
Area III	S122	17.3	8.6	14.2
	Z40	9.5	6.0	15.1
	Mizuho St.	15.3	7.8	9.7

${}^{t,a}\bar{M}$: Mean annual net accumulation in 1968/1972–1983.
S_c: Standard deviation of climatic effects for the same period.
S_r: Standard deviation of surface relief.

$$\frac{S_c^2}{S_c^2+S_r^2}\times 100\ (\%)\,,$$

this rate decreases from about 80% in the coast region to 10% in the inland. As to the order of ${}^{t,a}\bar{M}$ values,

(S16, H68 and H180) : ${}^{t,a}\bar{M}$ is two to five times as large as S_c or S_r,

(S122, Z40 and Mizuho St.): ${}^{t,a}\bar{M}$ is almost the same value with S_c or S_r.

On the basis of these results, when a mass balance variation due to the climate is discussed by a core analysis at only one site, it is important to consider the following: a core in a high accumulation zone has a larger possibility of reflecting the effect of the climate, while a core in the farther inland might show a considerable effect of the surface relief.

4. Conclusion

Through the analysis of annual net accumulation measured by means of the stake farms, stake rows and stakes at intervals of 2 km along the traverse routes in the Mizuho Plateau for the period from 1968 to 1983, the following is revealed:

(1) The mean annual surface mass balance was 0.52 m in snow depth in Area I (600–1300 m a.s.l.), 0.30 m in Area II (1300–1900 m a.s.l.), and 0.13 m in Area III (1900–2230 m a.s.l.).

(2) A year-to-year variation of the surface mass balance in Areas I and II of a high accumulation zone was obtained for the period from 1968 to 1983. The larger part of the variation in these areas was considered to be due to climatic changes, not to the effect of surface relief. The mass balance was higher in 1970, 1977, 1981 and 1982, and was lower in 1969, 1971, 1974 and 1976. The general trend of annual balance shows an increasing tendency during the period of this measurement.

(3) The climatic effect S_c and the surface microrelief effect S_r such as sastrugi and dunes on surface mass balance variability were assessed. And it was proved that S_c prevailed in a high accumulation zone of the coastal region, and the latter S_r became larger in an irregular accumulation zone inland.

WHILLANS (1978) estimated in this connection that S_c and S_r were about 20 kg m^{-2} near Byrd Station, where the annual surface mass balance was nearly 150 kg m^{-2}. Though S_c and S_r were same values near Byrd Station, the contribution rate of S_c to the total variation of surface mass balance in the Mizuho Plateau decreases from about 80% in the coastal region to 10% in the inland. It is thus necessary to pay close attention to a typical value or its secular variation of some information such as the climate from a core analysis at any site on the ice sheet, especially an inland core.

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