Sublimation and Condensation at the Ice Sheet Surface of Mizuho Station, Antarctica

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みずほ基地の氷床表面における昇華と凝結

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要旨: みずほ基地の氷床表面における昇華量と凝結量を，1977年2月から1978年1月の期間について，蒸発皿法・バルク公式・雪尺による3つの異なった方法を用いて推定した．これらの方法で求めた1977年～1978年の夏期間の日昇華量は，満足できる一致を示した．特に週平均昇華量はよく一致した．凝結は4月中旬から9月中旬の5ヵ月間卓越し，その他の7ヵ月間は昇華が卓越するという明りょうな季節変化が認められた．年間凝結量，昇華量はそれぞれ 0.19 g/cm², 4.92 g/cm² となり，昇華の卓越が著しい．日昇華量のピークは，日射量がピークを示した12月22日に，92 mg/cm² の値となった．これらの結果は，斜面下降風領域の夏期の昇華が，氷床表面の熱収支・質量収支に大きな役割を果していることを示唆している．

Abstract: Sublimation and condensation were estimated by three different methods, that is, atmometer, bulk formula and stake methods, at Mizuho Station from February 1977 to January 1978. The comparison of the three different methods of obtaining the sublimation rate in the summer of 1977–1978 showed a satisfactory agreement, especially in the weekly values. Condensation prevails in the period of five months from the middle of April to the middle of September and sublimation in the remainder seven months. The daily amount of sublimation showed its maximum, 92 mg/cm² on December 22 when the solar radiation was maximum. The annual amounts of sublimation and condensation are estimated to be 4.92 g/cm² and 0.19 g/cm² respectively. The present study implies that sublimation plays an important role in the heat and mass exchanges at the surface and in the metamorphism of surface texture.

1. Introduction

Some observations of sublimation from ice surface have been made near the coast of Antarctica (LOEWE, 1956, 1962; WELLER, 1968). However, little is known about the relative importance of the roles of sublimation and condensation at the surface in heat

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and mass exchanges and in the metamorphism of surface texture of snow on such a strong katabatic wind slope as Mizuho Plateau.

The attempt on the atmospheric water vapor measurements was made at Mizuho Station during the 1977–1978 summer by NISHIO (1978) with the Karl Fisher method and the Assmann ventilated psychrometer method The daily amount of sublimation estimated from the water vapor pressure obtained showed unsatisfactory agreement with that obtained by direct measurement with the snow-stake method.

The study on sublimation and condensation at the ice sheet surface was made at Mizuho Station, East Antarctica during the period from February 1977 to January 1978, as a part of research activities of the 18th Japanese Antarctic Research Expedition. The sublimation rates obtained using three different methods, that is, atmometer, bulk formula and stake methods, are compared with each other The purpose of the present study is to show the net balance caused by sublimation and condensation processes at the surface throughout the year and the extent of agreement among these three methods, before consideration is attemped on the relative importance of the roles played by sublimation and condensation in the heat and mass exchanges and in the metamorphism of surface snow texture.

2. The Period of Observation and Instrumentation

The present study was carried out from February 1977 to January 1978 at Mizuho Station (70°41′53″S, 44°19′54″E, 2230 m a s l.) which is located at about 260 km southeast of Syowa Station (Fig. 1). The observational period for each element concerned with the present study is summarized in Table 1. The micrometeorological observations were made at about 20 m windward from the observational hut of the Station. The 9-stake farm consisting of 1 m squares was established at about another 30 m windward from the micrometeorological observation field.

The atmometer used here is the glass laboratory dish of diameter about 9 cm and depth about 1.5 cm filled with frozen water Two or three atmometers were set flat in hollows made in glazed surface consisting of multilayered ice crust in the micrometeorological observation field The weight was measured to 0.01 g daily in the snow cave of the Station where the air temperature was 5 to 15°C higher than that outdoors Therefore, hoarfrost formed on the atmometer but it was wiped off before weighing. Whenever the ice surface in the atmometer lowered some mm from the rim of the laboratory dish, another ice-filled laboratory dish was used

Wind speeds were measured in a logarithmic profile (0 25, 0.5, 1, 2 and 4 m) above the surface "Makino-Oyosokki" 3-cup micrometeorological wind sensors which have low starting velocities (0 2 m/s) were used to measure wind speed. For every revolu-

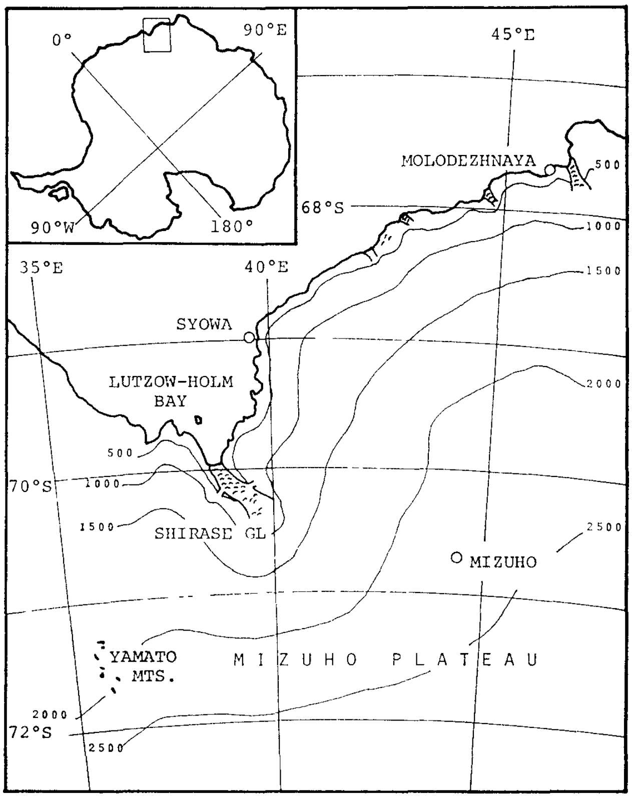

Fig. 1　Location of Mizuho Station

Table 1. Summary of observation items and the duration of observation related to the present study.

	'77 1	2	3	4	5	6	7	8	9	10	11	12	'78 1
Atmometer method							—	—	—	—	—	—	—
Bulk formula method													
Wind profile						—	—	—	—	—	—	—	—
Surface temperature	—	—	—	—	—	—	—	—	—	—	—	—	—
Air temperature	—	—	—	—	—	—	—	—	—	—	—	—	—
Frost temperature									- -	- -	- —	—	—
Stake method													
9-stake farm	—	—	—	—	—	—	—	—	—	—	—	—	—
Additional stake											—	—	—

tion of the anemometers, an electrical pulse was transmitted to digital counters located in the observational hut and the integrated numbers of revolutions were recorded every three hours from 03 LT (local standard time, GMT+3) to 24 LT except 06 LT. Simultaneously electronical second pulse was counted for the measurement of observation time.

Surface snow temperature was measured by using a thermistor installed at about 0.5 cm depth of the glazed surface in the micrometeorological observation field. The sensor was reset whenever deposition of snow newly occurred on it. The data are published in JARE Data Reports, No. 48 (Glaciology) (FUJII, 1979)

The air temperature was measured at the height of 2 m above the surface using the Agari-type mercury thermometer which was used in routine weather observation. The data are published in JARE Data Reports No 47 (Meteorology) (FUJII and KAWAGUCHI, 1978).

A small mirror with an electronical thermo-element (Peltier cooler) and an automatic optical control system was used as a detector of frost- (or dew-) point Coating of the mirror surface was made with silver iodide by vacuum evaporation, by which the supercooled water trouble was reduced and the temperature at which water vapor forms almost as frost was improved to be -7°C in most cases The inlet of air was set at the height of 2 m above the surface

The daily measurement of 9 stakes was made from January 25, 1977 to January 31, 1978 and the results are published in JARE Data Reports No. 48 (Glaciology) (FUJII, 1979). An additional stake was set on the glazed surface in early November 1977 since a considerable amount of snow covered the stable snow surface against wind erosion in the 9-stake farm during the period from the end of October to early November and these 9 stakes were not available for the measurement of sublimation rate.

3. Climatology and Weather Conditions

The monthly climatological conditions can be obtained from Table 2 The mean annual temperatures of air and snow surface are the same, -31.3°C, but the mean monthly air temperature is higher than the mean monthly snow surface temperature during the period from April to September when the mean monthly wind speed exceeds 10.0 m/s.

The monthly net accumulation was obtained from the measurements of 9 stakes,

Table 2. Monthly meteorological data at Mizuho

	1977 Feb.	Mar	Apr.	May	June	July
Atmospheric pressure (mb)	741.7	738.3	737.5	739.3	738.6	739 0
Air temperature (°C)	−25.7	−31.8	−39.0	−36.8	−36.7	−33.3
Surface temperature (°C)	−25.0	−31 3	−39.3	−37.7	−37.6	−34.2
Wind speed (m/s)	7.8	9.2	10.8	12 2	10 8	12.6
Net accumulation (cm water equivalent)	−0.2	+4.7	−4.2	+0.1	+0.2	+0.2
Number of days with snowfall	6	14	8	9	8	15

assuming the density of 0.40 g/cm^3. The negative value indicates ablation caused by both sublimation and erosion and the positive value accumulation.

4. Results of Sublimation/Condensation Measurements

4.1. Results of atmometer method

Two or three glass laboratory dishes filled with frozen water were buried in the glazed surface and were weighed daily at 15 LT from July 7, 1977 to January 31, 1978.

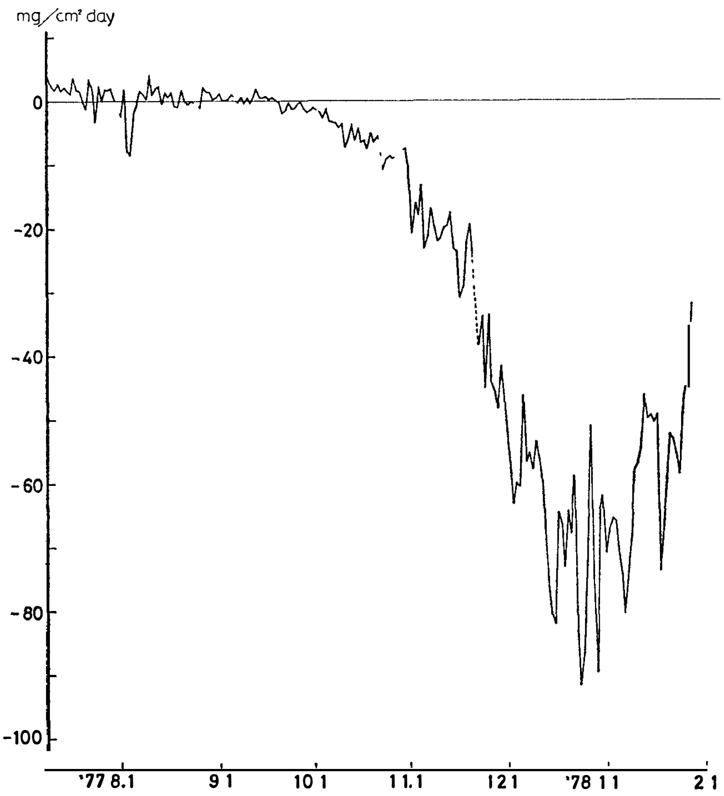

Fig. 2. Daily amounts of condensation and sublimation obtained by the atmometer method, July 7, 1977–January 31, 1978.

Station, February 1977- January 1978.

1977 Aug.	Sep.	Oct.	Nov.	Dec.	1978 Jan.	Year
736.3	725.8	728.9	734.4	742.9	740.0	736.9
−33.7	−39.3	−33.5	−26.3	−18.9	−20.7	−31.3
−34.3	−39.8	−33.4	−25.2	−18.4	−19.8	−31.3
10.2	10.8	8.9	7.2	7.3	6.2	9.5
+1.8	−0.1	+3.3	+4.1	−1.3	−0.4	+7.9
13	14	19	10	4	14	131

Table 3 Monthly amounts of condensation, sublimation and the balance obtained by the atmometer method, July 1977–January, 1978.

		Condensation		Sublimation		Monthly balance (mg)
		Monthly total (mg)	Number of days	Monthly total (mg)	Number of days	
1977	July	+50 38	26	−9 52	5	+40 86
	August	+24 24	19	−25 56	12	−1 32
	September	+7 35	13	−15.62	17	−8 27
	October	0	0	−208 68	31	−208 68
	November	0	0	−902 32	30	−902 32
	December	0	0	−2085.88	31	−2085.88
1978	January	0	0	−1794 53	31	−1794 53

Positive and negative values indicate condensation and sublimation respectively

The daily sublimation (negative value) and condensation (positive value) rates can be seen in Fig. 2. The monthly values are shown in Table 3.

It can be seen that the daily sublimation surpassed the daily condensation from the middle of September to the end of the present observation period even though a small amount of hoarfrost was detected on the glass dome of phyrheliometer in this period. The daily sublimation rate showed its maximum, 92 mg/cm^2, on December 22 when the daily solar radiation showed its maximum. Fig. 2 shows also the existence of sublimation even in the winter.

The effect of the disturbance of surface temperature field or subsurface vapor flux caused by the installation of atmometer was not estimated. Therefore, the amount obtained by the atmometer method is compared in the next section with the other different methods

4.2. Results of bulk formula method

The amount of sublimation rate F_e is calculated with the bulk formula based on the eddy diffusion theory, written as,

$$F_e = C_e \rho (q_s - q_z) \bar{U}_z \, , \tag{1}$$

where,

C_e : Transfer coefficient for latent heat,

ρ : Density of air,

q_z, q_s : Specific humidity at height Z and surface where the water vapor pressure is assumed to be saturated to surface temperature,

$\bar{U}_z$: Wind speed at height Z.

Values of q and ρ are given in the following equations,

$$q=\frac{0.622e}{p}\,, \tag{2}$$

$$\rho=348.38\frac{p}{273.16+t}\,, \tag{3}$$

where,

e : Water vapor pressure,

t : Air temperature,

p : Atmospheric pressure.

Under adiabatic conditions, transfer coefficients for latent heat and momentum are assumed equal, that is,

$$C_e=C_d=\left(\frac{k}{\ln Z/Z_0}\right)^2, \tag{4}$$

where,

Z_0 : Roughness parameter,

k : Von Kármán constant (0.4).

Taking all wind profiles obtained after considerable snow deposition from the end of October to early November, the mean value of roughness parameter Z_0 is calculated as 0.033 cm. Substituting eq. (2) to (4) into eq. (1), the sublimation rate F_e is given by,

$$F_e=3.96\frac{\bar{U}_2(e_s-e_2)}{273.16+t}\times 10^{-3}\ \mathrm{mg/cm^2\cdot day}. \tag{5}$$

Fig. 3 shows the e_s, e_2 and relative humidity at 2 m height. As shown in this figure, the vapor pressure at the surface and 2 m height shows the diurnal variation which corresponds to that of the incoming short-wave radiation. The water vapor pressure difference between the snow surface and in the air shows also the diurnal variation which may depend upon the radiation balance as indicated by NISHIO (1978).

4.3 Results of stake method

Nine stakes were set at 1 m grid intervals near the micrometeorological observation field and were read at 15 LT daily to the nearest mm. Simultaneously, each surface condition was described (FUJII, 1979). After the heavy snow deposition which occurred from the end of October to early November, an additional stake of wooden scale was set on the glazed surface for the measurement of sublimation and was read to 0.1 mm.

Fig. 4 shows the daily net accumulation in depth of No. 6 stake of 9-stake farm (shown as A in this figure) and the additional stake installed on the glazed surface (shown as B). In this figure, solid circle, white circle and triangle indicate the following surface conditions respectively; glazed surface consisting of multilayered ice crust (see Fig. 6), depositional surface consisting of barchan or dune, and erosional surface consisting of

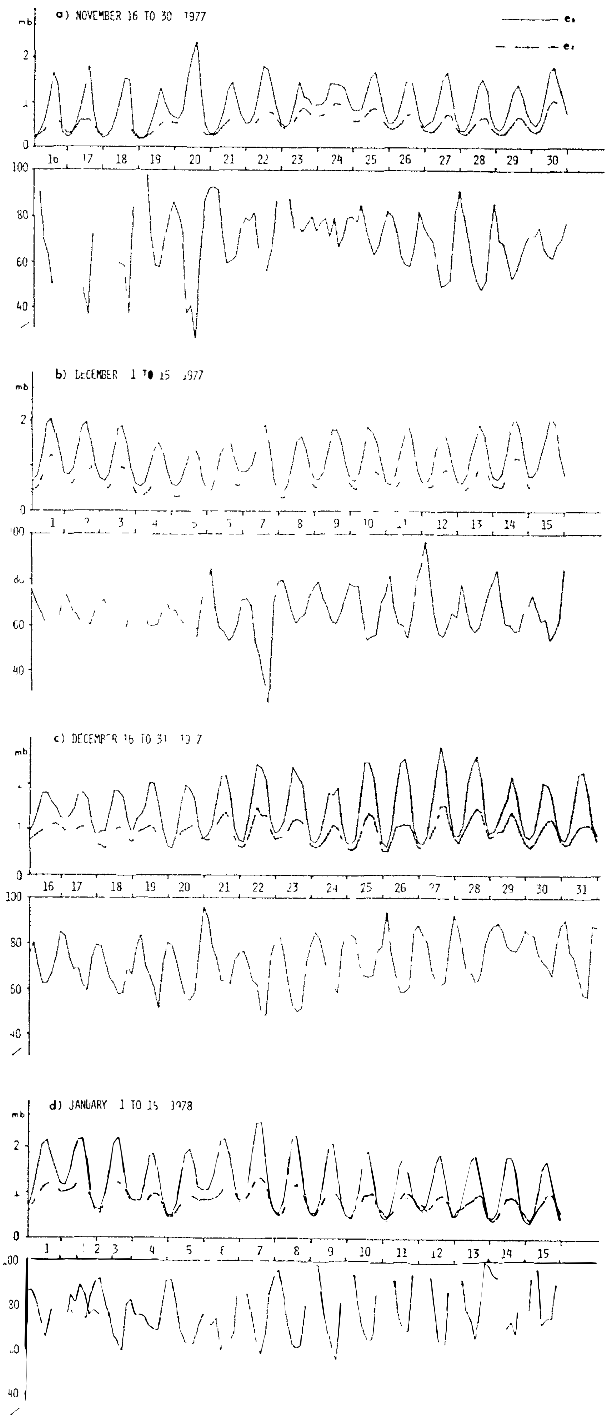

Fig 3 Water vapor pressures at the snow surface and at a height of 2 m and relative humidity at a height of 2 m, November 16, 1977 – January 15, 1978.

sastrugi, erosion pit or smooth surface.

It can be seen that the glazed surface gradually rose at a rate of 2 4 mm/month from the middle of April to early August when the glazed surface was covered by snow deposition. In the summer, the rapid lowering of the glazed surface was observed as shown in Fig 4-B caused by strong sublimation at a rate of 29 3 mm/month in December when

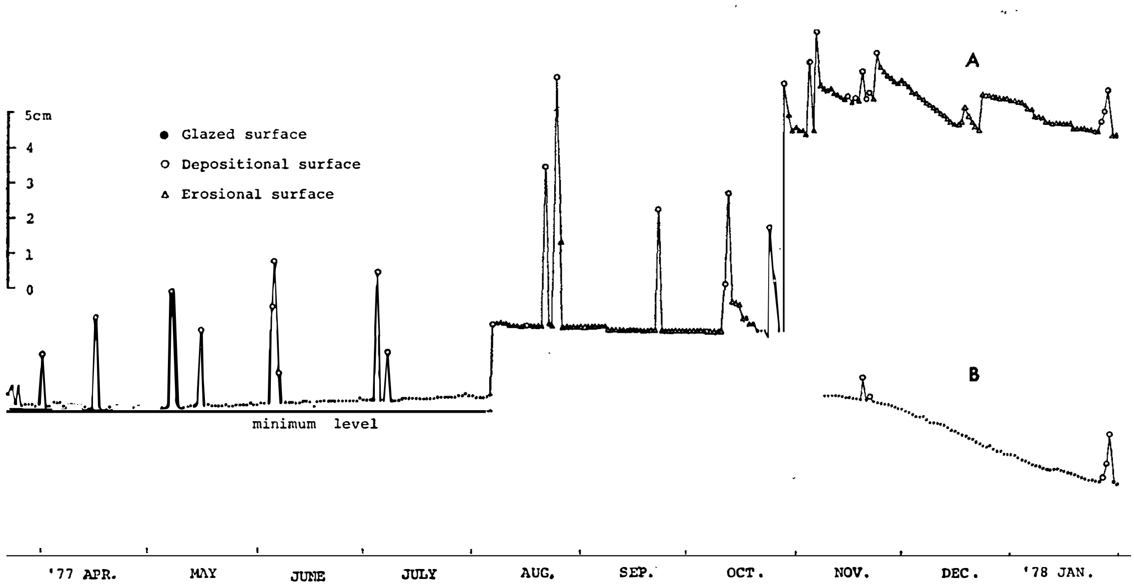

Fig. 4. Daily net accumulation in depth, March 22, 1977 – January 31, 1978.

the water vapor at the snow surface was considerably higher than above it as shown in Fig. 3.

5. Discussion

5.1 Comparison of the three methods of obtaining the sublimation rate

Comparison of the sublimation rates is done in three different methods for the

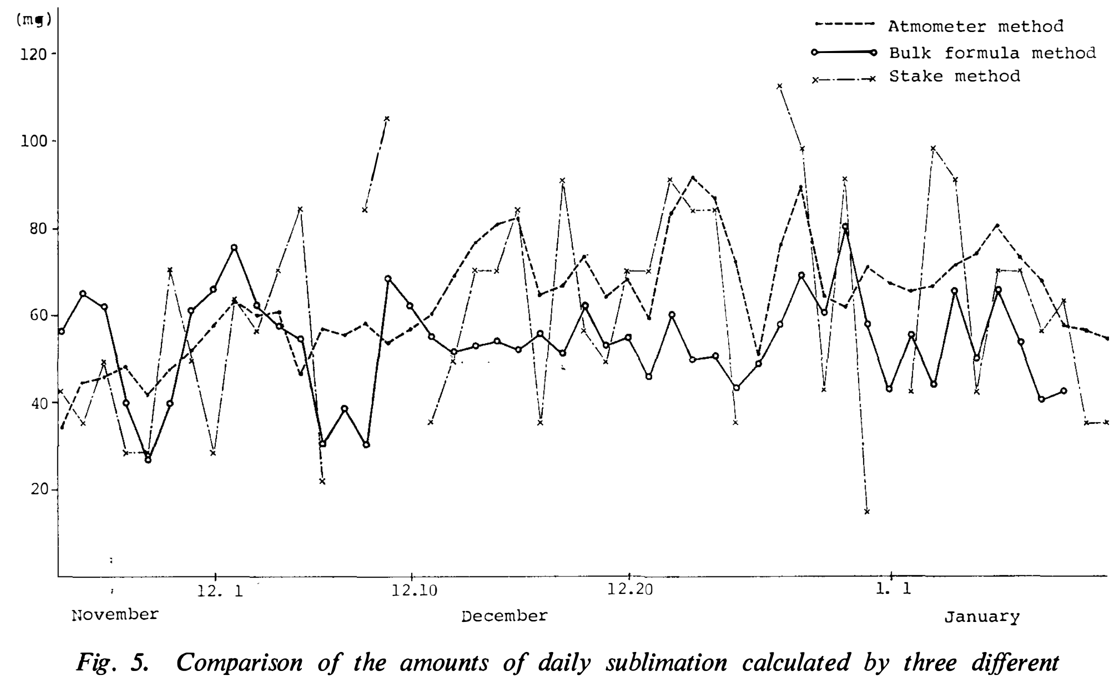

Fig. 5. Comparison of the amounts of daily sublimation calculated by three different methods, November 24, 1977 – January 11, 1978.

period from the middle of November 1977 to the middle of January 1978 as the instrumentation of frost temperature measurements was not in good working condition untill the middle of November 1977.

The daily values of sublimation are given in Fig. 5, showing that the agreement is generally good. In this figure, the sublimation rate obtained by the stake method is calculated using the density of multilayered ice crust of glazed surface, 0.69 g/cm^3. The density was determined on the basis of areal ratio of ice in the crust obtained from the thin section (sampled on October 2, 1977) as shown in Fig 6 Though the reading of

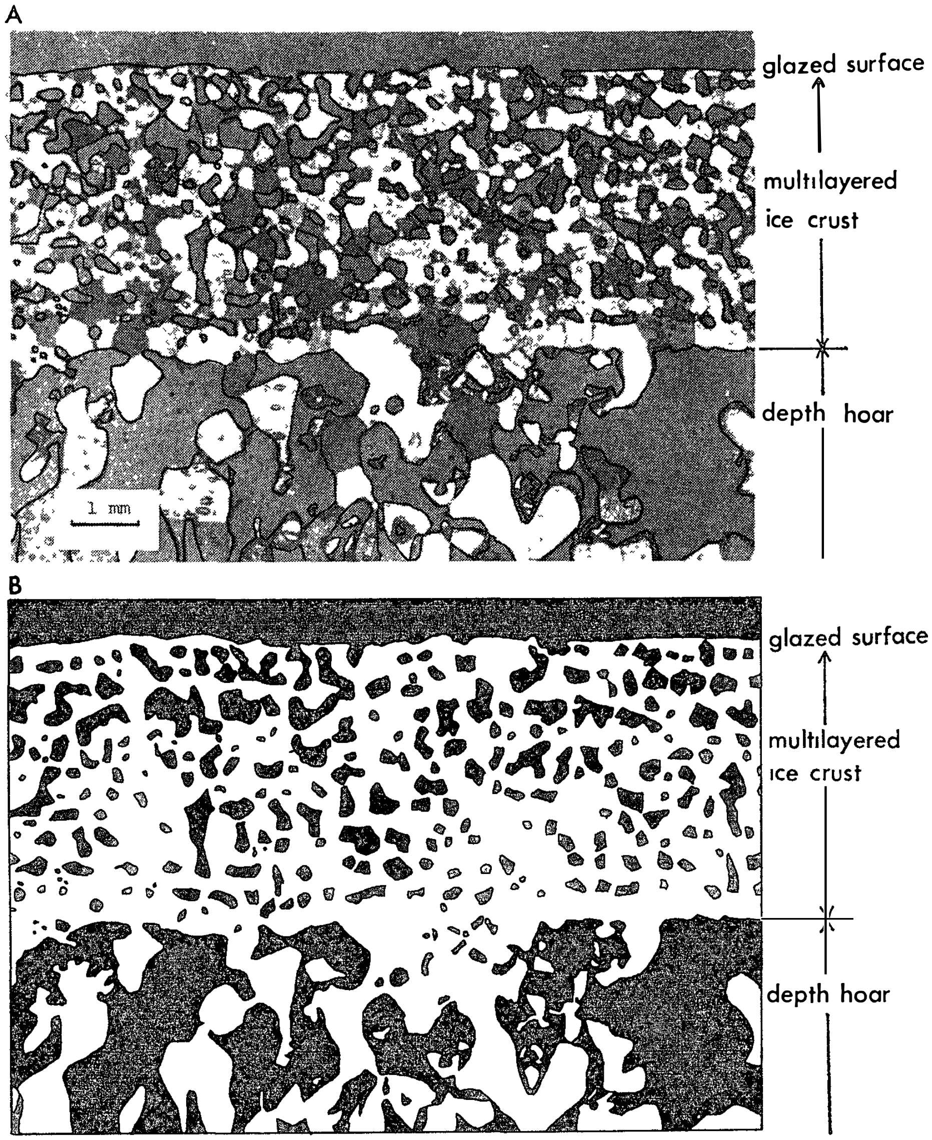

Fig 6 A. Microphotograph of thin section of surface snow layer with multilayered ice crust in crossed polarized light. B. Sketch of the microphotograph showing the snow particles and vacant spaces in white and black respectively

Table 4. Comparison of weekly mean sublimation rates obtained by three different methods, November 24, 1977-January 11, 1978.

Period (1 week)	Sublimation rate (mg/day)		
	Atmometer method	Bulk formula method	Stake method
November 24 to November 30	44.5	50.0	43.0
December 1 to December 7	57.0	54.8	53.7
December 8 to December 14	64.8	53.5	68.8
December 15 to December 21	68.8	53.4	65.0
December 22 to December 28	78.5	54.0	84.0
December 29 to January 4	66.8	58 1	63 0
January 5 to January 11	62.6	—	52.0
Mean for 42 days from November 24 to January 4	63.3	54 0	62.3

the additional stake was done to 0.1 mm, the accuracy might be ± 0.2 mm which results in ± 14 mg error of sublimation rate. Therefore, it seems to be advantageous to compare not individual days but rather periods of several days' duration.

Table 4 shows the weekly mean sublimation rates and the total amounts for 6 weeks from November 24 to January 4 obtained by the three methods. It can be seen that the agreement for the weekly mean values and the 6 week totals between two direct measurements, *i. e.* the atmometer and stake methods, is very satisfactory. However, the value obtained by the bulk formula method showed less weekly variation than others and larger disagreement. This may be ascribed to the assumption of $C_e = C_d$, roughness parameter and surface temperature. According to NISHIO (1978), the sublimation rate estimated by the bulk formula method was nearly two or three times larger than the rate obtained by the snow stake method. This may be caused by the underestimation of the density of surface snow layer, 0.45 g/cm^3.

5.2 Seasons of sublimation and condensation

The daily amount of sublimation prevails in the summer and condensation in the winter. Here sublimation and condensation seasons can be defined as the seasons when the net balance due to sublimation-condensation processes is negative and positive respectively. As shown in Figs. 2 and 4, the condensation season was the period of five months from the middle of April to the middle of September and the sublimation season was the remainder of the year at Mizuho Station in 1977.

5.3 Annual amounts of sublimation and condensation

These values can be estimated using the half-year amounts from the winter solstice to the summer solstice by the atmometer method for the period from July 7 to December 22 and by the stake method for the period from June 22 to July 6. On the basis of the above-mentioned estimation method, the annual amounts of sublimation and condensation come to 4.92 g/cm² and 0.19 g/cm². As the annual net accumulation of snow was 7.9 g as shown in Table 2, the surface mass balance at Mizuho Station was much controled by sublimation in the summer.

6. Conclusions

It has been shown that satisfactory agreement is obtained among the amounts of sublimation estimated by three different methods; atmometer, bulk formula and stake methods. The research results summarized herein lead to the following conclusions: (1) The daily amount of sublimation prevails in the summer from the middle of September to the middle of April and the daily amounts of condensation in the winter of the remainder five months (2) The daily sublimation rate showed its maximum, 92 mg/cm² on December 22 when the daily solar radiation showed its maximum. (3) The annual amounts of sublimation and condensation are estimated to 4.92 g/cm² and 0.19 g/cm² respectively. Sublimation largely affects the annual net accumulation of snow. The result of the present study implies that sublimation at the ice sheet surface of Mizuho Station might play an important role in the heat and mass exchanges and in the metamorphism of surface texture, though the minor importance was indicated in both coastal and interior regions of Antarctica by LOEWE (1962).

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References

FUJII, Y (1979): Glaciological research at Mizuho Station, Antarctica in 1977. JARE Data Rep, **48** (Glaciol), 198 p.

FUJII, Y. and KAWAGUCHI, S (1978): Meteorological data at Mizuho Station, Antarctica in 1977–1978 JARE Data Rep, **47** (Meteorol), 107 p

LOEWE, F (1956): Notes on firn temperatures and ablation in MacRobertson Land J Glaciol, **2**, 725–726

Loewe, F. (1962): On the mass economy of the interior of the Antarctic ice cap J. Geophys Res., **67**, 5171–5177.

Nishio, F. (1978): Atmospheric water vapor measurements at Mizuho Camp, East Antarctica in 1976–1977 Nankyoku Shiryô (Antarct. Rec.), **61**, 1–10.

Weller, G. E. (1968): The heat budget and heat transfer processes in Antarctic Plateau ice and sea ice. ANARE Sci. Rep, Ser. A (IV), Glaciol, **102**, 155 p.

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