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SURFACE MASS BALANCE, SUBLIMATION AND SNOW TEMPERATURES AT DOME FUJI STATION, ANTARCTICA, IN 1995

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Abstract: This paper focuses on the first year-round observations of surface mass balance, sublimation and snow temperatures at Dome Fuji Station. This station was newly established at the highest point (77°19′01″S, 39°42′12″E; 3810 m) in Queen Maud Land, Antarctica by the Japanese Antarctic Research Expedition. It was found that average surface mass balance by the stake method was $+2.5\ gcm^{-2}$ from 25 January 1995 to 30 January 1996 (370 days), of which about 95% of the positive balance was obtained from February to the middle of October (eight and half months). Sublimation from atmosphere to snow surface (mass input: $+0.55\ gcm^{-2}$) was predominant in winter (March to October) and sublimation from snow surface to atmosphere (mass output: $-0.39\ gcm^{-2}$) was predominant in summer (November to February). In the annual balance, sublimation from atmosphere to snow surface ($+0.16\ gcm^{-2}$) prevailed. This corresponds to about 6% of the annual surface mass balance. The snow temperature at 10 m depth varied from −57.0 to −57.8°C, and the annual mean 10 m snow temperature was −57.3°C.

1. Introduction

A five-year glaciological research program, "Deep Ice Coring Project at Dome Fuji Station, East Antarctica", was started in 1992. Because Dome Fuji is located at the highest point (77°19′01″S, 39°42′12″E; 3810 m) in Queen Maud Land, Antarctica, this area was selected for deep ice coring. In 1992-93, surface and bedrock topographies and surface snow features were investigated around Dome Fuji to determine the site for the deep ice coring by the 33rd Japanese Antarctic Research Expedition (KAMIYAMA *et al*., 1994; MAENO *et al*., 1994; FURUKAWA, *et al*., 1996). Shallow ice coring 112 m deep and the casing of the borehole were carried out at the highest point around Dome Fuji during the austral summer in 1993/94 by JARE-34 (MOTOYAMA *et al*., 1995). During the next austral summer, Dome Fuji Station was constructed by members of JARE-35 (SHOJI *et al*., 1996).

In 1995, JARE-36 started to overwinter for the deep ice coring at Dome Fuji Station (Fig. 1). Glaciological and meteorological observations were carried out during that period. We describe here the results for surface mass balance, sublimation at the ice sheet surface and snow temperatures at Dome Fuji from February 1995 to January 1996.

2. Surface Mass Balance by the Stake Method

A 36-stake farm was established 300 m east of Dome Fuji Station (Fig. 2) on 25 January 1995. The distance between stakes was 20 m. Although wind direction around Dome Fuji Station was unstable, wind from east mostly prevailed (KAMEDA *et al.*, 1997). Heights of 36 stakes were measured on days 15 and 30 in each month*. Average surface mass balance was calculated from the height differences of the 36 stakes and surface snow density, and is shown in Fig. 3. The thick line (a) shows average surface mass balance for each 15 to 16 days** and the thin line (b) shows cumulative surface mass balance obtained from integration of line (a). The cumulative surface mass balance was 2.5±1.0

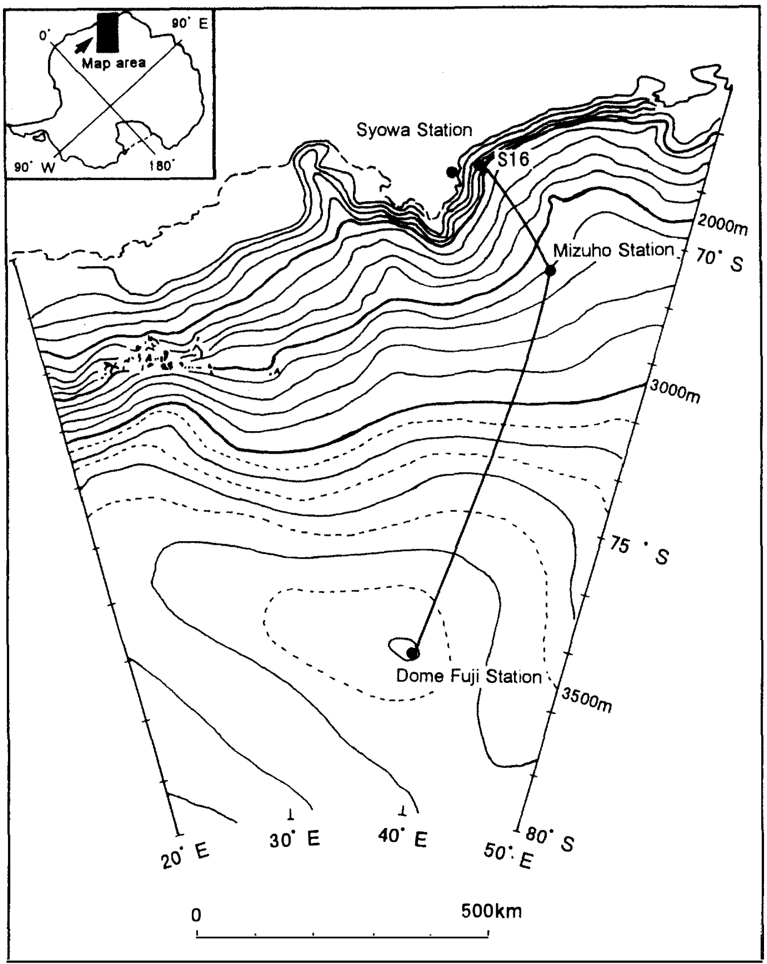

Fig. 1. Location map of Dome Fuji Station in East Queen Maud Land, Antarctica.

* The stake-height was measured at 25 January (initial mesurements) and 28 February 1995 as exceptions.

** Data for 21 days (25 January-15 February) and 13 days (15-28 February) are also shown in Fig. 3.

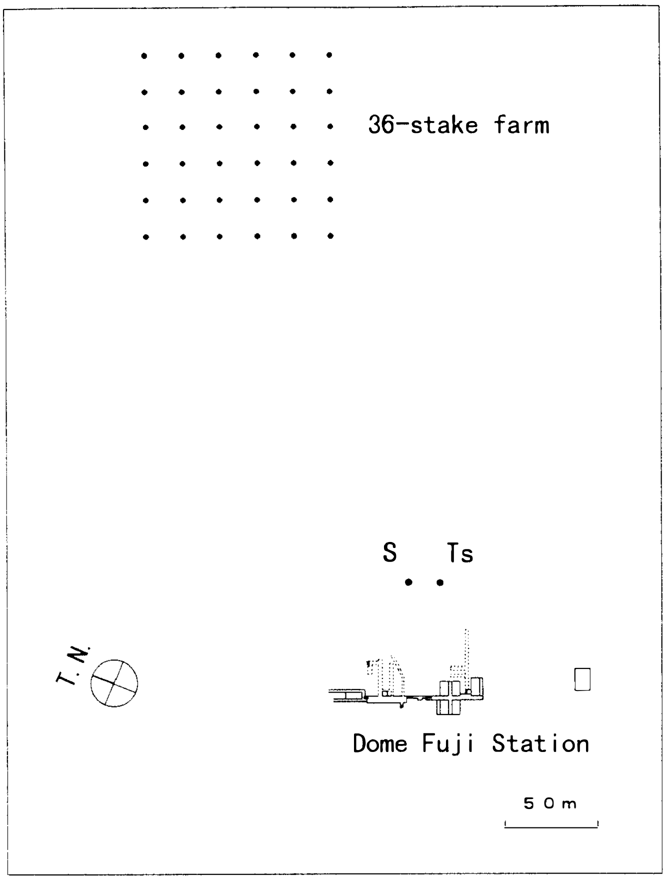

Fig. 2. Glaciological observational area at Dome Fuji Station.
S: site for sublimation observations, T_S: site for snow temperature observations.

gcm^{-2} yr^{-1} from 25 January 1995 to 30 January 1996 (370 days). This corresponds to 8.8$\pm$3.6 cm yr^{-1} increase in the surface snow height. More than 95% of the surface mass balance (2.4 gcm^{-2}) was accumulated from February to the middle of October during the eight and a half month. Less accumulation (0.1 gcm^{-2}) was obtained during the rest of the period mainly caused by strong sublimation in summer.

Figure 4 shows standard deviations of surface mass balance in the 36-stake farm (dashed lines), which are calculated from line (a) in Fig. 3 plus and minus its standard deviations. Standard deviation has the largest value in 1-15 June, which suggests that snow accumulates in a certain area, not the whole area of the 36-stake farm (100 m$\times$100 m). The deviation is nearly the same as mean annual accumulation. Accumulated snow in the period was mainly supplied from the blizzard on the 5th of June. Snow accumulated at a fairly constant rate from 15 to 30 June, as suggested by the small standard deviation in Fig. 4. We had no blizzard during the period according to the definition of a blizzard at Dome Fuji Station by the Japan Meteorological Agency (the lowest class blizzard "C": wind speed exceeds 7 m/s and visibility is less than 1 km; both conditions must remain more than 6 hours). Surface mass balance from 30 June to 15 July is negative and its standard deviation is large. This negative mass balance was mainly caused by erosion of snow during the blizzard on the 8-9th and 14th of July. Thus, snow accumulation by

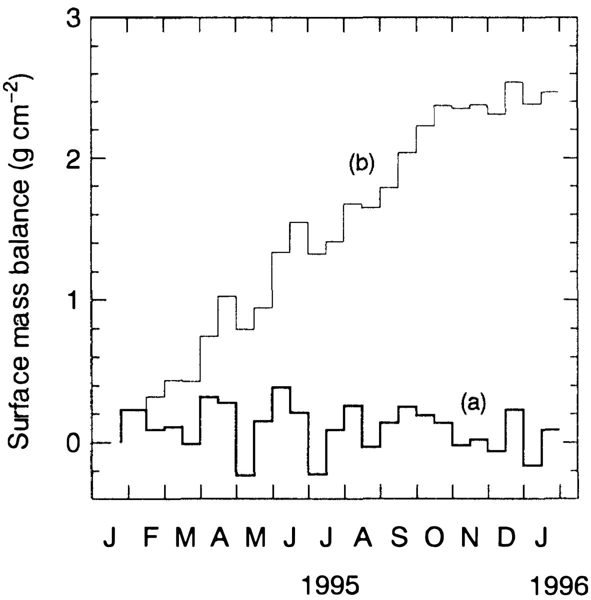

Fig. 3. Average surface mass balance at Dome Fuji by 36-stake farm from 25 January 1995 to 31 January 1996. Thick line (a) shows average surface mass balance for each 15 to 16 days and thin line (b) shows cumulative surface mass balance which are obtained from integration of line (a).

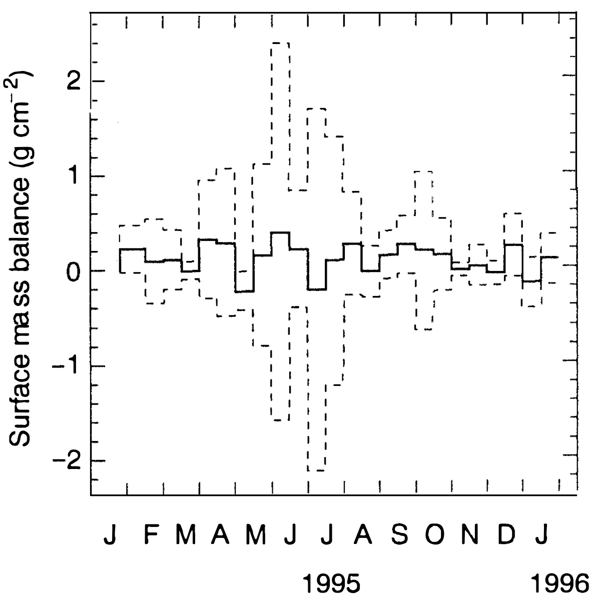

Fig. 4. Average surface mass balance with its standard deviations at Dome Fuji by 36-stake farm from 25 January 1995 to 31 January 1996.

blizzard is important for the surface mass balance at Dome Fuji.

Average surface mass balance at DF80 (77°22′24″S, 39°36′50″E; 3807 m) which is located 8 km southeast of Dome Fuji Station was 2.6 ± 1.2 gcm^{-2} yr^{-1} (9.3 ± 4.2 cm yr^{-1} in snow height) by measurements of the 50-stake row from 19 January 1995 to 23 January

1996 (369 days). Thus, it seems that the surface mass balance of 2.5–2.6 gcm^{-2} yr^{-1} for 1995–96 season well represents the value in the Dome Fuji area. KAMIYAMA *et al.* (1989) showed 3.2 gcm^{-2} yr^{-1} of average surface mass balance during 1966–85 by using a Tritium peak at 1966 in the snow layer at Dome Camp (77°00′01″S, 35°00′00″E; 3761 m), which is located 120 km west-northwest of Dome Fuji Station. The surface mass balance (2.5 gcm^{-2} yr^{-1}) at Dome Fuji for the 1995–96 season was, therefore, about 80% of the previous data at Dome Camp. All numerical data in Fig. 3 are described in AZUMA *et al.* (1997).

3. Sublimation for Snow and Ice Surfaces, and its Contribution to Surface Mass Balance

Sublimation for snow and ice surfaces were measured by weighing sublimation-pans filled with snow or ice from February 1995 to January 1996. Undisturbed snow was set in a plastic container (25 cm × 25 cm × 8 cm) and ice (frozen water) was set in three glass petri dishes (8.5 cm in diameter and 4 cm in depth). The plastic container and the petri dish were the same type as used in SHIRAIWA *et al.* (1996) and TAKAHASHI *et al.* (1988), respectively.

These pans were located 50 m from the Station ("S" in Fig. 2). The surfaces of these pans were set at the snow surface level. The weights of these pans were mainly measured in a snow cave by an electronic balance to 0.01 g resolution two times a day (5 February to 10 April 1995 and 14 to 23 January 1996) and once a day (11 April to 7 January 1996). Some periods lack data: 5–15 February 1995 for ice pans, 16–24 November, 1–2 and 8–11 January for snow and ice pans. After weighting ice pans, surfaces of the pans were cleaned by a small brush and weights were again measured for the next measurements. This procedure was only applied for ice pans, not for snow pans. Because surfaces of ice and snow pans were sometimes covered with surface frost and snow, we try to keep ice surface condition for ice pans.

The weights of pans varied by snow deposition, wind erosion and sublimation process. When we observed drifting and falling snow, we excluded the weight data of snow and ice pans from sublimation data. We also excluded the data which were affected by wind erosion. On the other hand, ice prisms (diamond dust) were observed in the air almost every day (YOSHIMI *et al.*, 1997), and some of the diamond dust was probably deposited on the ice sheet surface. Because it was difficult to separate the deposited diamond dust from the surface frost which was observed on the snow and ice pans, sublimation data in this paper include the weight of the deposited diamond dust.

Figure 5 shows results of seasonal variation of sublimation for snow and ice pans. For the ice pans, average values for three ice pans are shown. Positive values in Fig. 5 refer to mass inputs to the pans and negative values refer to mass outputs from the pans. Due to snow deposition by falling and drifting snow and wind erosion, more than 200 data out of totally 390 data were eliminated in Fig. 5.

For snow pan measurements, sublimation from atmosphere to surface is predominant, about +1 to +6 $mgcm^{-2}$ day^{-1} from the middle of March to the middle of November, while sublimation from surface to atmosphere is predominant during the rest of the period. This increased −2 $mgcm^{-2}$ day^{-1} in the middle of November to −16 $mgcm^{-2}$ day^{-1} in

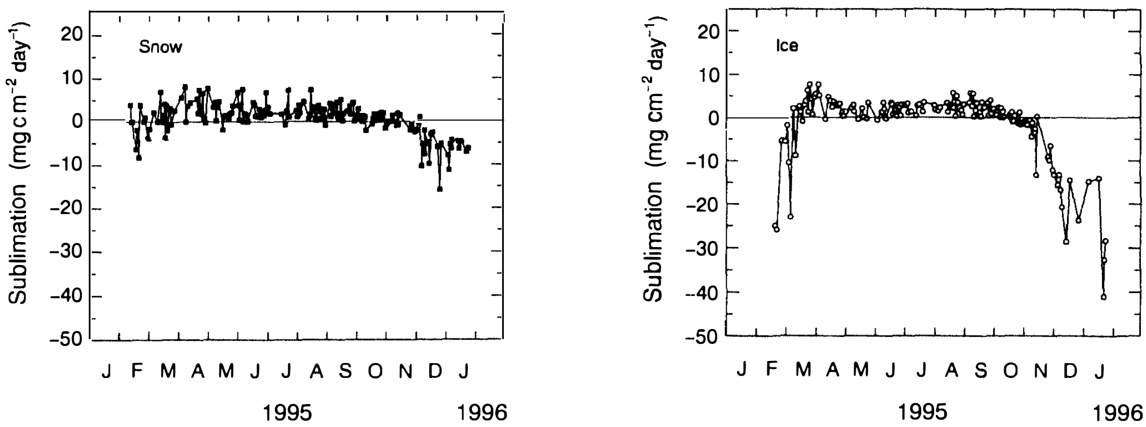

Fig. 5. Sublimation from snow and ice surface at Dome Fuji from February 1995 to January 1996.

late December. Sublimation from atmosphere to ice pan was predominant, about +1 to +6 mgcm^{-2} day^{-1}, from the middle of March to early November, while sublimation from ice pan to atmosphere was predominant during the rest of the period; this increased −2 mgcm^{-2} day^{-1} in early November to −42 mgcm^{-2} day^{-1} in the middle of January. Thus, the amount of sublimation during winter tends to be the same for snow and ice pans, however, sublimation for ice pan in summer was much larger than as for snow pans. This was probably caused by the differences of surface albedo between snow and ice.

To estimate monthly total sublimation, the daily mean sublimation for each month in Fig. 5 was calculated, and this was multiplied by the number of days in each month. Table 1 and Fig. 6 show the monthly total sublimation. For yearly total, sublimation from atmosphere to snow surface prevailed for snow pans (+0.16 gcm^{-2} yr^{-1}), while sublimation from ice surface to atmosphere prevailed for ice pans (−1.58 gcm^{-2} yr^{-1}). Because the surface condition in the Dome Fuji area is snow, the results for the snow pan represent the amount of sublimation in the Dome Fuji area. On the other hand, ice pans were used for sublimation studies at Mizuho Station (FUJII and KUSUNOKI, 1982; TAKAHASHI *et al.*, 1988) since glazed surface (ice crust surface) was commonly observed in this area. Thus, results for the ice pan in Table 1 will be compared with the results at Mizuho Station

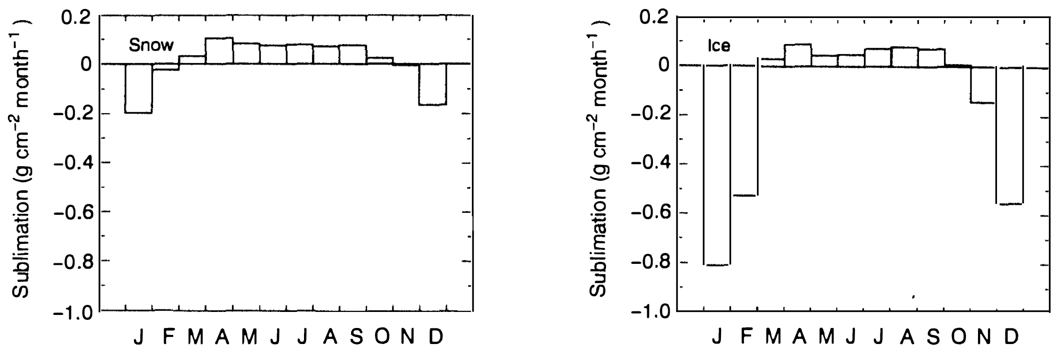

Fig. 6. Monthly total sublimation from snow and ice surfaces at Dome Fuji.

Table 1. Sublimation for snow and ice, and surface mass balance for each month at Dome Fuji Station from February 1995 to January 1996.

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Sublimation for snow (A) g cm^{-2}	−0.20	−0.02	0.03	0.10	0.08	0.08	0.08	0.07	0.08	0.03	−0.01	−0.16	0.16
Sublimation for ice g cm^{-2}	−0.81	−0.52	0.03	0.09	0.05	0.05	0.07	0.08	0.07	0.01	−0.14	−0.05	−1.58
Surface mass balance (B) g cm^{-2}	−0.07	0.32	0.11	0.60	−0.08	0.60	−0.14	0.24	0.39	0.33	0.00	0.17	2.48
Surface mass balance without sublimation for snow (B−A) g cm^{-2}	0.13	0.34	0.08	0.50	−0.16	0.52	−0.22	0.17	0.31	0.30	0.01	0.33	2.32

in the last part of this chapter.

To estimate the contribution of the sublimation process for surface mass balance, surface mass balance without sublimation is calculated, and is shown in the last row in Table 1. The broken line (a) in Fig. 7 shows the data. Broken line (b) shows the integral of broken line (a). The solid line (a) shows the monthly mean surface mass balance from the results for the 36-stake farm, and the solid line (b) was obtained by integration of the solid line (a). In winter from March to October, the surface mass balance (solid line (b)) was 2.05 gcm^{-2}, while the surface mass balance without sublimation (broken line (b)) during the same months was 1.50 gcm^{-2}. Thus, the total sublimation (0.55 gcm^{-2}) corresponds to 25% of the surface mass balance during that period. In summer from November to February, the surface mass balance was +0.42 gcm^{-2}, while the

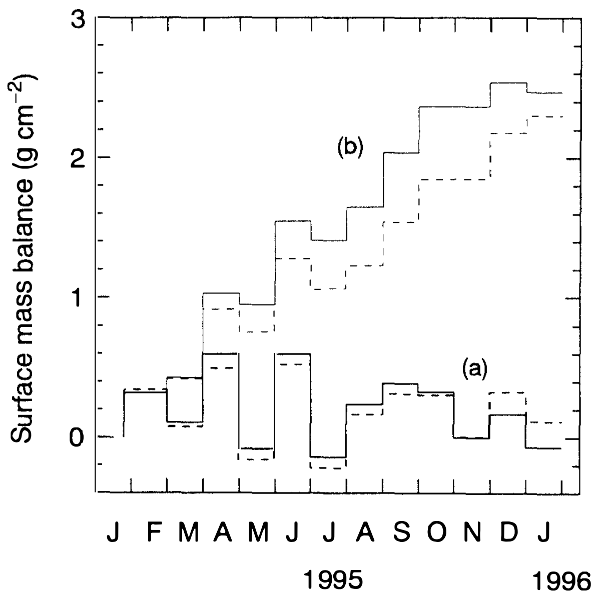

Fig. 7. Surface mass balance (solid line (a) and (b)) and surface mass balance without sublimation process (broken line (a) and (b)). Lines (b) are obtained from integration of lines (a).

surface mass balance without sublimation during the same period was $+0.81$ gcm^{-2}. Thus, total sublimation during the period was -0.39 gcm^{-2}. Consequently, surface mass balance in summer was reduced to half by the strong sublimation, especially from December to January. For the annual balance, sublimation from the atmosphere to the snow surface ($+0.16$ gcm^{-2} yr^{-1}) prevailed. This corresponds to about 6% of the annual surface mass balance ($+2.5$ gcm^{-2} yr^{-1}).

TAKAHASHI *et al.* (1988) showed year-round results of monthly mean sublimation at Mizuho Station in 1982 for ice in a glass petri dish which is the same as we used. Compared with TAKAHASHI *et al.* (1988) it was found that the total of positive monthly sublimation (0.45 gcm^{-2}) from the ice surface at Dome Fuji Station was about five times larger than that at Mizuho Station (0.093 gcm^{-2}). The total negative monthly sublimation (-2.03 gcm^{-2}) at Dome Fuji was about 40% of that (-5.300 gcm^{-2}) at Mizuho Station. For the annual balance, sublimation from the ice surface to the atmosphere (-1.58 gcm^{-2} yr^{-1}) prevailed at Dome Fuji Station. This value corresponds to about 30% of the annual sublimation balance for ice (-5.2 gcm^{-2} yr^{-1}) at Mizuho Station. Thus, sublimation at Dome Fuji is characterized by much positive sublimation (condensation) in winter and less negative sublimation (evaporation) in summer than at Mizuho Station.

4. Snow Temperatures

Snow temperatures at Dome Fuji were measured at depths of 0.01, 0.1, 0.2, 0.5, 1, 2, 5 and 10 m using a platinum resistance thermometer (Pt 100 ohm) with a data logger (Datamark LS-3000PtV, Hakusan Corporation). The distance from Dome Fuji Station is about 50 m as shown in "T_S" in Fig. 2. The thermometers of 5 and 10 m in depths were set in a borehole using a bamboo stake on 16 February 1995. Because the thermal conductivity of bamboo is small compared with that of snow, it seems that there is little problem in using a bamboo stake as a guide for the thermometers. Six other thermometers were set in the surface of a pit wall horizontally on the same day. The borehole and the snow pit were filled with snow after setting the thermometers. Stable snow temperatures were obtained from 20 February.

Because snow was sometimes accumulated on the thermometers, the depths of thermometers were sometimes changed. We tried to keep the initial depths for the thermometers; accumulated snow around the thermometers (1 m$\times$1 m area) was removed as fast as possible. Data at 30 min intervals were recorded from 15 February to 12 May, 1995. Data at 10 min intervals were recorded from 13 May 1995 to 25 January 1996 during the JARE-36 operations. Due to a lack of batteries for the data logger, snow temperature data from 14 to 16 October were missed. The data logger was installed in a room at Dome Fuji Station where air temperature changed from about 5 to 20°C. The resolution of snow temperatures was 0.1°C.

Figure 8 shows the snow temperature variations with time at depths of 0.1, 0.5, 2, 5 and 10 m. Increases of snow temperatures in mid- and late July from 0.1 to 2 m depth were caused by increases of air temperature during the period (KAMEDA *et al.*, 1997). Tautochrones of snow temperature as a function of depth at the beginning of each month* at noon (1200) are plotted in Fig. 9. It is clear that fluctuations of snow temperatures

* 21 February is an exception.

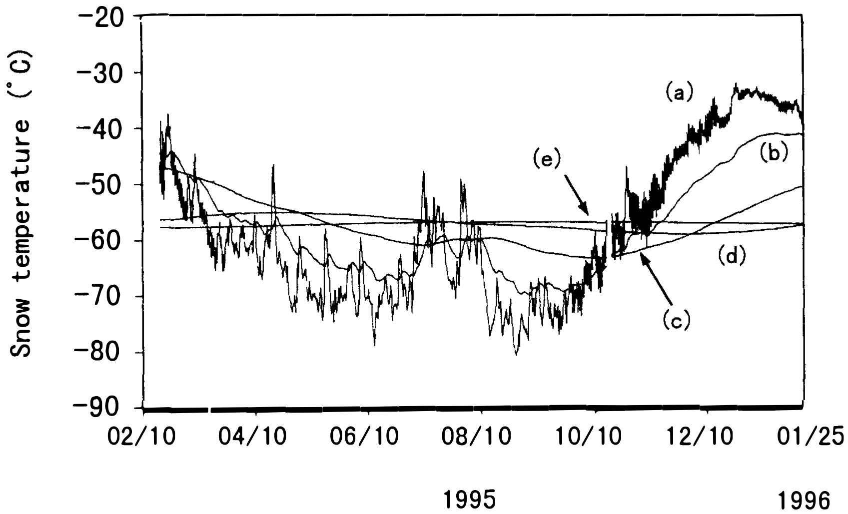

Fig. 8. *Snow temperatures at depths of 0.1 m (a), 0.5 m (b), 2 m (c), 5 m (d) and 10 m (e) at Dome Fuji.*

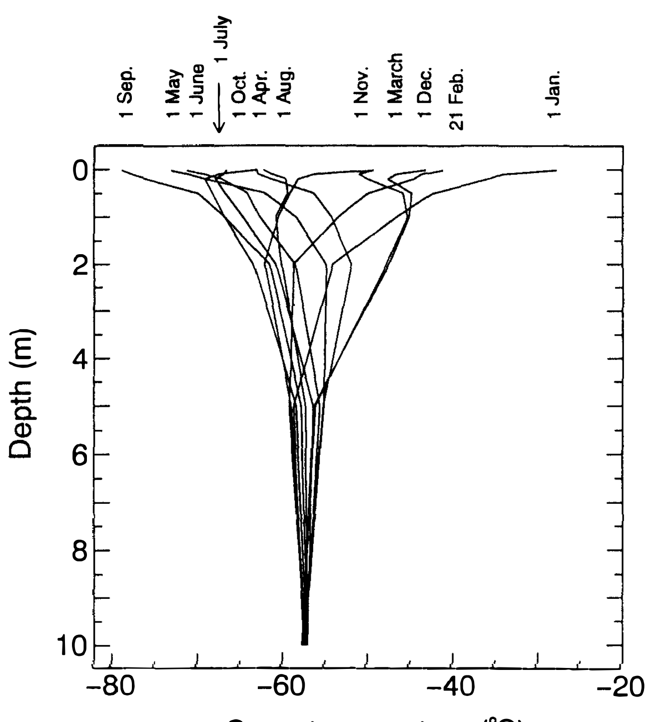

Fig. 9. *Tautochrones of snow temperatures as a function of depth at the beginning of each month at noon (1200).*

gradually decrease with depth. Snow temperature at 10 m depth (T_{10}) varies from −57.0 to −57.8°C, and annual mean 10 m snow temperature is −57.3°C. Because annual mean air temperature at 1.5 m height from 1 March 1995 to 28 February 1996 was −53.9°C (T_a; YOSHIMI *et al.*, 1997), the averaged 10 m snow temperature was 3.4°C colder than the meteorological annual mean air temperature.

Compared with previous studies (LOEWE, 1970), this difference is similar to the results at "Plateau Station*" (3.3°C and 3.9°C), about 220 km south (79°15′S, 40°30′E; 3625 m) of Dome Fuji Station. The difference for other stations in the Antarctic ice sheet ranges from −1.1 to 1.7°C. Thus, it can be a common feature for the area from Dome Fuji Station to Plateau Station that relatively large differences between T_{10} and T_a exist. Because T_{10} is mainly determined from the average surface snow temperatures, radiation cooling for surface snow is a key factor to understand the large differences between T_{10} and T_a. Numerical data in Fig. 8 at 12 hour intervals are described in AZUMA *et al.* (1997).

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