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Characteristics of heat balance and ablation on Moreno and Tyndall glaciers, Patagonia, in the summer 1993/94

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Abstract

In order to better understand heat balance characteristics, meteorological conditions were measured at Moreno Glacier from November 12 to 27, 1993 and at Tyndall Glacier from December 9 to 17, southern Patagonia. With seven ablation stakes at each glacier, the mean daily ablation rate measured during the period ranged from 4.9 to 7.3 cm/day at Moreno Glacier and from 6.0 to 6.9 cm/day at Tyndall Glacier. The heat source for ice melting consisted mostly of net radiation and sensible heat flux on both glaciers. In spite of the difference in meteorological conditions during the observation periods between the two glaciers, there were little difference in the mean daily ablation except for the days when a Föhn-like phenomenon occurred at Moreno Glacier. There was also little difference between the mean values of net radiation at the two glaciers. The mean sensible heat flux on Moreno Glacier was a little larger than that on Tyndall Glacier, and evaporation predominated on Moreno Glacier, while condensation on Tyndall Glacier. When Föhn-like air temperature rise and wind speed increase were observed at Moreno Glacier, all heat balance components, especially sensible heat flux, increased and the amount of ablation increased almost twice as much as the ordinary mean value.

1. Introduction

In order to obtain the meteorological features and to clarify the heat balance and ablation of glaciers in southern Patagonia, measurements were made at Moreno Glacier in November and at Tyndall Glacier in December 1993. Moreno Glacier discharges northeastward from the Southern Patagonia Icefield (SPI) into a channel of Lake Argentino at an elevation of about 180 m (Fig. 1). The ablation area is 30 km long and 4 km wide. Tyndall Glacier flows southward from the icefield and terminates in a proglacial lake at an elevation of about 50 m (Fig. 1). The ablation area is about 16–22 km long and 3.5–10 km wide (Naruse and Aniya, 1992).

In Patagonia, studies on ice ablation and heat balance have been carried out at Soler and San Rafael glaciers of the Northern Patagonia Icefield (NPI) in 1983–84 and 1985–86 (Kobayashi and Saito, 1985 ; Ohata *et al.*, 1985a, 1985b ; Fukami and Naruse, 1987 ; Kondo and Inoue, 1988). It was found out that at Soler Glacier, on the eastern side of the NPI, the sensible heat was a more important factor to ablation while at San Rafael Glacier, on the western side of the NPI, the turbulent heat flux and radiative heat flux contributed evenly to ablation. The amount of surface ablation at Soler Glacier was greater by 50 % than that at San Rafael Glacier (Ohata *et al.*, 1985b). It was reported that the large turbulent heat fluxes in the surface heat balance components at Soler Glacier were probably due to the occurrence of Föhn accompanied with strong wind and high temperature.

In the Southern Patagonia Icefield (SPI), Koizumi and Naruse (1992) carried out researches for the first time on meteorological conditions and ice ablation at Tyndall Glacier. No detailed studies on characteristics of heat balance have been made at glaciers in southern Patagonia. This paper presents some char-

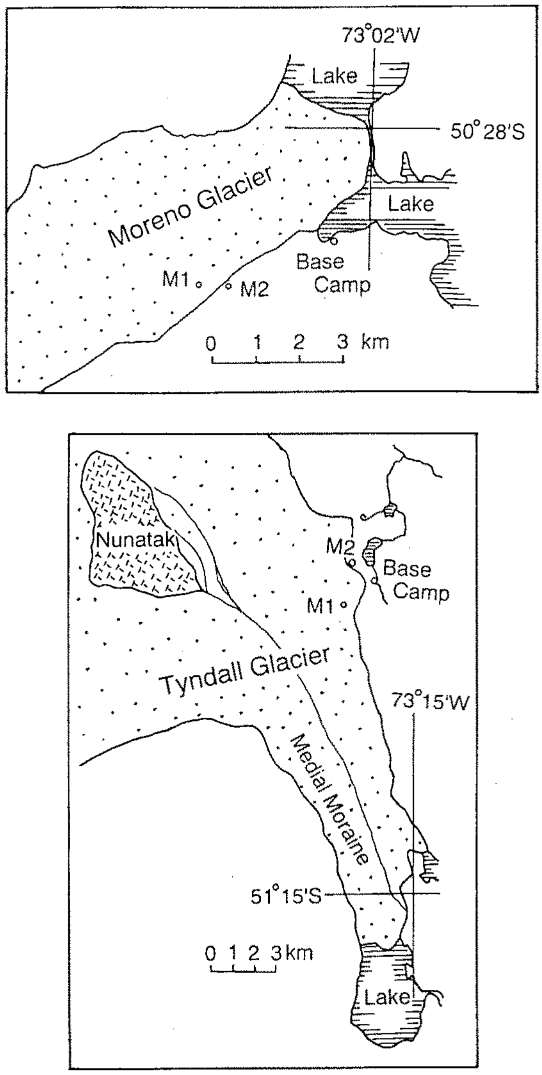


Fig. 1. Location map of Moreno and Tyndall glaciers in southern Patagonia and observation sites. M1 : the main observation site on the glacier. M2 : the subsidiary observation site on the lateral moraine.

acteristics of heat balance and ablation at Moreno and Tyndall glaciers. Details of measurement methods and meteorological features are reported on a separate paper (Takeuchi *et al.*, 1995).

2. Observation sites and measurement methods

Locations of three observation sites, M1, M2, and Base Camp, are shown in Fig. 1. Site M1 was the main observation site set up on almost flat bare-ice in the ablation area of each glacier. Their altitudes are about 330 m at Moreno Glacier and 700 m at Tyndall Glacier. Site M2 was the subsidiary observation site located on the lateral moraine close to the glacier margin. Air temperature, relative humidity, wind speed at 1 m above the glacier surface and radiation were continuously measured and recorded with portable data loggers at site M1. Ablation was measured once or twice a day with seven stakes planted along the route from sites M1 to M2 on each glacier (Fig. 2). Stake 1 was set up at site M1 on each glacier. On Moreno Glacier, stakes 3, 4 and 5 were set up at the ridges of seracs and the other four stakes were at flatter areas. On Tyndall Glacier, all stakes were set up at almost flat area. Albedo of the ice surface at each stake was measured once or twice during the period at about 11 : 00−16 : 00 on fine days. Global radiation and precipitation were measured at site M2. Some routine observations, such as atmospheric pressure, air temperature, cloud amount and precipitation, were made at the Base Camp. The observation periods were from November 12 to 27, 1993 at Moreno Glacier and from December 9 to 17, 1993 at Tyndall Glacier.

3. Methods of heat balance computation

The heat fluxes at the glacier surface were calculated hourly and summed up for the daily value. The heat balance equation at the melting glacier surface can be written as follows :

$$NR + S + L - M = 0, \quad (1)$$

where NR is the all wave net radiation, S the sensible heat flux, L the latent heat flux and M the heat for ice melting. Heat conduction to the sub-surface ice layer is zero, because ice near the surface was saturated with water at 0 °C during the observation period. Fluxes toward the surface are regarded as positive, and those away from the surface as negative. Values of NR were measured directly by a net radiometer. The turbulent heat fluxes (S and L) were calculated using a bulk aerodynamic approach following Stull (1988). The formulae are

$$S = \rho_a C_p D_H (T_Z - T_0), \quad (2)$$

and

$$L = \rho_a L_e D_E (0.622/P_a)(e_Z - e_0), \quad (3)$$

where ρ_a is the air density (kg/m³), C_p the specific

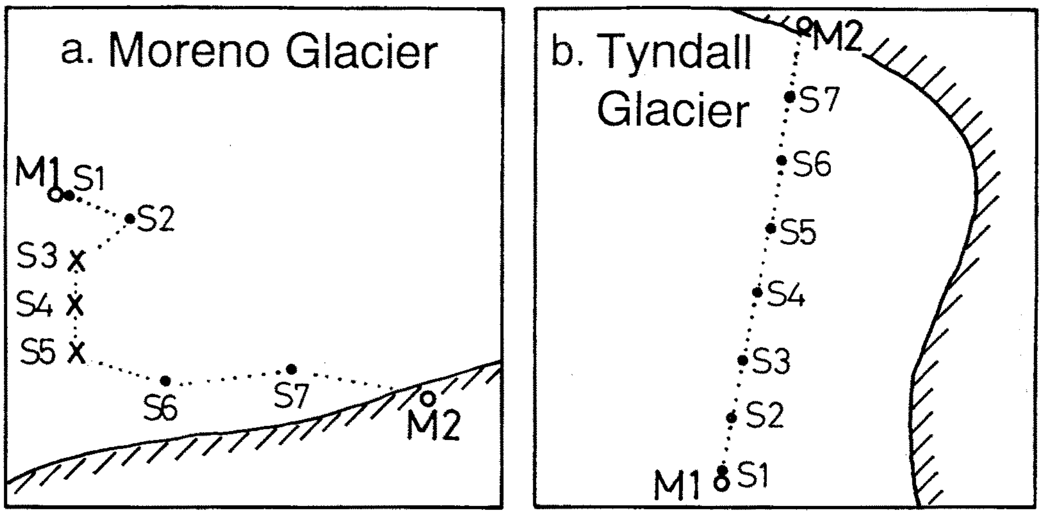


Fig. 2. Schematic maps showing stake sites on Moreno and Tyndall glaciers. ● : the stakes at the flat area. × : the stakes on the ridges of seracs. Dotted lines are the routes between M1 and M2.

heat of air at constant pressure (J/kg°C), T_Z the air temperature (°C) at the height of Z, T_0 the surface temperature (°C), L_e the latent heat of vaporization of water (J/kg), P_a the atmospheric pressure (hPa), e_Z the vapor pressure (hPa) at the height of Z, e_0 the vapor pressure (hPa) at the surface, D_H the bulk exchange coefficient for heat (m/s), and D_E the bulk exchange coefficient for water vapor (m/s). The temperature and vapor pressure at the melting ice surface are taken as 0 °C and 6.11 hPa, respectively.

It is assumed that, under a neutral condition, D_H and D_E are the same as the momentum exchange coefficient given by

$$D_0 = k^2 U_Z[\ln(Z/Z_0)]^{-2}, \quad (4)$$

where k is von Karman constant (=0.4), U_Z the wind speed (m/s) at the height of Z, Z the measurement height (m), and Z_0 the roughness height (m). When the atmospheric conditions are not neutral, the exchange coefficients should be corrected by using the following stability functions (Thom, 1975) :

$$\left.\begin{array}{ll} D = D_0(1-5R_b)^2 & 0 < R_b < 0.25, \\ D = D_0(1-16R_b)^{0.75} & 0 > R_b, \end{array}\right\} \quad (5)$$

where R_b is the bulk Richardson Number defined by

$$R_b = g(T_Z - T_0)Z/TU_Z^2, \quad (6)$$

where g is the gravitational acceleration (m/s²) and T the mean absolute temperature of air (K).

The roughness height Z_0 is calculated from wind speeds at two heights under neutral conditions ($|R_b| < 0.01$) using the equation,

$$Z_0 = \exp[U_2 \ln Z_1 - U_1 \ln Z_2)/(U_2 - U_1)]. \quad (7)$$

The values of Z_0 were 0.9 mm on Moreno Glacier and 0.6 mm on Tyndall Glacier.

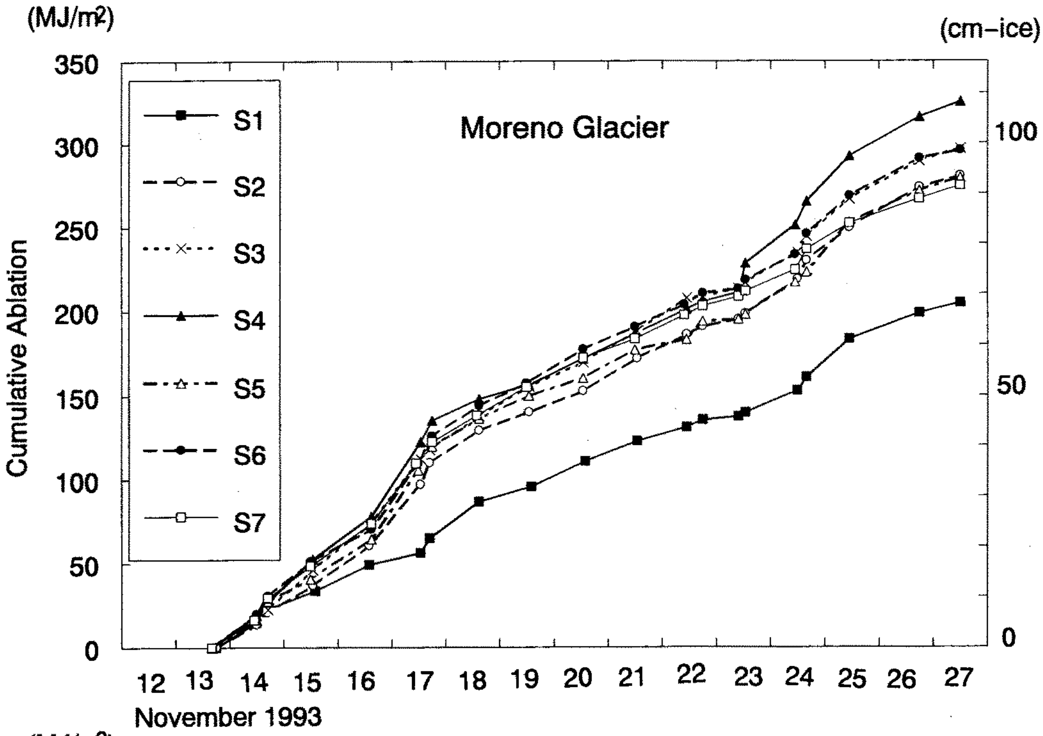
The amount of ablation measured by the stake was transformed into the heat (QM) used for ice melting, namely,

$$QM = \rho_i L_i h_i, \quad (8)$$

where ρ_i is the density of glacier ice (kg/m³), L_i the latent heat of ice fusion (J/kg), and h_i the ablation amount (m). The density of glacier ice was taken as 900 kg/m³ following Koizumi and Naruse (1992).

4. Ablation of ice during the observation period

The cumulative amounts of ablation measured with seven stakes at each glacier are shown in Fig. 3. Some differences can be seen among the stakes. The mean ablation rates during the observation periods ranged from 4.9 to 7.3 cm/day at Moreno Glacier and from 6.0 to 6.9 cm/day at Tyndall Glacier. Heat used for ablation (M) consists of the radiative heat flux (NR) and turbulent heat flux ($S + L$), as shown in equation (1). The net radiation (NR) is a sum of absorbed global radiation and net longwave radiation



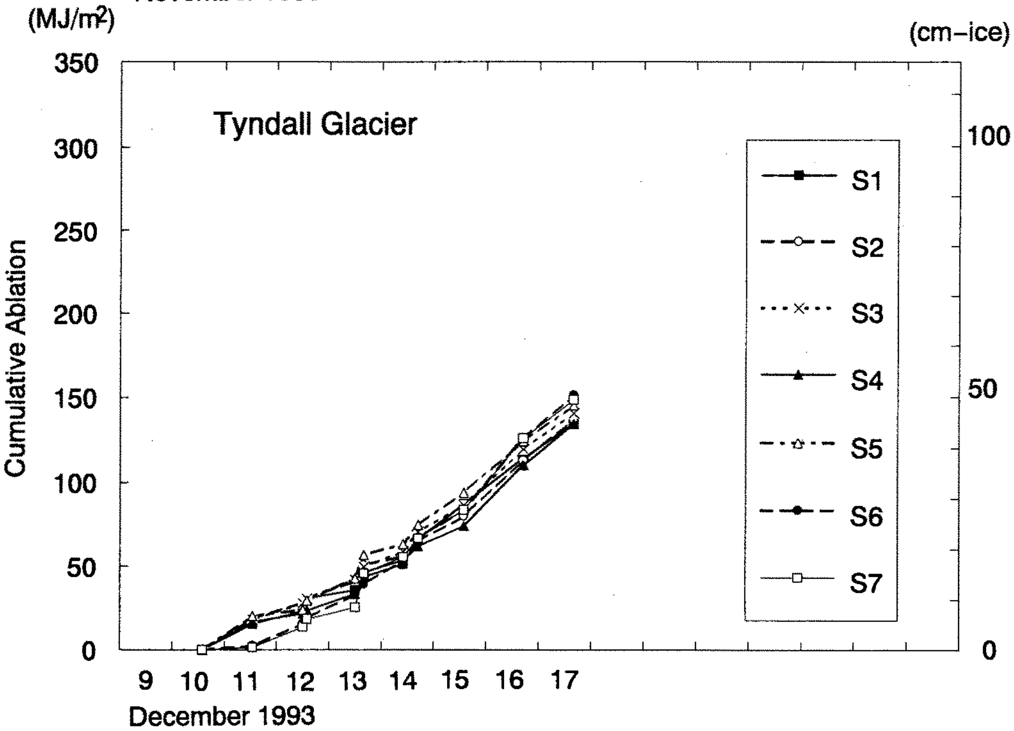


Fig. 3. Cumulative amounts of ablation measured with seven stakes during the observation periods at Moreno and Tyndall glaciers. Ablation amounts are expressed by cm in ice thickness on the right ordinate and by the energy on the left ordinate. Letters S1 to S7 are the stake numbers.

(LR) which is a sum of atmospheric and terrestrial radiations. That is,

$$NR = (1 - a)SR + LR, \quad (9)$$

where a is the albedo of glacier surface and SR the global radiation. It can be considered that the global and atmospheric radiations do not change within the small area of the seven stakes. Furthermore, because the glacier ice was melting at 0 °C and the emissivity of ice can be considered to be constant, there is no significant difference in the outgoing terrestrial radiation among the stakes. Therefore, the difference in ablation rates among stakes on the same glacier (Fig. 3) is caused by the difference in albedo (a) and turbulent heat flux ($S + L$).

The relationships between the albedo and the mean daily ablation rate at the each stake is shown in Fig. 4. From equations (1) and (9),

$$M = -aSR + (SR + LR) + (S + L), \quad (10)$$

is obtained. Then, it is considered that the slopes of the fitted lines in Fig. 4 indicate the global radiation (SR) during the whole period and values at which the lines intersect the vertical axis at $a = 0$ depend on turbulent heat flux ($S + L$), because the radiation term ($SR + LR$) does not change with the measurement sites on a glacier. At Moreno Glacier, the relationship between albedo and ablation rate could be expressed by two separate lines with the same slope as shown in Fig. 4. Difference between two groups, namely stakes (1, 2, 6 and 7) and stakes (3, 4 and 5), should be resulted from the difference in the turbulent heat flux ($S + L$). Since three stakes in the latter group were placed at the ridges of seracs (Fig. 2a), then $S + L$ may have been larger than that of the former group on the flat area. At Tyndall Glacier, the relationship could be expressed by one line (Fig. 4), because all stakes were set up on the flat surface.

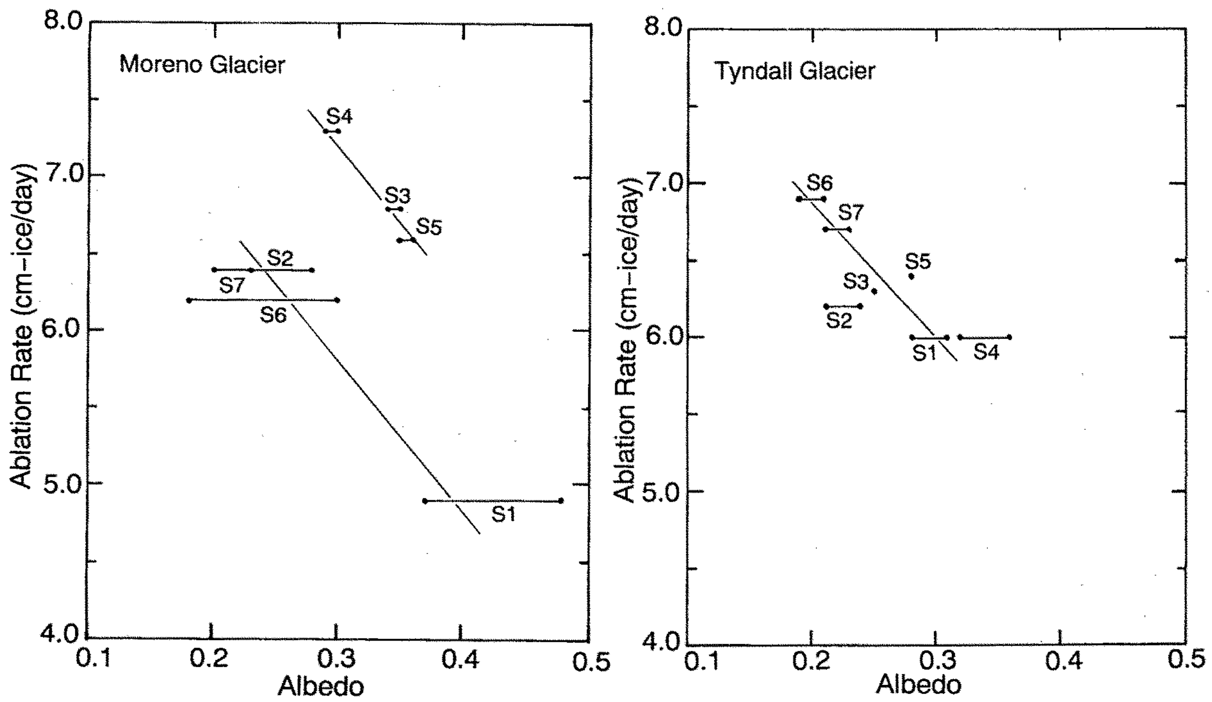


Fig. 4. Relationships between the albedo and the mean daily ablation rate in ice thickness at Moreno and Tyndall glaciers. Letters S1 to S7 are the stake numbers.

5. Heat balance at the glacier surface

5.1. Calculated heat for melting

Heat for ice melting calculated by the heat balance method was compared with that measured by stake 1 at site M1, as shown in Fig. 5. Energies for ablation calculated with equation (1) and others are slightly larger than the measured ones. Causes for this difference are not well understood at present. Nonetheless, the characteristics of contribution of heat balance terms to ice melting on both glaciers can be discussed with this heat balance method.

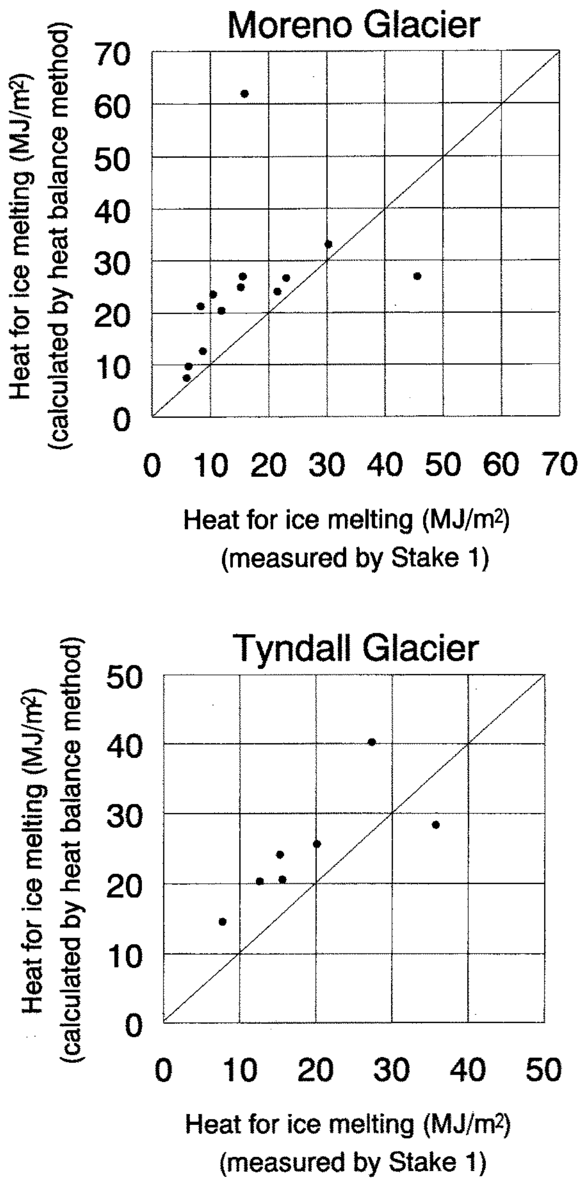


Fig. 5. Comparison of the heat for ice melting calculated by the heat balance method with that measured by a stake.

5.2. Characteristics of heat balance

Daily values of the heat balance components are shown in Fig. 6 at Moreno and Tyndall glaciers. The heat source for ice melting consisted mainly of net radiation and sensible heat flux. At Moreno Glacier, large sensible heat flux and ablation were observed on November 16 and 17. These were caused by high air temperature and strong wind, which were considered to be due to a Föhn phenomenon (Takeuchi *et al.*, 1995).

The daily heat balance components were separated into the daytime components with global radiation from 5 : 00 to 22 : 00 and the nighttime components without global radiation from 22 : 00 to 5 : 00 (Fig. 7). There was a clear difference in the heat balance components between the daytime and the nighttime. In the daytime, the amount of net radiation was more than a half of the total heat flux, indicating that net radiation is the most important factor for ice melting. In the nighttime, ice was melting continuously by the sensible heat in spite of negative net radiation.

The relationships between the daily ablation rate and the radiative heat flux or the turbulent heat flux are shown in Fig. 8. Values of ablation are obtained by averaging the data of seven stakes at each glacier. It was found that the contribution of turbulent heat flux was larger when the daily amount of ablation was larger on both glaciers. At Moreno Glacier, when the amount of ablation was smaller, radiative heat flux is nearly equal to turbulent heat flux, and the ablation increases with an increase in these heat fluxes as shown by fitted lines in Fig. 8. At Tyndall Glacier, although the amount of ablation increases with an increase in the turbulent heat flux, net radiation does not change day by day.

The mean daily values of heat balance components at the two glaciers during the respective observation period are compared in Fig. 9. The values on November 16 and 17, when a Föhn-like phenomenon occurred, were excluded from the mean for Moreno Glacier, and are shown separately in Fig. 9. Net radiation and sensible heat flux are the major heat sources for ice melting on both glaciers. It is noted that there are little difference between the values of net radiation of two glaciers. Because the mean air temperature was higher on Moreno Glacier, sensible heat flux was a little larger than that on Tyndall

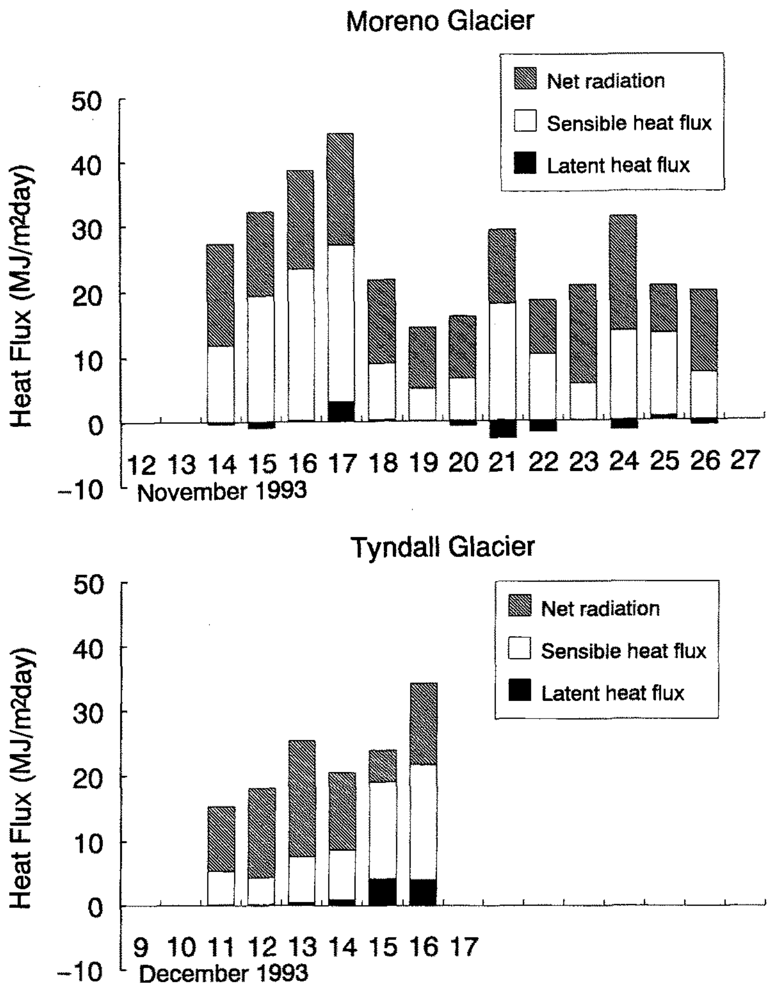


Fig. 6. Daily values of the heat balance components.

Glacier (Fig. 9). Latent heat flux was negative (that means evaporation) on Moreno Glacier where the relative humidity was small, while it was positive (that means condensation) on Tyndall Glacier where the relative humidity was large (Takeuchi *et al.*, 1995). Therefore, turbulent heat flux, that is a sum of sensible and latent heat flux, was slightly larger on Tyndall Glacier. It is an interesting result that there is little difference in the total heat for ice melting between two glaciers in spite of the considerable difference in meteorological conditions. During a Fohn-like phenomenon observed at Moreno Glacier, all heat balance components especially sensible heat flux increased, therefore ablation became almost twice as large as those in the ordinary days.

These results of heat balance characteristics in summer at southern Patagonia glaciers are compared with previous works at other glaciers in northern Patagonia and in New Zealand (Table 1). Those studies whose observation periods were December are selected and compared in Fig. 10. Among them, only the study at Moreno Glacier was made in November. At Franz Josef and Soler glaciers, the sensible heat flux is the largest component and the latent heat flux is the second, and they are larger than the net radiation. At San Rafael Glacier, the net radiation is the largest and the latent heat flux is the smallest component, which is similar to Moreno and Tyndall glaciers. Though the latent heat flux is the smallest component at San Rafael Glacier, it is more than twice as large as that at Tyndall Glacier and contributes substantially to ice melting. Only at Moreno Glacier, the latent

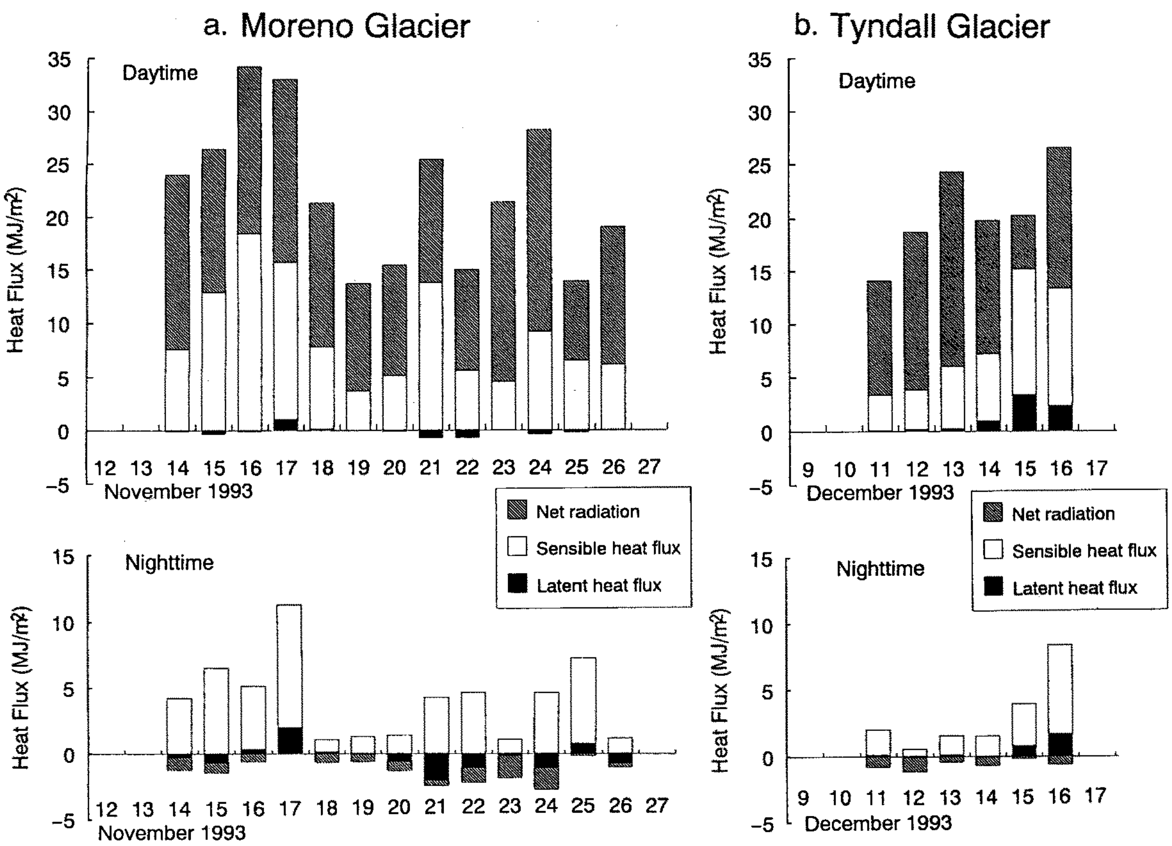


Fig. 7. Heat balance components for the daytime and the nighttime on Moreno Glacier (a) and Tyndall Glacier (b).

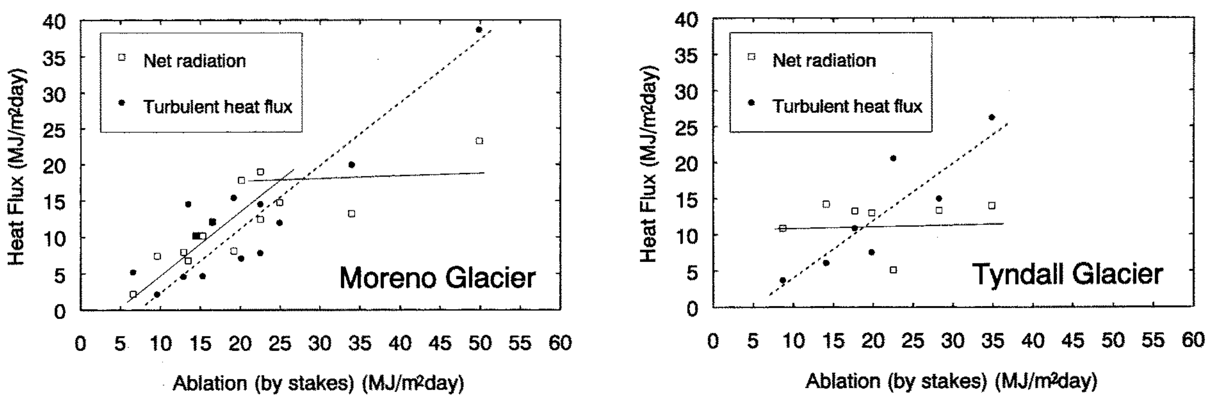


Fig. 8. The relationship between the daily ablation rate and the radiative/turbulent heat flux. Solid lines are fitted to the net radiation and broken lines to the turbulent heat flux.

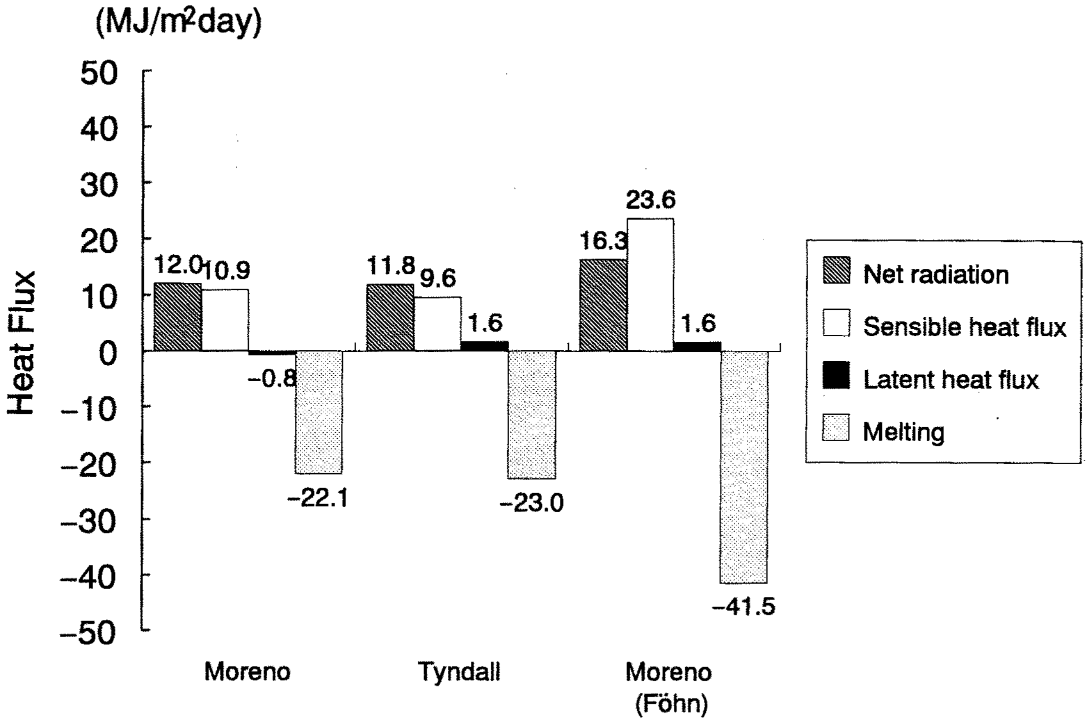


Fig. 9. The mean values of heat balance components during the respective observation period at the two glaciers. For Moreno Glacier, values on November 16 and 17, during which a Föhn-like phenomenon was observed, were excluded and shown separately.

Table 1. Heat balance on glaciers in middle latitude of the southern hemisphere in summer. *NR* is the net radiation, *S* the sensible heat flux, *L* the latent heat flux, *P* the precipitation heat flux and *M* the heat used for ice melting.
* References ; 1) Ishikawa *et al.* (1992), 2) Fukami and Naruse (1987), 3) Kobayashi and Saito (1985), 4) Ohata *et al.* (1985a), 5) Kondo and Inoue (1988), 6) This study.

Glaciers	*NR*	*S*	*L*	*P*	*M*	Observation Periods	References*
Franz Josef Glacier (43.4°s, 170.2°W)	6.66	5.08	2.96	—	-14.7	Oct. 19-21, 1981	1)
	6.8	8.56	7.37	0.71	-23.44	Dec. 15-17, 1981	1)
	9.62	25.50	11.44	—	-46.56	Feb. 9-13, 1990	1)
Soler Glacier (46°54′s,73°10′W)	5.30	5.54	-0.76	—	-9.01	Nov. 1-5, 1985	2)
	14.34	7.62	-0.32	—	-17.7	25-29, 1985	2)
	7.0	11.9	7.1	—	-25.9	Dec. 15-29, 1983	3)
San Rafael Glacier (46°41′s, 73°51′W)	11.7	8.9	3.5	—	-21.2	Dec. 29-Jan. 1, 1983/84	4)
Northern Patagonia Icefield	2.3	4.5	2.5	0.3	-9.6	Jan. 19-23 and Jan. 30-Feb. 1, 1985	5)
Merono Glacier (50°28′S, 73°02′W)	12.0	10.9	-0.8	—	-22.1	Nov. 12-27, 1993	6)
Tyndall Glacier (51°15′S, 73°15′W)	11.8	9.6	1.6	—	-23.0	Dec. 9-17. 1993	6)

Unit : MJ/m² day

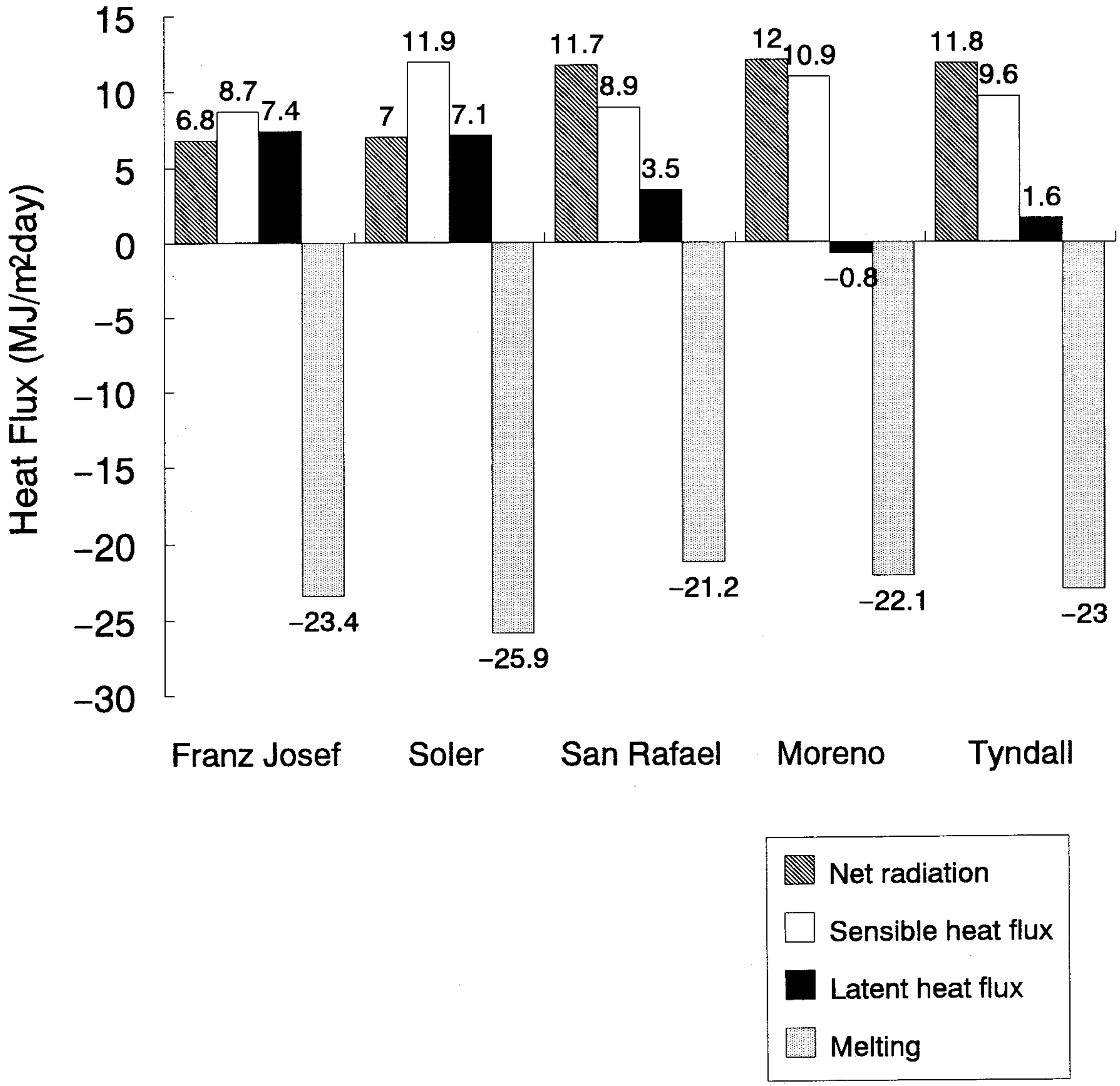


Fig. 10. Comparison of heat balance studies on glaciers in the middle latitude of the southern hemisphere in December. Only the study of Moreno Glacier was carried out in November.

heat flux is negative. At Soler Glacier in the eastern side of the icefield like Moreno Glacier, evaporation predominated in November, while condensation predominated in December (Table 1). Therefore, at Moreno Glacier, if air temperature should increase in December, condensation may predominate and ice melting may increase like at Soler Glacier. It is interesting that, in spite of the large differences in the ratio of heat balance components among glaciers, the total heat flux that is the heat for ice melting is almost the same value.

6. Relationship between ablation and air temperature

In glaciers, where it is difficult to make rigorous observation for a long period, the estimation of ablation using only the air temperature is very useful. The relationships between cumulative daily mean air temperature (ΣT) and cumulative ablation (ΣM) during the each observation period at two glaciers are shown in Fig. 11. If the relationship can be approximated linearly, an equation

$$\Sigma M = k \Sigma T \tag{11}$$

is given. Here, the parameter k has been called the degree-day factor (mm-water/°Cday). The relationships between ΣM and ΣT have been studied conventionally by a number of researchers (e.g. Kuusisto,

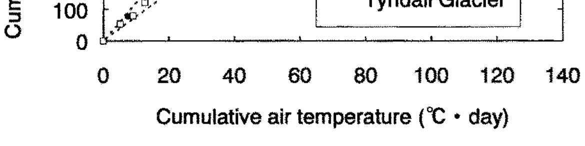


Fig. 11. The relationship between the cumulative amount of ablation and the cumulative daily mean air temperature during the periods from November 12 to 26 at Moreno Glacier, and from December 9 to 16, 1993 at Tyndall Glacier. The degree-day factors k were obtained as 7.6 and 12.4 (mm-water/°C day) for Moreno and Tyndall glaciers.

1984 ; WMO, 1965). The value of k was obtained as 7.6 at Moreno Glacier and 12.4 at Tyndall Glacier for the each observation period. In spite of the higher mean air temperature at Moreno Glacier than Tyndall Glacier, the heat for ice melting was almost the same value at both glaciers (Fig. 9), then the value of k at Moreno Glacier became smaller than that of Tyndall Glacier. The value at Moreno Glacier is comparable with the values at the debris covered surface of Soler Glacier and much larger than those at the bare ice surface of the glacier (Fukami and Naruse, 1987). The value at Tyndall Glacier was almost the same as the previous value of 11.8 obtained by Koizumi and Naruse (1992).

7. Summary

Comparisons of characteristics of ablation and heat balance between Moreno and Tyndall glaciers were made. Results obtained are summarized as follows :

1) The mean daily ablation rate ranged from 4.9 to 7.3 cm/day among seven stakes at Moreno Glacier and from 6.0 to 6.9 cm/day among seven stakes at Tyndall Glacier. The variation of the ablation rates can be accounted for by the differences in the surface albedo and turbulent heat flux at each stake site.
2) The heat source for ablation consisted mainly of net radiation and sensible heat flux on both glaciers. In the nighttime, ice melting was caused by sensible heat in spite of negative net radiation.
3) At Moreno Glacier, evaporation predominated during the observation period, while at Tyndall Glacier, condensation predominated.
4) In spite of differences in meteorological conditions during the observation periods, there was little difference in the mean daily ablation between the two glaciers except for the days when a Föhn-like phenomenon occurred at Moreno Glacier.
5) During a Föhn-like phenomenon at Moreno Glacier, all heat balance components, especially sensible heat flux, increased so that the ablation rate became almost twice as large as that in the ordinary days.
6) A degree-day factor, k, was obtained from a linear relationship between the cumulative ablation amount and the cumulative air temperature. The value of k is 7.6 at Moreno Glacier and 12.4 (mm-water/°C day) at Tyndall Glacier.

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