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Meteorological features at Moreno and Tyndall glaciers, Patagonia, in the summer 1993/94.

Yukari TAKEUCHI[1], Kazuhide SATOW[2], Renji NARUSE[1], Teresa IBARZABAL[3], Kenro NISHIDA[1] and Kenichi MATSUOKA[4]

1 Institute of Low Temperature Science, Hokkaido University, Sapporo 060 Japan

2 Nagaoka College of Technology, Nagaoka 940 Japan

3 Servicio Meteorolõgico Nacional, Buenos Aires Argentina

4 Department of Applied Physics, Faculty of Engineering, Hokkaido University, Sapporo 060 Japan

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Abstract

Details of meteorological conditions were studied at Moreno Glacier from November 12 to 27, 1993 and at Tyndall Glacier from December 9 to 17, southern Patagonia. Only a little precipitation was observed at Moreno Glacier, while a large amount was observed every day at Tyndall Glacier during the observation period. Glacier winds were blowing almost continuously on both glaciers, with the speed ranging from 0.6 m/s to 11.9 m/s on Moreno Glacier, and from 1.4 m/s to 15.2 m/s on Tyndall Glacier. A Föhn-like air temperature rise accompanied by the wind-speed increase was observed at Moreno Glacier. There was no difference in radiation characteristics between the two glaciers in spite of notable differences in weather conditions. The diurnal range of air temperature on Moreno Glacier was larger than that on Tyndall Glacier. The air temperature on Moreno Glacier tended to rise with an increase in the wind speed but did not correlate with global radiation. The air temperature on Tyndall Glacier correlated poorly with either global radiation or wind speed. These differences in the characteristics of air temperature fluctuations between the two glaciers can be attributed to the difference in the glacier expanse around the observation sites and the surface condition of the glaciers.

1. Introduction

Moreno Glacier flows northeastward from the Southern Patagonia Icefield (SPI) and terminates in a channel of Lake Argentino at an elevation of about 180 m. The snout is located at 50°28′S and 73°02′W (Fig. 1). The glacier has an area of about 257 km^2, with a length of 30 km from the southern divide and a mean width of 4 km in the ablation area. The general elevation of the divide is around 2000 m with the highest peak of 2950 m (Naruse and Aniya, 1992).

Tyndall Glacier flows southward from the SPI and terminates in a proglacial lake at an elevation of about 50 m around 51°15′S and 73°15′W (Fig. 1). The glacier area is about 355 km^2 and with a length of 40 km. The width of the ablation area is from 3.5 km to 10 km and the length is about 16–22 km (Naruse and Aniya, 1992).

In Patagonia, extensive studies on meteorological conditions, 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, 1985a, 1985b ; Kondo and Nakajima, 1985 ; Ohata *et al.*, 1985a, 1985b ; Fukami *et al.*, 1987 ; Fukami and Naruse, 1987 ; Fujiyoshi *et al.*, 1987 ; Inoue, 1987 ; Kondo and Inoue, 1988). As a result, much information and knowledge on meteorological conditions in Patagonian glaciers were obtained. For example, Ohata *et al.* (1985b) have reported that the east-west contrast in the meteorological conditions is due to three main factors, namely, the difference in cloud distribution, the existence of almost perpetual glacier winds and the occurrence of strong wind considered to be Föhn on the

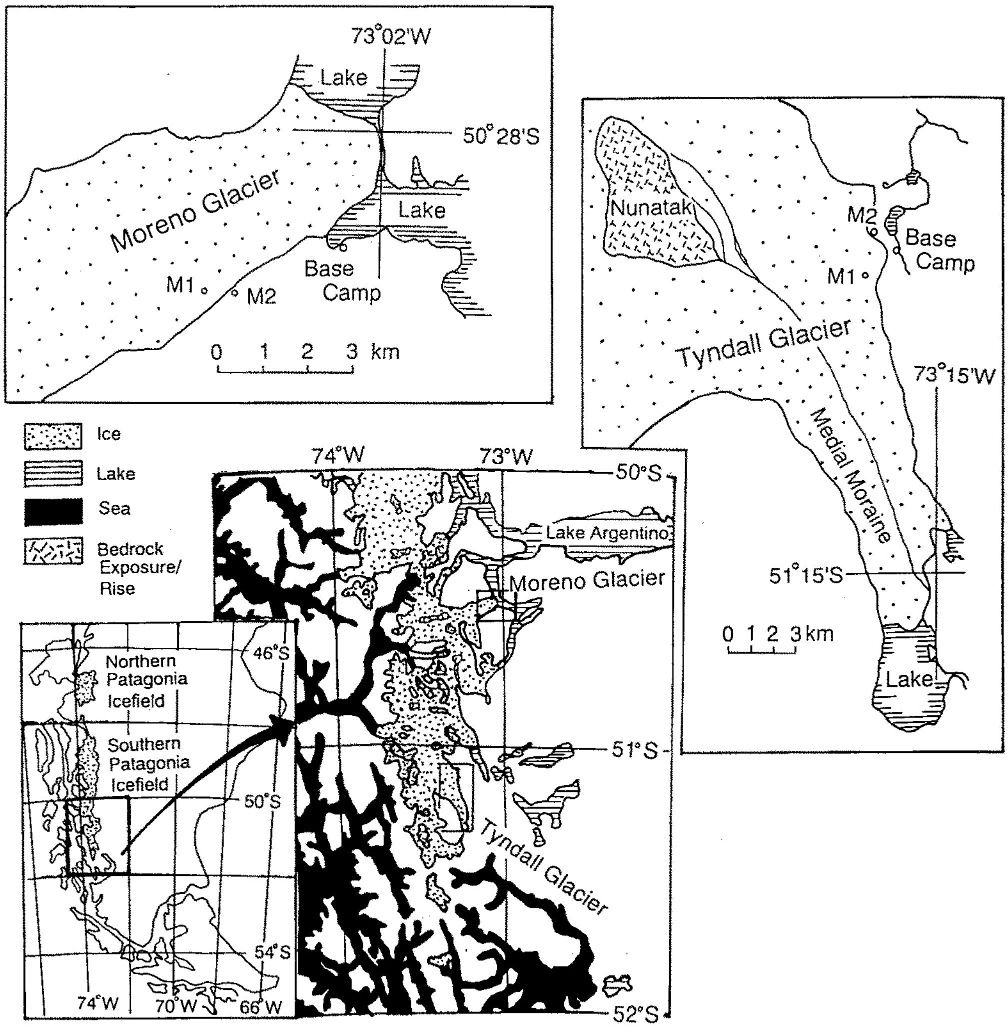

Fig. 1. Map of Moreno and Tyndall glaciers in southern Patagonia and observation sites at the glaciers. M1 : the main observation site on the glacier. M2 : the subsidiary observation site on the lateral moraine.

eastern side. Kobayashi and Saito (1985a) and Fukami *et al.* (1987) have also reported the occurrence of strong wind of Föhn at Soler Glacier (the eastern NPI).

In southern Patagonia, the report on Tyndall Glacier by Koizumi and Naruse (1992) has been the only study on meteorological conditions and ice ablation. No other meteorological data have been obtained in the SPI.

In order to investigate meteorological features, heat balance and ablation of glaciers in southern Patagonia, meteorological measurements were made at Moreno Glacier in November and at Tyndall Glacier in December 1993. This paper presents the observation methods and the measurement results at both glaciers and the characteristics of meteorological features of Moreno and Tyndall glaciers. Details of studies on heat balance and ice ablation are reported on a separate paper (Takeuchi *et al.*, 1995).

2. Observation site and measurement method

Three observation sites, M1, M2 and Base Camp, were established at each glacier, as shown in Fig. 1. Site M1 was the main observation site set up on nearly -flat bare-ice in the ablation area of each glacier.

Site M2 was the subsidiary observation site placed on the lateral moraine close to the glacier margin of each glacier. Some observations were made at the base camps : their altitudes are 180 m at Moreno Glacier and 400 m at Tyndall Glacier. The difference in altitude between the Base Camp and the observation site M1 was about 150 m at Moreno Glacier and about 300 m at Tyndall Glacier. The ground at the Base Camp was not covered with snow or ice at both glaciers during the observation periods. Observation periods were from November 12 to 27, 1993 at Moreno Glacier and from December 9 to 17, 1993 at Tyndall Glacier.

Meteorological elements and instruments used are summarized in Table 1. A sensor of hygrothermometer was inserted in a double vinyl chloride pipe for insulating global radiation and ventilated by a micro-fan with a solar battery during daytime. Maintenance of all instruments was made every day. Most of data measured at M1 and M2 were continuously recorded with portable data loggers. Air temperature and relative humidity data were corrected using the data measured occasionally with an Assmann psychrometer.

The net longwave radiation (LR) was calculated by

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

where NR is the net radiation, SR the global radiation and a the surface albedo of ice at the observation site. The mean value of a was 0.38 at Moreno Glacier and 0.28 at Tyndall Glacier.

3. Measurement results

Variations in major meteorological elements observed at Moreno and Tyndall glaciers are shown in Fig. 2. Mean and extreme values are shown in Table 2. A mean value of air temperature, 7.9 °C, on Moreno Glacier during the observation period was 2.8 °C higher than that on Tyndall Glacier. No systematic daily fluctuation in air temperature can be recognized on either glacier. The fluctuation of air temperature resembles that of wind speed on Moreno Glacier (Fig. 2a).

Glacier winds, which blow from the upglacier to the downglacier, were observed continuously on both glaciers. The direction of the prevailing wind did not

Table 1. Meteorological elements.
Site : Observation sites on the glaciers (M1).

Elements	Instruments	Frequency of measurement
Air temperature (1m)	Hygrothermometer (with sunshade and ventilation)	Continuous recording
Relative humidity (1m)	Hygrothermometer	Continuous recording
Wind speed (1m)	Three-cup anemometer	Continuous recording
Global radiation	Solarmeter pyranometer	Continuous recording
Reflected radiation	Solarmeter pyranometer	Continuous recording
All wave net radiation	Net rediometer	Continuous recording
Ablation amount	Ablation stakes	Once or twice a day

Site : Subsidiary observation sites on the lateral moraine (M2).

Elements	Instruments	Frequency of measurement
Global radiation	Pyranometer	Continuous recording
Precipitation	Tank type rain gauge	Once or twice a day

Site : Observation sites at the Base Camp.

Elements	Instruments	Frequency of measurement
Atmospheric pressure	Aneroid barometer	Continuous recording
Air temperature	Thermistor thermometer	Continuous recording
Air temperature (dry-bulb)	Assmann psychrometer	Every three-hours
(wet-bulb)	Assmann psychrometer	Every three-hours
Wind speed	Anemometer	Every three-hours
Wind direction	Visual observation	Every three-hours
Cloud amount	Visual observation	Every three-hours
Precipitation	Tank type rain gauge	Every three-hours

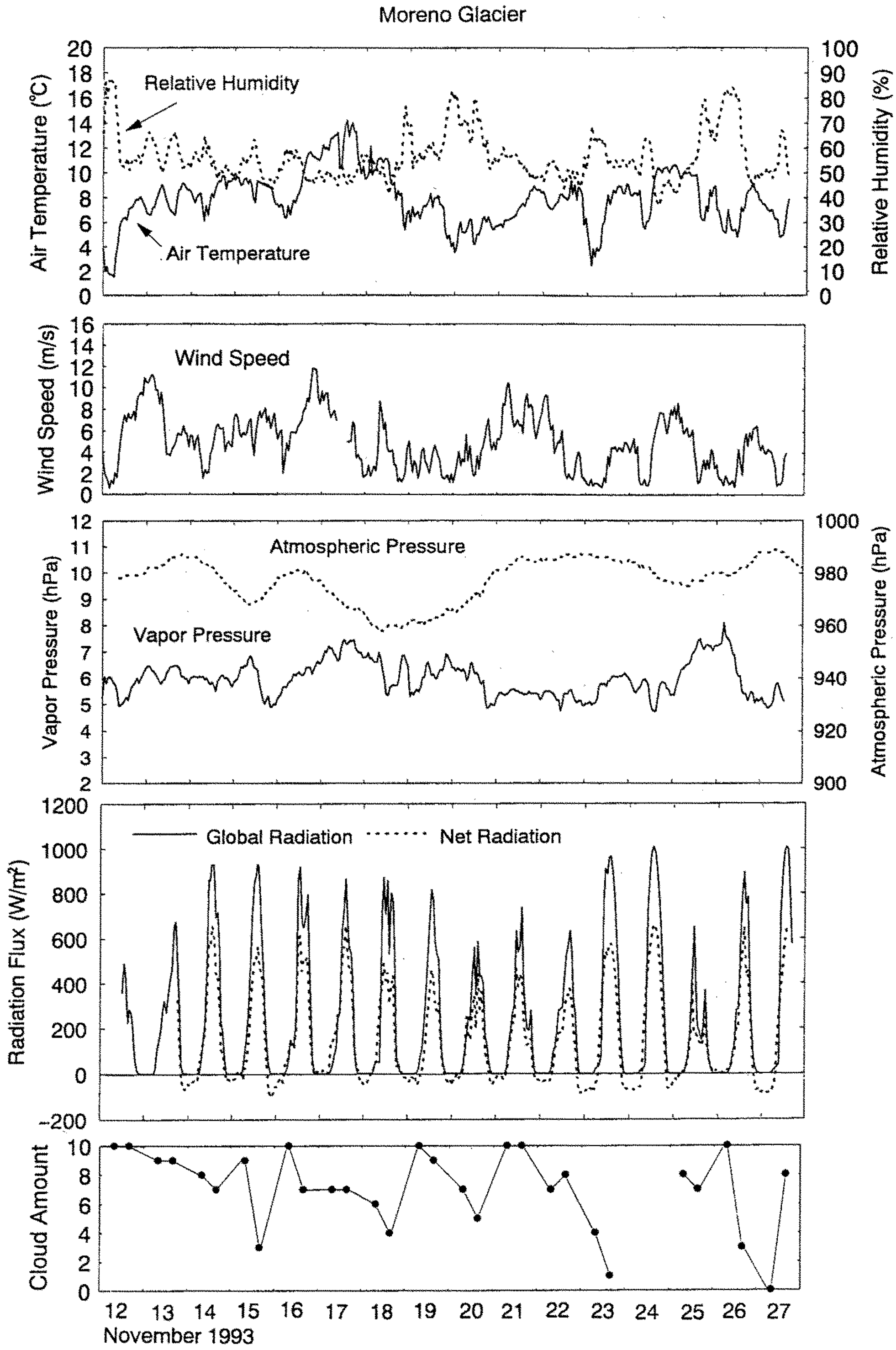

Fig. 2a. Variations in major meteorological elements at Moreno Glacier during the observation period.

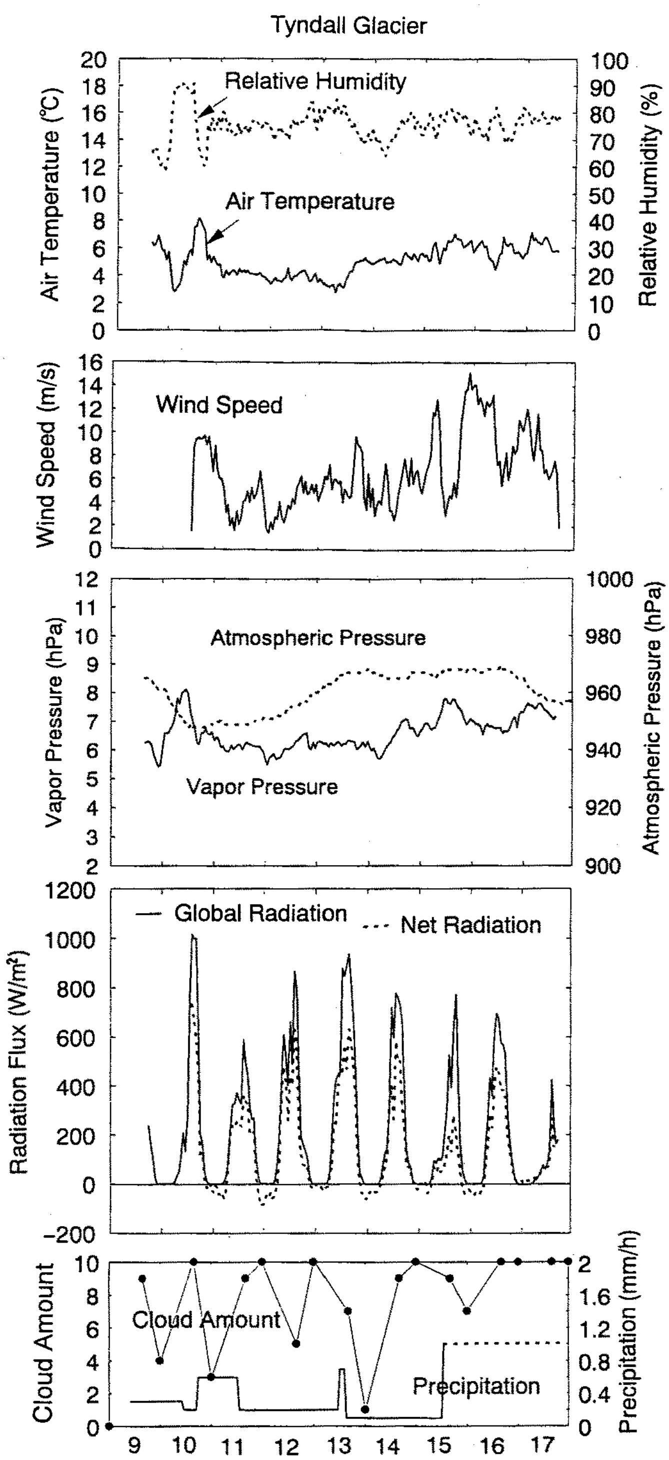

Fig. 2b. Variations in major meteorological elements at Tyndall Glacier during the observation period.

Table 2. Means and extremes of meteorological elements obtained at Moreno and Tyndall glaciers for each observation period.

Elements	Moreno Glacier			Tyndall Glacier		
	Maximum	Minimum	Average	Maximum	Minimum	Average
Air Temperature (℃)	14.3	1.5	7.9	8.2	2.7	5.1
Relative Humidity (%)	87.8	37.5	56.5	90.6	58.7	75.3
Vapor Pressure (hPa)	8.1	4.7	6.0	8.1	5.4	6.6
Wind Speed (m/s)	11.9	0.6	4.9	15.2	1.4	6.6
Atmospheric Pressure (hPa)	989	958	977	969	948	960
Global Radiation (W/m^2)	1010.0	0.0	239.4	938.6	0.0	234.3
Net Radiation (W/m^2)	655.0	−99.3	146.1	629.5	−84.7	136.9
Global Radiation (MJ/m^2 day)	28.1	11.4	20.5	28.0	14.8	20.2
Net Radiation (MJ/m^2 day)	17.3	7.2	12.6	17.9	4.9	11.8

change and it was the westerly on Moreno Glacier and the northerly on Tyndall Glacier. The hourly mean wind speed ranged from 0.6 m/s to 11.9 m/s and the mean value was 4.9 m/s on Moreno Glacier. On Tyndall Glacier, it ranged from 1.4 m/s to 15.2 m/s and the mean was 6.6 m/s. These ranges were comparable with those observed previously on Soler Glacier and Tyndall Glacier (Kobayashi and Saito, 1985a ; Koizumi and Naruse, 1992).

Air temperature on Moreno Glacier rose rapidly to reach a maximum of about 14 °C on November 16 and 17. Winds were very strong on these days. Due to the strong winds, a cup of the anemometer had tilted at about 9 : 00 on November 16, therefore there were no data of wind speed from 9 : 00 to 14 : 00. It may have been a Föhn phenomenon which was also observed at Soler Glacier on the eastern side of northern Patagonia (Kobayashi and Saito, 1985a ; Fukami *et al.*, 1987).

Relative humidity on Moreno Glacier was much smaller than that on Tyndall Glacier where precipitation occurred every day. On Moreno Glacier, the value of the relative humidity ranged from 37.5 % to 87.8 % and the mean was 56.5 %, whereas on Tyndall Glacier, it ranged from 58.7 % to 90.6 % and the mean was 75.3 %. The mean value of vapor pressure was 6.0 hPa on Moreno Glacier and 6.6 hPa on Tyndall Glacier. Since the vapor pressure of ice at 0 °C is 6.11 hPa, evaporation was dominant on Moreno Glacier, whereas condensation was dominant on Tyndall Glacier (Takeuchi *et al.*, 1995). Means of global and net radiation amounts were almost the same on both glaciers.

Only a little precipitation occurred at Moreno Glacier during the observation period. The total precipitation was about 2 mm from November 18 to 21 and 7.6 mm from November 25 to 26. On the other hand, at Tyndall Glacier precipitation was observed intermittently every day mostly with sunshine during the observation period. It rained continuously from December 15 to 18, and the total precipitation was more than 100 mm for three days. The precise amount of precipitation could not be measured due to an overflow from the rain collection bottles (the lowest plot in Fig. 2b). The clear difference in precipitation between the two glaciers is probably attributed to the different synoptic weather patterns between November and December 1993, as well as the topographical differences, such as the directions and scales of the glaciers.

4. Comparison of meteorological parameters at Moreno and Tyndall glaciers

4.1. *Characteristics of radiation*

The relationships between global radiation and net radiation are shown in Fig. 3. There is no significant difference between the two linear relationships at Moreno and Tyndall glaciers. The extremes and means of global radiation, net radiation and net longwave radiation are shown in Fig. 4. Because the observation period at Tyndall Glacier was closer to the summer solstice and the latitude of Tyndall Glacier is slightly ($<1°$) higher, the global radiation received at the top of the atmosphere over Tyndall Glacier should be about 10 % (daily value) larger than that over Moreno Glacier. However, the extremes and means of global, net all wave and net longwave

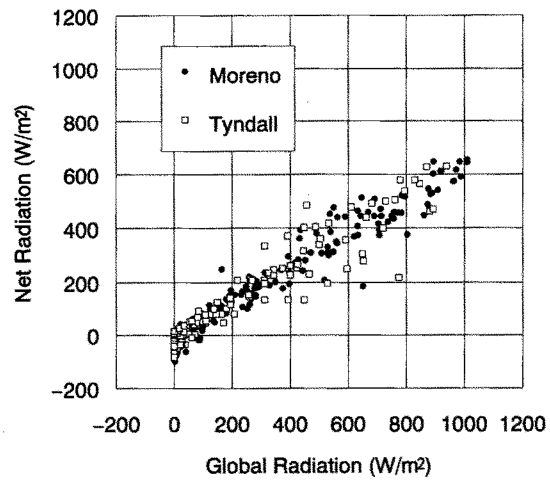

Fig. 3. Relationships between global radiation and net radiation on Moreno and Tyndall glaciers.

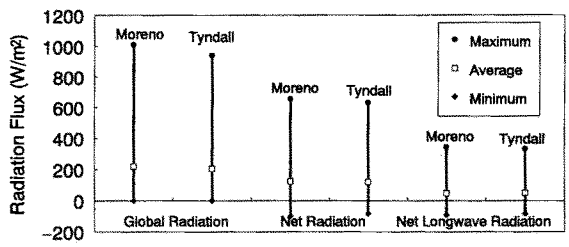

Fig. 4. The extremes and means of global radiation, net all wave radiation and net longwave radiation.

radiations were not much different between the two glaciers (Fig. 4). This may be due to the larger cloud amount at Tyndall Glacier than Moreno Glacier.

4.2. Variation of air temperature

4.2.1. Diurnal range of air temperature (ΔT)

The extremes and daily means of air temperature are shown in Fig. 5. Both maximum and minimum values on Moreno Glacier were generally higher than those on Tyndall Glacier. Here, the diurnal range of the air temperature, ΔT, is defined as the difference between the maximum and the minimum daily air temperature. It is noted that ΔT on Moreno Glacier was larger than that on Tyndall Glacier. The mean of ΔT was 4.4 °C on Moreno Glacier and 2.3 °C on Tyndall Glacier.

The relationships between ΔT at M1 on the glacier and that at the Base Camp are shown in Fig. 6. It is found that ΔT at the Base Camp was much larger than ΔT at M1 on both glaciers. Also noted is that

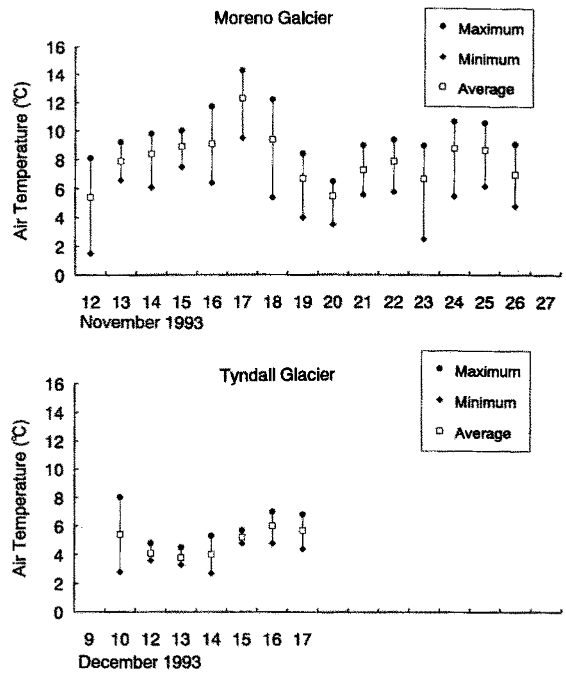

Fig. 5. The extremes and daily means of air temperatures.

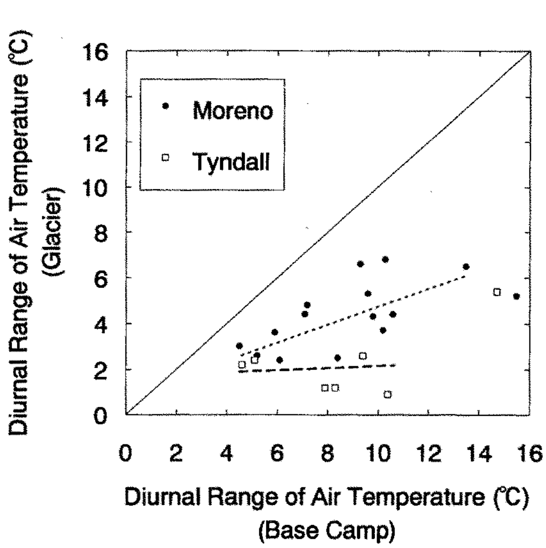

Fig. 6. Relationships between the diurnal range of air temperature (ΔT) on the glacier and at the Base Camp in Moreno and Tyndall glaciers.

ΔT at M1 of Moreno Glacier was larger than that of Tyndall Glacier. Although ΔT at M1 of Tyndall Glacier was almost constant as about 2 °C and is not related to that at the Base Camp, ΔT at M1 of Moreno Glacier tends to increase as that at the Base Camp increases.

Since it is expected that ΔT depends on the global radiation, ΔT was compared with the daily global radiation (Fig. 7). An apparent difference can be seen between the relationships at Moreno Glacier and at Tyndall Glacier ; ΔT was larger on Moreno Glacier than on Tyndall Glacier. On Tyndall Glacier, ΔT is a constant value of about 2 °C in spite of large changes in the global radiation, whereas on Moreno Glacier ΔT increases with an increase in the global radiation until about 23 MJ/m^2 day, after that ΔT do not change. On the other hand, there are no difference between these relationships at the base camps ; ΔT increases with an increase in the global radiation. These characteristics are discussed later.

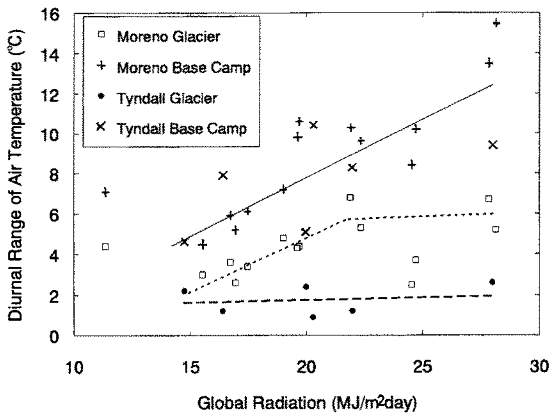

Fig. 7. Relationships between the daily global radiation and diurnal range of air temperature (ΔT) on the glacier and at the Base Camp in Moreno and Tyndall glaciers. A dotted line is fitted to values at Moreno Glacier, a broken line is to Tyndall Glacier, and a solid line is to the base camps of the two glaciers.

4.2.2. Relationships between air temperature and other meteorological parameters

The relationships between air temperature and global radiation are shown in Fig. 8. Air temperature

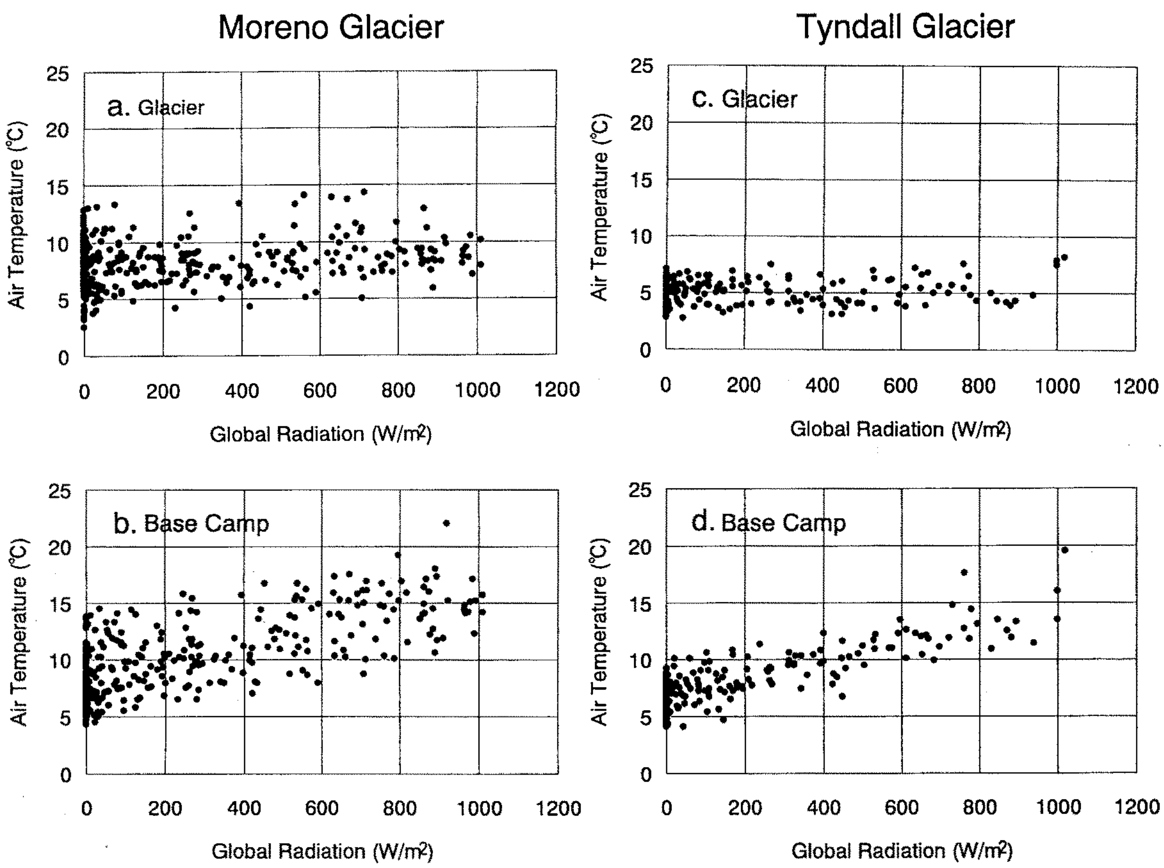

Fig. 8. Relationships between air temperature and global radiation on the glacier (a, c) and at the base camp (b, d) in Moreno and Tyndall glaciers.

at the Base Camp tended to rise with the increase in global radiation, as shown in Fig. 8b and 8d. However, there is no clear relationships between them at either glacier (Fig. 8a and 8c). This is probably because that the surface temperature of melting glacier was kept at 0 °C even when it received much radiation.

The relationships between air temperature and wind speed on the glaciers are examined in Fig. 9. Air temperature on Moreno Glacier correlated well with wind speed, that is, the air temperature tended to rise with the wind speed. On the other hand, air temperature on Tyndall Glacier poorly correlated with wind speed.

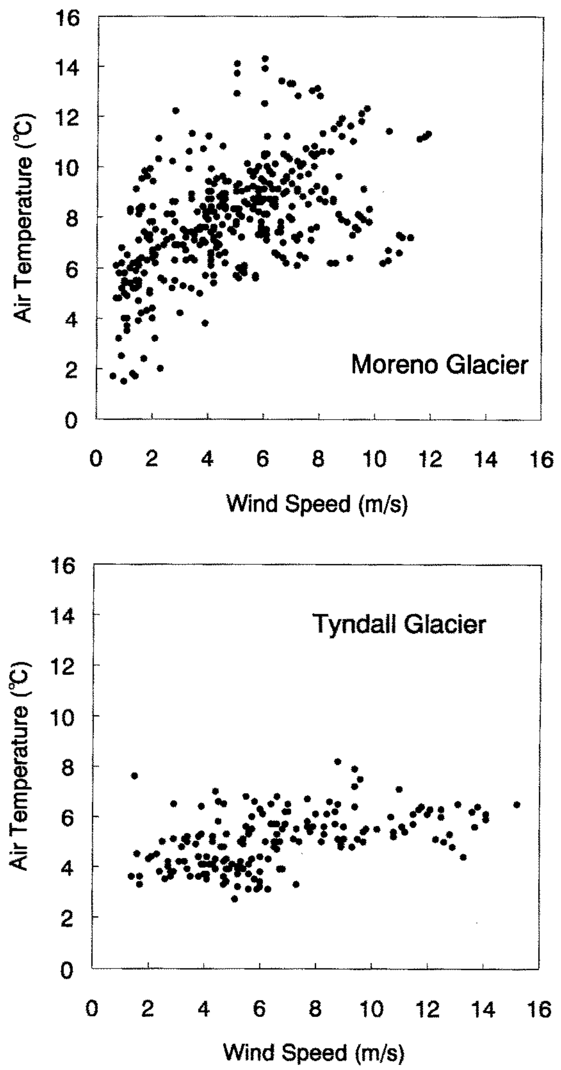

Fig. 9. Relationships between air temperature and wind speed on Moreno and Tyndall glaciers.

5. Discussion and conclusion

The following results were obtained. Air temperature was independent of the global radiation both on Moreno and Tyndall glaciers, and the diurnal range of air temperature (ΔT) on Moreno Glacier was larger than that on Tyndall Glacier in spite of the same surface temperature of 0 °C. The air temperature correlated well with the wind speed on Moreno Glacier, while it correlated poorly with the wind speed on Tyndall Glacier.

These differences in the characteristics of air temperature fluctuations between these two glaciers may be attributed to the difference in the areal expanse around the observation site and the surface condition of the glacier ice. Because the surface expanse of Tyndall Glacier at the M1 site is much larger than that of Moreno Glacier and is not confined by the side-walls, the air temperature at M1 on Tyndall Glacier may not be strongly influenced by the surrounding ice-free surface, but rather controlled by the glacier ice. Therefore, the air temperature was kept low, being independent of global radiation and wind speed, and hardly fluctuated. On the other hand, on Moreno Glacier where glacier surface expanse around M1 is smaller and the glacier is confined by valley walls, the warm air mass heated on the rock or bare ground around the glacier may have advected to the glacier readily. Also since there are many seracs and crevasses, active convections caused by the rough surface could transport the upper warm air mass into the surface boundary layer of the glacier. Consequently, air temperature correlated well with wind speed and ΔT increased with daily global radiation.

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