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Annual air-temperature measurement and ablation estimate at Moreno Glacier, Patagonia

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Abstract

Continuous, annual records of air temperature were successfully obtained at two sites around the lower reach of Moreno Glacier, Patagonia, from November 1993 to December 1994. Monthly mean air temperatures near the glacier front (180 m a.s.l.) in the warmest month (January) and the coldest month (June) were 11.3°C and 0.3°C, respectively. The lapse rate of air temperature was about 0.8°C/100 m throughout the year. Annual ablation at a point of 330 m a.s.l. was estimated at 12.8 m-water in 1993/94 using a degree-day method with the measured air temperatures at two sites. Year-to-year variation in ablation caused by a change in annual mean air temperature was estimated at $\pm 1-2$ m-water based on 10-years air temperature data at the nearest Meteorological Station Lago Argentino.

1. Introduction

At several glaciers in Patagonia, southern South America, detailed glaciological and meteorological studies were carried out four times since 1983 as the Glacier Research Project in Patagonia (GRPP). Short-term data in summer as to meteorological conditions, ice ablation and heat balance have been much accumulated (Kobayashi and Saito, 1985a, 1985b ; Kondo and Nakajima, 1985 ; Ohata *et al.*, 1985a, 1985b, 1985c ; Fukami *et al.*, 1987 ; Fukami and Naruse, 1987 ; Fujiyoshi *et al.*, 1987 ; Inoue, 1987 ; Kondo and Inoue, 1988 ; Koizumi and Naruse, 1992 ; Takeuchi *et al.*, 1995a, 1995b). However, no annual continuous data have been obtained, because the glaciers are far from the human habitation and it is difficult to acquire reliable data without maintenance at or around glaciers.

In order to discuss the recent glacier variation, that is the main theme of the GRPP, the amount of annual ablation is one of the important factors to be known. Long-term ablation rates during four months in summer of 1993/94 were measured (Naruse *et al.*, 1995b) at Moreno Glacier, an eastward outlet glacier from the Southern Patagonia Icefield (Naruse and Aniya, 1995). From November 1993 to December 1994, a yearly complete record of air temperature was successfully obtained at the lateral bank of the glacier. This report presents the characteristics of annual variation in air temperature and an annual ablation rate estimated from daily means of air temperature at Moreno Glacier.

2. Method of air temperature measurement

Two measurement sites of air temperature were established on November 28, 1993 at the right-hand bank of Moreno Glacier, namely Base Camp (B.C.) near the calving front and Upper Camp (U.C.) in the middle reach of the ablation area, as shown in Fig. 1. The altitude of B.C. was 180 m a.s.l. and U.C. was about 150 m higher than B.C. The both sites were located in a forest, but close to a boundary between the glacier and the forest. Therefore, it is considered that the thermometers were thoroughly shaded with leaves and branches, and the strong downglacier winds could pass through the measurement sites.

At each site, a thermistor sensor was inserted in a double vinyl-chloride pipe to be insulated from radiation. The pipe was fixed to a tree, at about 2 m

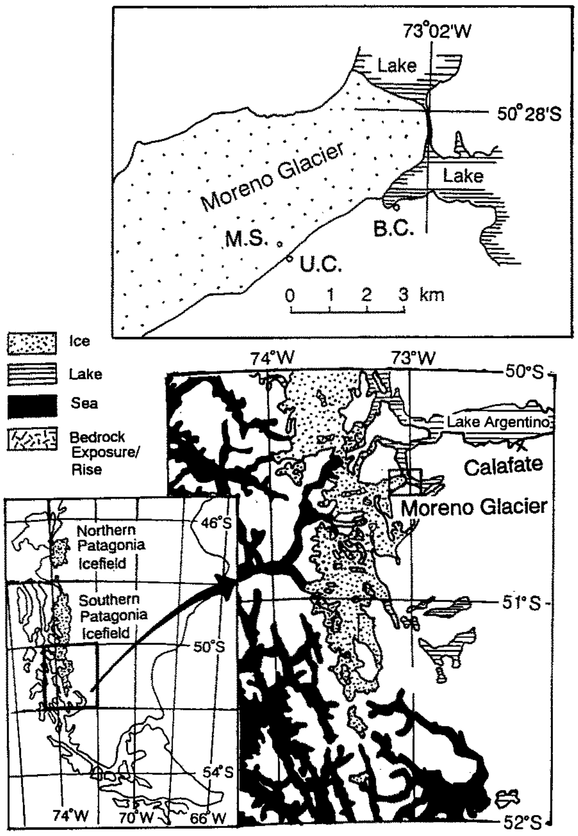

Fig. 1. Map of Moreno Glacier in southern Patagonia and observation sites at the glacier. M.S.: Meteorological Station on the glacier. B.C.: Temperature measurement site at Base Camp. U.C.: Temperature measurement site at Upper Camp.

above the ground, and was set toward the upglacier direction, i.e. the prevailing wind direction. Hourly mean air temperatures were recorded with a portable data logger (KADEC-U). No maintenance was made, until taking the logger off on December 15, 1994.

M.S. in Fig. 1 indicates the Meteorological Station on the glacier (about 330 m a.s.l.) where detailed observations were made in November 1993 (Takeuchi *et al.*, 1995a).

3. Results

3.1. Characteristics of air temperature variation

Daily mean air temperatures from December 1, 1993 to November 30, 1994 at two sites, B.C. and U.C., are shown in Fig. 2. The temperature fluctuated by about several degrees with a mean cycle of four days. Low temperatures were observed in the end of May and in the late July in 1994. Except for a few days, the daily mean air temperature at B.C. was higher than U.C. Temperature differences between the two sites are also shown in Fig. 2. No seasonal variations in the difference are seen, and the annual mean difference was obtained as 1.2°C, which is equivalent to 0.8°C/100 m in a lapse rate.

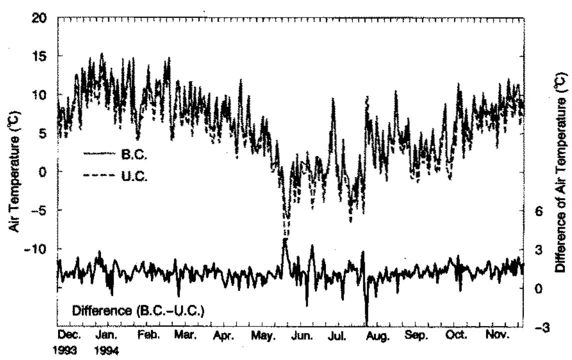

Fig. 2. Daily mean air temperatures at Base Camp (B.C.) and Upper Camp (U.C.), and the difference between them from December 1, 1993 to November 30, 1994.

Monthly mean air temperatures, from January to November 1994 and December 1993, are shown in Fig. 3. Values in the warmest month (January) and coldest month (June) were 11.3°C and 0.3°C at B.C., and 10.0°C and −0.9°C at U.C. The annual range of monthly mean air temperature was about 11°C.

In Fig. 3, monthly mean temperature data at the Meteorological Station Lago Argentino (L.A., 220 m a.s.l.) in Calafate are also shown. Calafate is a nearest town located at about 60 km east of the front of Moreno Glacier. The solid line (L.A.) indicates the mean value over ten years from 1981 to 1990, and two broken lines show the maximum and minimum values during the period, respectively. The difference in monthly mean air temperature between the glacier area (B.C. and U.C.) and the Station L.A. was small in

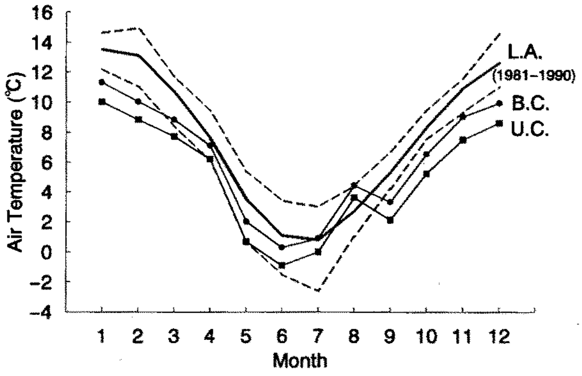

Fig. 3. Monthly mean air temperatures at Base Camp (B. C.) and Upper Camp (U.C.) from December 1993 to November 1994. The solid line is the mean over ten years from 1981 to 1990, and the broken lines are the maximum and the minimum during that period at the Meteorological Station Lago Argentino (L.A.).

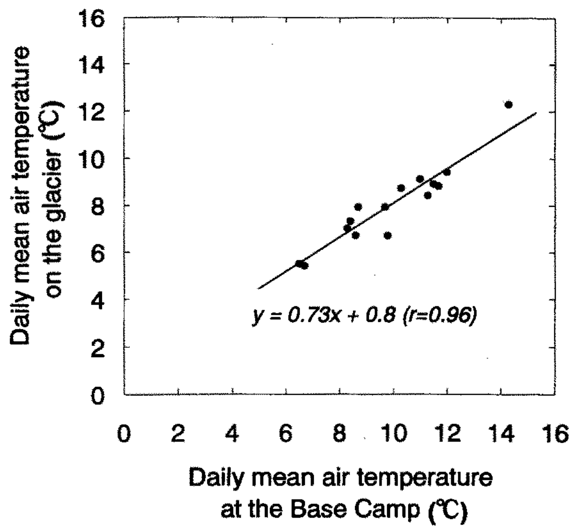

Fig. 4. The relationship between daily mean air temperatures at Base Camp and Meteorological Station on the glacier, during 15 days in November 1993.

the cold season (April to August), but the temperature in the glacier area was apparently lower than L.A. in the warm season (November to March). This tendency may have been caused by the difference in local climatic and topographic features, namely the existence of large-scale ice-covered area near B.C. (and U.C.), and a dry, inland climate around the Station L. A.

3.2. Annual ablation estimate

Annual ablation is estimated using a degree-day method, which is shown as,

$$M = k \Sigma T, \qquad (1)$$

where, ΣT is called a degree-day (i.e. cumulative daily mean air temperature above 0°C), M is the total ablation (mm in water equivalent) during the period, and k is a factor which should be determined empirically. When an annual record of daily air temperature is available and an appropriate value of k is known, then M can be calculated.

Air temperature (T) at M.S. on the glacier and at U. C. (T_{UC}) were not measured at the same time, so the relationship between them cannot be known. Then T was estimated from the measured temperature (T_{BC}) at B.C. In Fig. 4, the relationship between T and T_{BC} during the observation period from November 12 to 27, 1993 is shown. A linear relation between T and T_{BC} can be expressed by,

$$T = 0.73 \times T_{BC} + 0.8, \qquad T_{BC} > 7^{\circ}\mathrm{C} \qquad (2)$$
$$T = T_{UC}, \qquad T_{BC} \leqq 7^{\circ}\mathrm{C}$$

A correlation coefficient (r) is 0.96. The relationship was obtained in a summer season, then it may not be applicable well in colder conditions than about 7°C. Since U.C. was set up in an ice-free area at the same altitude of M.S., T_{UC} is expected to be equal to or higher than T. When T_{BC} was below about 7°C, T calculated by the equation (2) became higher than T_{UC}. Then, in such conditions, T is assumed to be equal to T_{UC}. Daily mean air temperatures estimated for M.S. from T_{BC} and T_{UC} are shown in Table 1, during one year from December 1993 to November 1994.

Ablation rates were measured with four stakes around 330 m a.s.l. on Moreno Glacier during a summer from November 12, 1993 to March 1, 1994. Due to high air temperature, no accumulation of snow was expected to occur for the period (Table 1). The mean ablation was 7.0 m in ice thickness, that is 6.3 m in water equivalent by assuming the ice density as 900 $\mathrm{kgm^{-3}}$ (Naruse *et al.*, 1995b). Cumulative daily mean air temperature on the glacier (ΣT) during this period was 884 (°Cday). Figure 5 shows the relationship between cumulative air temperature and cumulative

Table 1. Daily mean air temperature at the meteorological station (M.S., 330m a.s.l.) on Moreno Glacier

Date	'93Dec.	'94Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.
1	7.7	9.3	3.8	3.7	3.7	3.8	-1.4	0.8	3.5	5.9	0.7	6.1
2	6.4	8.5	2.9	7.0	4.6	2.3	-0.3	4.5	5.7	3.0	-0.1	6.0
3	4.4	10.8	5.8	6.9	7.2	5.3	0.6	2.6	5.8	-0.7	-0.8	5.3
4	6.9	12.0	7.2	9.3	7.9	2.7	-3.9	7.8	3.6	-0.8	-1.0	6.3
5	6.9	12.0	6.9	9.4	4.8	2.8	-2.1	7.2	0.9	-0.8	1.4	7.4
6	6.8	9.9	8.7	8.3	3.8	2.4	2.2	3.5	0.5	2.5	1.9	5.6
7	4.3	11.2	8.7	6.6	5.0	3.5	-4.2	-0.5	5.5	1.3	4.8	6.9
8	4.5	8.2	7.4	5.8	7.0	3.1	-2.6	0.5	4.6	-1.3	3.5	7.2
9	7.9	9.6	9.7	6.4	7.5	5.5	1.2	-2.9	3.2	-1.0	7.2	3.2
10	6.0	7.4	10.9	8.9	6.3	6.1	0.1	-3.8	-0.2	3.3	9.0	6.2
11	5.3	8.4	8.3	7.0	8.0	2.1	-0.2	-0.7	0.5	4.2	7.0	9.2
12	6.6	10.6	8.6	6.3	5.7	5.0	-0.2	3.2	4.8	1.3	8.2	7.2
13	7.4	9.3	7.6	6.2	6.7	5.8	0.0	-0.1	1.2	1.2	5.5	6.9
14	7.4	9.6	6.7	9.3	7.9	2.6	1.7	-1.6	0.9	2.8	1.8	7.9
15	10.0	6.2	7.5	9.3	4.6	3.8	0.5	-1.8	-1.2	3.0	4.8	5.2
16	10.0	8.3	9.6	4.5	4.7	2.9	-2.1	-2.0	2.8	0.6	6.9	6.6
17	9.4	9.6	8.8	6.6	5.4	0.1	-2.2	-5.0	5.5	-0.3	4.0	8.8
18	5.5	7.7	9.3	8.8	5.9	0.0	-4.8	-6.7	4.4	2.0	4.3	9.7
19	5.5	5.5	9.5	6.9	3.3	0.3	-3.5	-3.9	3.0	2.9	2.9	8.2
20	10.7	7.7	6.6	6.1	1.7	0.4	-1.9	-3.5	2.4	4.9	4.2	8.0
21	9.3	11.5	6.4	7.7	5.7	3.1	1.9	-3.9	4.1	2.3	7.2	7.0
22	10.3	7.4	9.9	8.8	8.7	1.0	1.7	-2.1	8.5	0.3	8.1	9.1
23	8.0	8.5	11.2	6.9	9.6	-2.0	-1.1	-4.8	7.6	0.0	6.8	7.6
24	7.7	9.0	9.3	7.6	5.2	-0.9	1.0	-0.1	4.7	1.3	6.6	8.2
25	10.1	10.5	10.7	8.0	4.5	0.0	0.6	1.7	4.0	0.3	5.4	9.1
26	11.6	11.3	11.6	7.1	3.2	-2.7	-1.0	-0.5	2.9	2.9	6.1	9.0
27	8.4	8.4	6.6	4.9	4.1	-7.1	-3.9	-3.3	4.3	3.3	7.2	6.1
28	10.4	5.8	3.6	7.1	7.1	-8.7	-2.0	-5.4	2.4	4.7	5.1	7.7
29	11.2	11.6		8.2	8.0	-8.8	-0.3	0.4	3.3	6.6	8.3	6.9
30	8.7	6.8		4.7	4.4	-8.3	-0.4	6.9	4.6	7.2	7.2	7.4
31	9.4	6.7		4.6		-5.6		5.8	3.1		7.7	

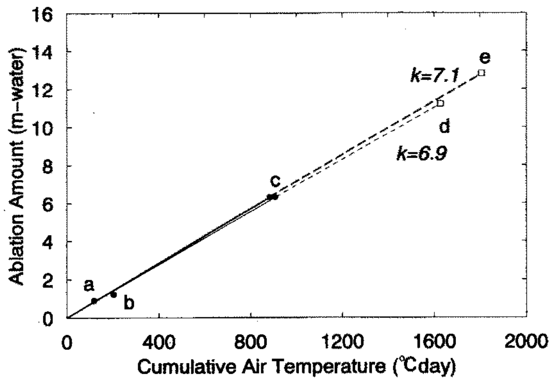

Fig. 5. Cumulative amount of ablation plotted against cumulative daily mean air temperature (degree-day). The solid line indicates a relationship obtained during a period from November 12, 1993 to March 1, 1994 ; the broken line is an extrapolated relationship throughout the year. The point **a** is the value from November 12 to 26, 1993 ; **b** is from November 12 to December 9, 1993 ; **c** is from November 12, 1993 to March 1, 1994 ; **d** is quoted from Naruse et al. (1995b) ; **e** is from December 1, 1993 to November 30, 1994.

ablation starting from November 12, 1993. The solid line indicates a relationship obtained during the period from November 12, 1993 to March 1, 1994 ; the broken line is an extrapolated relationship throughout the year. A gradient of the solid line gives a degree-day factor k and was obtained as 7.1 (mm $°C^{-1}day^{-1}$), which was very close to the value 6.9 obtained using the air temperature at the Station L.A. (Naruse *et al.*, 1995b). Points **a**, **b** and **c** indicate values on November 26, 1993 (Takeuchi *et al.*, 1995b), December 9, 1993 and March 1, 1994, respectively, and the point **d** is a yearly value estimated from the data at the Station L. A. (Naruse *et al.*, 1995b).

Cumulative daily mean air temperature (ΣT) on the glacier for one year from December 1, 1993 to November 30, 1994, was calculated as 1806 (°Cday), in which daily mean air temperature below 0°C was excluded because it could not contribute to melting. A point **e** is plotted in Fig. 5 for a yearly value in 1993/94. Accordingly, the annual ablation M for this year was derived as 12.8 m in water equivalent.

4. Discussion

The annual ablation of 12.8 m-water derived in this study is larger than 11.2 m-water (±1 m) estimated by Naruse *et al.* (1995b). Their value results from that, during a winter from May to August, mean air temperature was regarded to be close to or below 0°C, then the daily mean air temperatures in this period were excluded from the annual cumulative temperature. However, from the temperature data (Table 1) at Moreno Glacier, it is known that the daily mean air temperature became below 0°C for about 50 days from the end of May to July and melting of ice or snow may have occurred intermittently even during a winter season.

Annual ablation estimated here is a sum of annual balance and melting of newly deposited snow. If the glacier surface is supposed always to be the exposed ice (of density 900 kg m^{-3}), the annual ablation of 12.8 m in water equivalent corresponds to 14 m in ice thickness. According to the precipitation record at the Station L.A. (Ibarzabal *et al.*, 1996), the amount of precipitation in autumn and winter (from March to August) is clearly larger than that in spring and summer (from September to February). Also with the temperature data, it is considered that the ablation area of Moreno Glacier is often covered with new snow in winter. Therefore, a certain part of 12.8 m -water is due to melting of snow. Hence, an annual ablation of 14 m in ice thickness indicates a maximum, possible annual balance.

Year-to-year variation in ablation caused by air temperature change is examined. The relationship between the daily mean air temperature (T_{LA}) at the Station L.A. and (T) at M.S. on the glacier in November 1993 is shown in Fig. 6. The relation was expressed by,

$$T = 0.62 \times T_{LA} + 0.6, \qquad T > 4°C \qquad (3)$$

A correlation coefficient (r) is 0.86. The mean, maximum and minimum values of annual air temperature at L.A. during the recent ten years from 1981 to 1990 are 7.5°C, 8.3°C and 6.9°C, respectively. If equation (3) can be applied also to the relationship of annual mean air temperature between at L.A. and M. S., the mean, maximum and minimum values of annual air temperature at M.S. for ten years are derived as 5.3°C, 5.7°C and 4.9°C, respectively. The annual mean air temperature at M.S. from December 1993 to November 1994 was 4.6°C, then this year could be regarded as cold. Assuming annual mean air temperature to be 5.7°C (the maximum value), the ablation is estimated as 14.8 m-water, and assuming it to be 4.9°C, the ablation is estimated as 12.7 m-water. On the other hand, assuming the range of air temperature variation at M.S. to be the same as that at L.A.(1.4°C), the ablation is estimated as 15.5 m-water and 11.9 m -water for the maximum and the minimum year, respectively. These values estimated from annual mean air temperatures are probably underestimated especially for the minimum values, because the daily mean air temperature below 0°C was not excluded from the annual mean. Then the difference between the maximum and the minimum values are probably smaller. Then the variation in glacier ablation caused by year-to-year variation in air temperature during the last 10 years can be estimated as ±1−2 m.

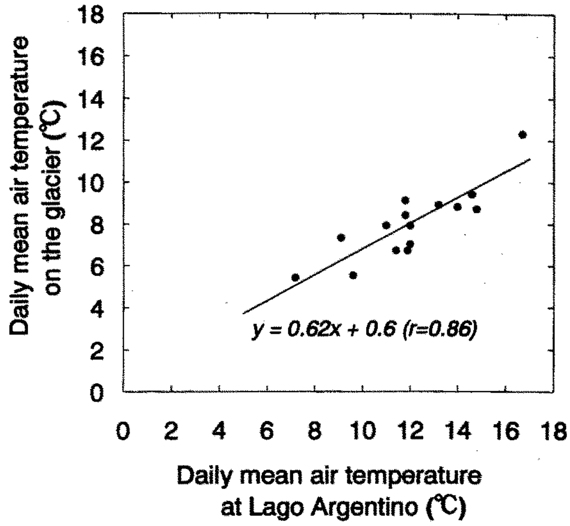

Fig. 6. The relationship between daily mean air temperatures at the Station Lago Argentino and at Meteorological Station on Moreno Glacier during 15 days in November 1993.

5. Conclusion

Continuous recording of air temperature was made during one complete year from November 1993 around Moreno Glacier. The warmest and coldest months were January and June, and the annual range of air temperature near the glacier front was about 11°C. The lapse rate was 0.8°C/100 m and no seasonal variation of it were seen.

Annual ablation estimated from annual air temperature by a degree-day method is 12.8 m in water equivalent. The corresponding ablation thickness, 14 ma^{-1}, indicates a maximum, possible annual balance. Year-to-year variations in ablation caused by changes in annual mean air temperature were estimated at $\pm 1-2$ m. That is to say, when the observed variations in ice thickness are larger than 1−2 m (Naruse *et al.*, 1995a), other causes than annual mean temperature variation should be investigated.

Acknowledgments

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