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Article

Heat balance on the icefield of San Rafael Glacier, the Northern Patagonia Icefield

Hiroshi KONDO* and Jiro INOUE
Disaster Prevention Research Institute, Kyoto University, Uji 611 Japan

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Abstract

Heat balance on the snow surface of the icefield area of San Rafael Glacier, the Northern Patagonia Icefield was studied. The following results were obtained through short term observations made for stormy and calm periods from January to February, 1986.

i) The major heat source term was turbulent heat in stormy period, and radiation in calm period. Their mean daily amount and contribution to the total heat flux were 9.0 MJ/m^{2}day (66 %), and 6.1 MJ/m^{2}day (64 %) respectively. ii) Daily amount of turbulent heat flux varied greatly from 1.3 to 20. 5 MJ/m^{2}day. This is caused not by the air temperature, but by the large variation of wind speed. iii) Daily amount of effective shortwave radiation had relatively small variation from 3.0 to 8.8 MJ/m^2 day due to the high surface albedo and large cloudiness. iv) Consequently, the daily amount of the total heat flux to the icefield varied greatly according to the amount of turbulent heat.

A comparison between the present study and previous works on the lower areas of the east and west outlet glaciers revealed the following results. i) The ratio of the mean daily amount of the total heat flux to glaciers at the three areas (west, icefield, east) was 2 : 1 : 3. ii) Percentage contributions of radiation, sensible and latent heat to the total heat flux were the same at the three areas. iii) Daily amount of the total heat flux varied according to the amount of effective shortwave radiation in the east, of turbulent heat flux on the icefield and of both effective shortwave radiation and turbulent heat flux in the west.

1. Introduction

The major heat source in summer heat balance on polar type glaciers is usually radiation, while the contribution of sensible heat becomes larger on maritime glaciers (Paterson, 1969). Patagonia has an extremely warm and humid climate compared with other glacial regions. In spite of its unique location, only a few heat balance studies have been done on the Northern Patagonia Icefield as well as on the Southern Patagonia Icefield (Inoue, 1983). Short term observations on the Northern Patagonia Icefield were made in summer on the lower area of San Rafael Glacier (Ohata et al., 1985a), the westward outlet glacier, and on the lower area of Soler Glacier (Kobayashi and Saito, 1985a ; Fukami and Naruse, 1987), the eastward outlet glacier. Although a large contribution of sensible heat to the total heat flux as well as radiation in both areas was demonstrated, the different climate of the two areas produces a remarkable east-west contrast in heat balance (Ohata et al., 1985b).

Outlet glaciers of Northern Patagonia are roughly classified into two parts. One is the icefield area above about 1000 m a.s.l. in elevation ; and the other is the lower area in valleys. The two areas are distinguished by their surface configuration : the former area with smooth snow surface ; and the latter

* present address : Japan Weather Agency, 3–16–11, Higashiimazato, Higashinari, Osaka 537 Japan

area with many crevasses or ice seracs. They are also compared by their surface climatic conditions (e. g. Inoue et al., 1987).

The summer surface ablation on San Rafael Glacier at about 100 m a.s.l. is three times larger than the ablation at about 1000 m (Kondo and Yamada, 1988), while the area of the icefield (between 1000 m and 1500 m a.s.l.) is about thirty times as large as the area in the valley (below 500 m). The most of surface ablation evidently occurs in the icefield area. Heat balance on the icefield is an essential problem for the estimation of glacier mass balance.

We made the first heat balance measurements on the icefield of San Rafael Glacier for 10 days from January to February, 1986. In the observation period we experienced the two different typical weather conditions. The results and a comparison with the heat balance in the lower area are discussed in this paper.

2. Observation site and method

San Rafael Glacier is located in the north-western part of the Northern Patagonia Icefield. The map is shown in Fig. 1. Meteorological observations on the icefield were made from October 26, 1985 to February 1, 1986 at C2 (1040 m a.s.l.) on a nunatak (Inoue et al., 1987). The Chilean Air Force has made year-round meteorological observations at BH (6 m), 3 km far from the glacier terminus, since November 1981. We measured the heat balance on the glacier surface at site H (1045 m), 1 km far from C2, during two periods : Period I from January 19 to 24 ; and Period II from January 29 to February 1, 1986. The surface around the site is wide and flat, and coverd by snow. The snow cover was gone and bare ice appeared after the observations.

Table 1 shows the observed elements and instruments employed. The measurements were made

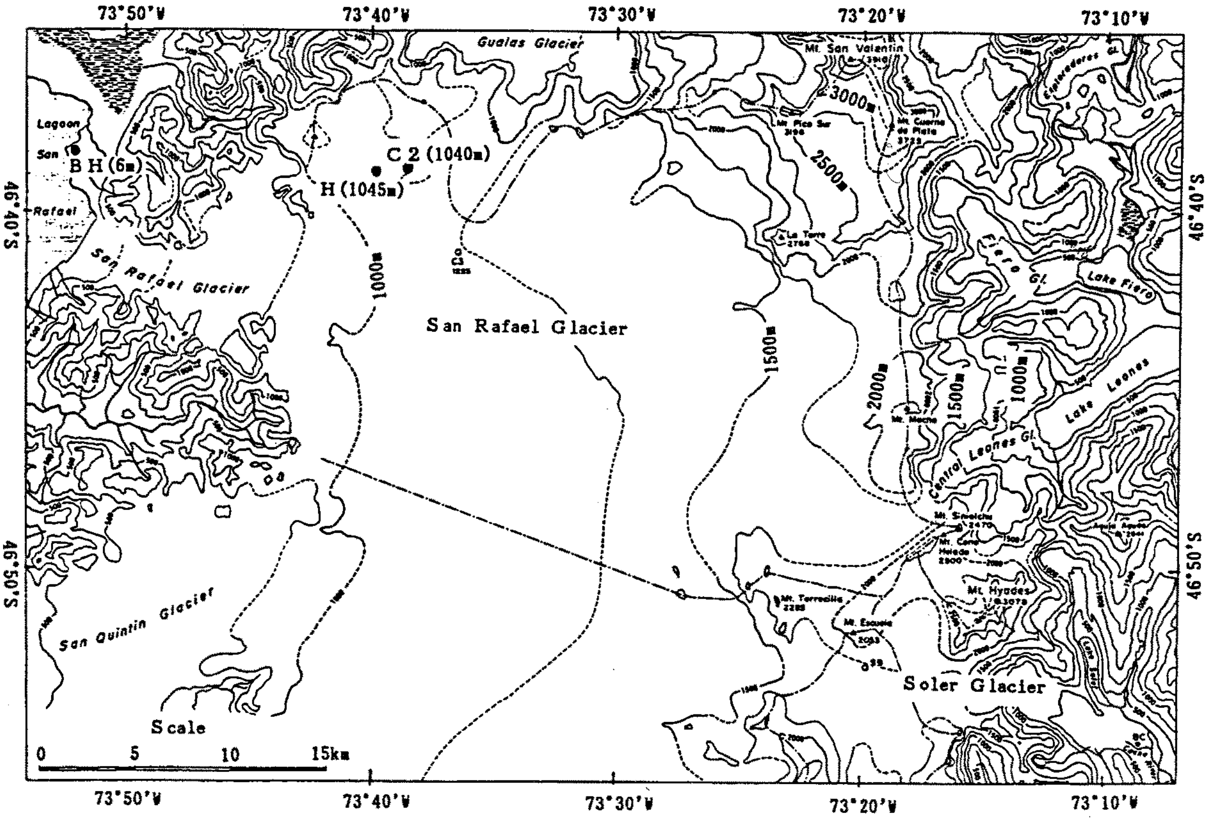

Fig. 1. Map of San Rafael Glacier, the Northern Patagonia Icefield.

every hour except for the albedo which was measured several times a day. Net radiation was not observed in Period II due to an instrumental trouble.

3. Meteorological condition during the observation period

Table 2 shows the average of daily meteorological data at C2 during Periods I and II and the summer average (from October 26, 1985 to February 1, 1986). Both air temperature and water vapor pressure in Period I were the same as the summer average, and in Period II they were lower than the summer average. It was frequently overcast with low cloud in Period I, and was occasionally fine in Period II. The major differences between the two Periods were found in wind speed and precipitation. Period I was stormy and Period II was calm. The weather around the glacier is highly influenced by the passage of synoptic disturbances (Kondo and Nakajima, 1985). Fronts passed over the region on January 20, 22 and 24. Period I represents the typical weather condition on the icefield with the influence of a synoptic disturbance, and Period II without.

The time-series of air temperature, water vapor pressure and wind speed at H are shown in Fig. 2. Wind speed was variable, having a maximum of 16 m/s. The diurnal range of air temperature was small in Period I due to the rainy condition. The maximum air temperature in Period II was 10°C. Water vapor pressure was relatively constant during both Periods. As shown in Fig. 2, air temperature and water vapor pressure conditions indicated that sensible and latent heats were almost always transported to the glacier from the atmosphere above throughout the observation period, since the snow surface was almost always melting. This indication agrees with the mean condition for the whole summer at C2 (Inoue et al., 1987).

Table 1. Observed elements and instruments employed at site H (1045 m).

Element	Level	Instrument
Air temperature	1 (1.5 m)	Assman psychrometer
Water vapor pressure	1 (1.5 m)	Assman psyehrometer
Wind speed	2 (0.5 m, 1.5 m)	Three-cup anemometer
Global radiation	1 (0.2 m)	Pyranometer
Net radiation	1 (1.0 m)	Net radiometer
Melting of snow		Snow stakes

Table 2. Mean daily meteorological data at C2 (1040 m) during Period I, Period II and the summer averages. *: Data at H were used when no data is available at C2.

Element	Period I (Jan. 19-24)	Period II (Jan. 29-Feb. 1)	Summer (Oct. 26-Feb. 1)
Air temperature (°C)	4.3 *	2.8	4.9
Water vapor pressure (mb)	7.6 *	6.0	7.1
Wind speed (m/s)	5.6 *	3.4 *	
Precipitation amount (mm)	34 *	8 *	19
Cloudiness (tenth)	9.9	8.8	7.9
Cloud base (m)	1040-1400	1040-5000	

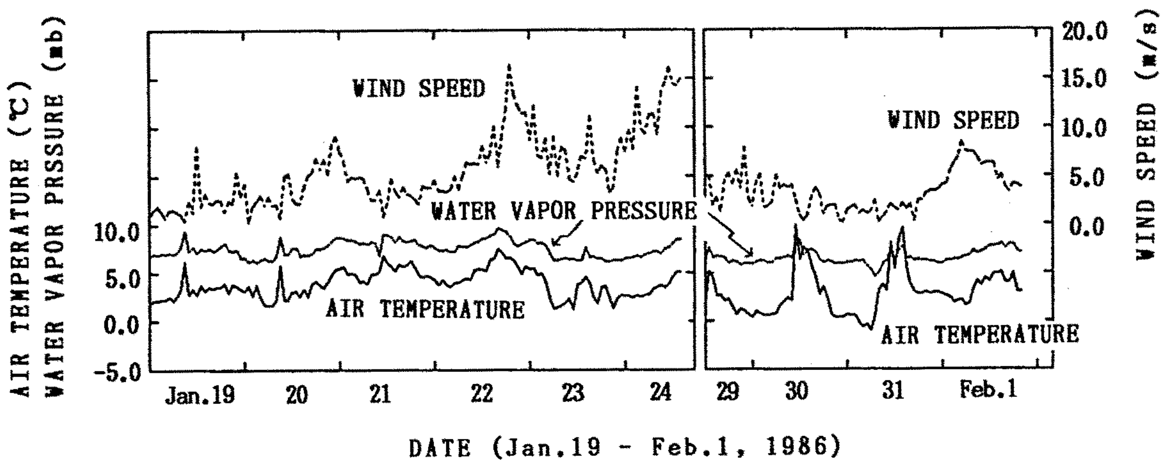

Fig. 2. Air temperature, water vapor pressure and wind speed at H during the observation period.

4. Heat balance on the icefield

The heat balance equation on the surface can be written as below ;

$$Q_{SW}+Q_{LW}+Q_S+Q_L+Q_P+Q_M=0$$

$$Q_{SW}=(1-a)Q_G$$

where Q_{SW} is the effective shortwave radiation, Q_{LW} the effective longwave radiation, Q_S the sensible heat flux, Q_L the latent heat flux, Q_P the heat transport by rain, Q_M the heat used to melt snow or ice, Q_G the global radiation, and a the surface albedo. Heat conduction to the sub-surface layer can be regarded as zero because the snow and ice temperature was 0 °C from the surface to 30 m depth (Yamada, 1987). Each flux toward the surface is taken as positive.

The global radiation Q_G, net radiation ($Q_{SW}+Q_{LW}$) were measured directly. The surface albedo a was obtained from Q_G and the reflected radiation. Its diurnal range was from 0.60 to 0.75. Q_{SW} was calculated using a mean a of 0.67. Q_{LW} was obtained as the residue of net radiation and Q_{SW}. Q_S and Q_L were calculated by the following equations assuming the logarithmic profile of air temperature (T), water vapor pressure (E) and wind speed (U).

$$Q_S=\rho C_P k^2 \frac{(T-T_0)U}{(\ln(Z/Z_0))^2} \quad (1)$$

$$Q_L=\rho L k^2 \frac{(E-E_0)U}{(\ln(Z/Z_0))^2}\frac{0.622}{P} \quad (2)$$

where ρ is the density of air, C_P the specific heat of air, L the latent heat of sublimation and k the von Karman's constant. Suffix 0 of T, E and U denotes at the surface. Z_0 is the roughness length, and the height Z is approximately 1.5 m. Although the atmosphere near the surface was stable, deviations of air temperature, water vapor pressure and wind speed from the logarithmic profile are usually considered to be small near the surface. Z_0 was derived as 0.07 cm from the measurements of wind speed at two levels in near-neutral cases assuming a logarithmic profile. T_0 and E_0 were regarded as 0 °C and 6.1 mb respectively, because the surface was melting almost all the time in the observation period. Q_P was calculated from the precipitation amount and wet-bulb temperature. Q_M was calculated from the surface lowering measured by snow stakes and snow density near the surface measured 2 times during the observation. Both of the times snow density was 0.5 Mg/m^3.

Figure 3 shows the time-series of hourly Q_{SW}, Q_S, Q_L and Q_M. Surface melting in Period I is not always larger in daytime than at night. This is caused by the large contribution of turbulent heat flux (Q_S+Q_L, denoted by Q_T) to the total heat flux compared with Q_{SW}. The large surface melting on January 20-21, 22 and 24 corresponds to the large Q_T. In Fig. 2, increases of air temperature and water vapor pressure on these days are not evident. Increase of wind speed caused the large Q_T. These days corresponded to the passage of synoptic disturbance mentioned in the

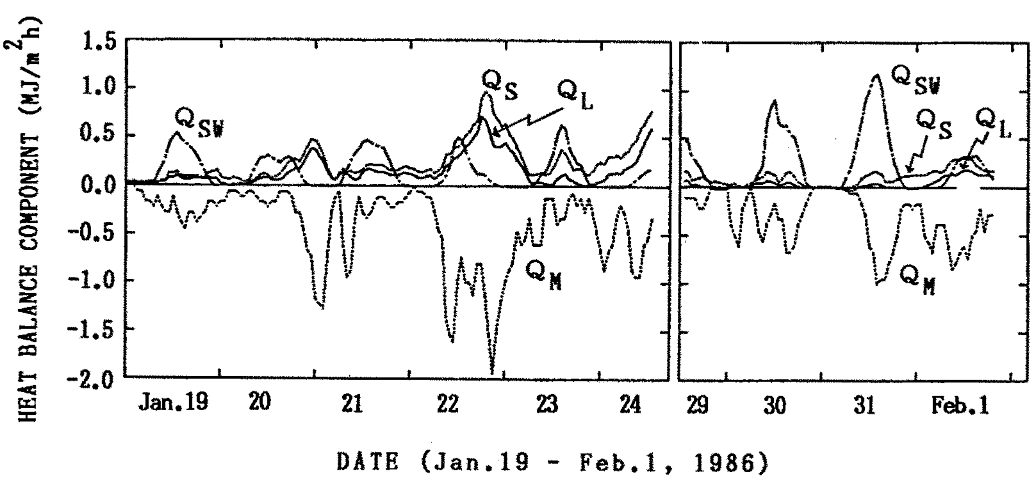

Fig. 3. Three-hour running mean of hourly effective shortwave radiation, sensible heat flux, latent heat flux and heat used to melt snow.

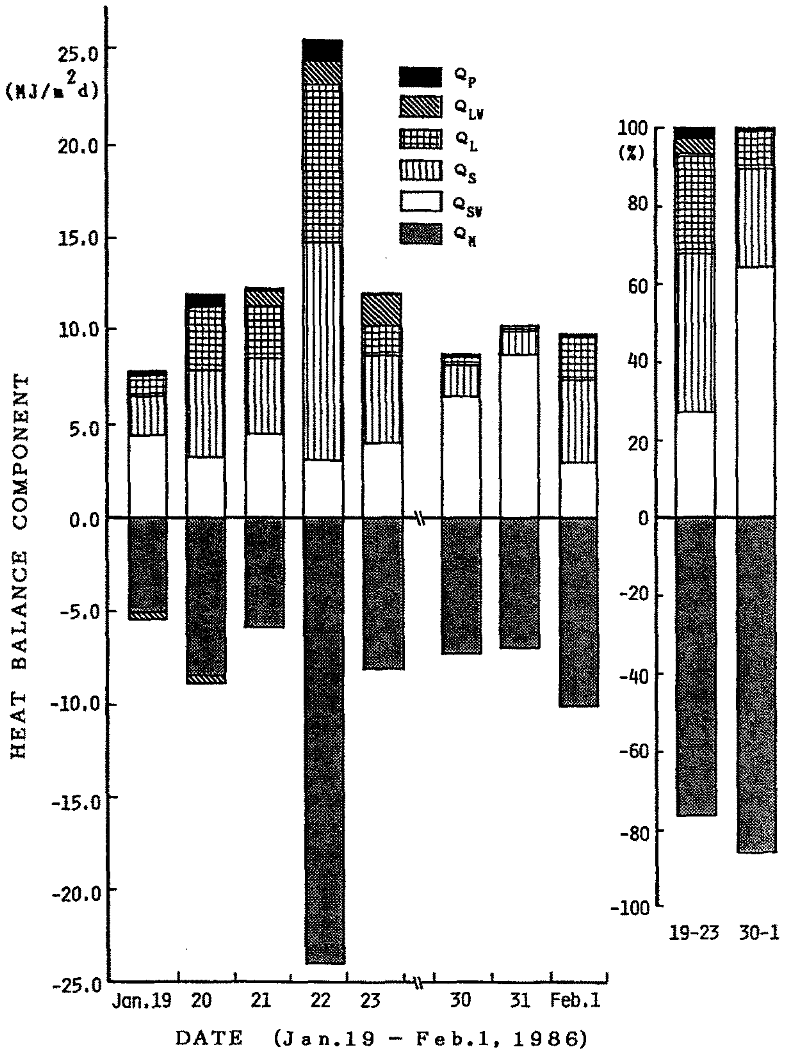

Fig. 4. Daily heat balance components on the icefield of San Rafael Glacier from January 19 to February 1, 1986. Q_{LW} was not obtained after January 23.

previous section. During the light to weak wind condition in Period II, Q_T was small in spite of high air temperature.

Daily heat balance components are shown in Fig. 4. The variation of Q_{SW} is relatively small from 3.0 to 8.8 MJ/m^{2}day due to the high albedo and large cloudiness. Q_{LW} obtained during Period I was small. Q_T has large variation from 1.3 to 20.5 MJ/m^{2}day. Q_P was small due to the low air temperature even for the heavy precipitation. As a result, the daily amount of the total heat flux to the glacier depends much on Q_T.

The percentage contribution of each component to the total heat flux to the glacier during each Period is shown at the right of Fig. 4. In Period I, Q_T occupies 66 % and Q_{SW} 27 %. Conversely Q_{SW} occupies 64 % and Q_T 35 % in Period II. Averaged daily Q_{SW}, Q_S and Q_L are 3.8, 5.6 and 3.4 MJ/m^{2}day in Period I, and 6.1, 2.5 and 0.9 MJ/m^{2}day in Period II. For all period, they are 4.7, 4.5 and 2.5 MJ/m^{2}day respectively.

Table 3. Daily heat balance components on the glaciers of Northern Patagonia Icefield.
* : Daily values were extrapolated from daytime observations.
** : The data was obtained as a residual term of the heat balance.
*** : Data near the observation site.

Item	San Rafael*	icefield	Soler
Q_{SW} (MJ/m²day,%)	9.5 (39)	4.7	15.6 (45)
Q_{LW}	2.2 (9)	–	−8.6(−25)**
Q_S	8.9 (37)	4.5	11.9 (34)
Q_L	3.5 (15)	2.5	7.1 (21)
Q_P	– (–)	0.3	–
Q_M	−21.2(−88)	−9.6	−25.9(−75)
Altitude (m)	103	1045	400
Surface / Albedo	bare ice / 0.26	snow / 0.67	bare ice / 0.31
Cloudiness	9.6	9.5	5.8
Wind speed (m/s)	2.7***	4.7	4.2
Period	Dec.29-Jan.1	Jan.19-23, 30-Feb.1	Dec.15-29
Literature	Ohata et al.,1985a	present study	Kobayashi and Saito, 1985a

5. Discussion

In the present study, the large influence of turbulent heat on summer heat balance on the icefield was found. We will discuss the difference between the present result and previous works on the heat balance in the Northern Patagonia Icefield.

The seasonal change of the heat balance on Soler Glacier from late spring (November 1−5) to early summer (November 25−29) was presented by Fukami and Naruse (1987). Although fine weather condition continued throughout the latter period, they showed the seasonal change of the heat balance. The total heat flux to the glacier in the former period was about half of that in the latter period. The east-west contrast of the mid-summer heat balance on the lower area of both San Rafael Glacier and Soler Glacier was discussed by Ohata et al. (1985b). Total heat flux to the glacier in daytime was 50 % larger in the east (Soler) than in the west (San Rafael). They concluded that the difference is due not to radiation but to turbulent heat.

Daily heat balance components in mid-summer over the Northern Patagonia Icefield are compared in Table 3. Average values of the present result for the whole period are compared with the previous works, since synoptic disturbances passed over the region during their observation periods. The observation period of the present study is one month later than their periods. The effect of this difference is evaluated as follows. The monthly mean air temperature at BH in January is only one degree higher than in December. The extra-terrestrial radiation at the latitude of 47 °S in January is 2 MJ/m²day smaller than in December. The difference of the effective shortwave radiation between January and December is considerd to be smaller than 0.7 MJ/m²day due to the surface albedo. The influence of the one month difference in the observation period among the three studies must be small, and the following features are valid.

Major heat source components are effective shortwave radiation (Q_{SW}) and sensible heat (Q_S) at every site. The ratio of Q_{SW} at the three sites (west, icefield, east) is approximately 2 : 1 : 3 ; and this is the same for Q_S. Consequently, the total heat fluxes to the glacier at the three sites are in the same ratio. The amounts are 24.1, 12.0 and 34.6 MJ/m²day respectively. As a result, percentage contributions of Q_{SW}, Q_S and Q_L (latent heat) to the total heat flux are approximately the same at the three sites. Q_{SW} occupies 40 - 50 % of the total heat flux, Q_S 30 - 40 % and Q_L 10 - 20 % respectively. Almost all of the heat is used for surface melting in the west and on the icefield, but 25 % of the heat is lost by effective longwave radiation in the east.

Mean cloudiness and wind speed are also shown in Table 3. The difference in Q_{SW} at each site can be explained by the cloudiness and surface albedo. Large cloudiness reduces Q_G (global radiation) in the west and on the icefield, and the large surface albedo reduces Q_{SW} on the icefield. Q_T (turbulent heat) depends mainly on wind speed, air temperature and surface configuration. Average wind speed is not small on the icefield. The major reason for the decrease of Q_T on the icefield can be attributed to the lower air temperature than that of the other area. Rough surface configuration such as seracs and crevasses in the lower area may also contribute to the difference. The same percentage contributions of Q_{SW}, Q_S and Q_L to the total heat flux between the site on the icefield and in the lower areas is caused by the low value of both Q_{SW} and Q_T on the icefield.

Remarkable different features in heat balance on the Northern Patagonia Icefield are also revealed in the three areas. Daily amount and variation of the total heat flux to the glacier in the west are greatly dependent on shortwave radiation, on the icefield on turbulent heat, and in the east on both components. The variation of Q_{SW} was small only on the icefield due to the high surface albedo. Q_T is proportional to the product of wind speed and air temperature as shown in eq. (1). In the west, since downward glacier wind was predominant and there is a negative correlation between the wind speed and air temperature (Inoue, 1987), the variation of Q_T is small. On the icefield, wind speed changed independently of air temperature. Synoptic wind system, which was quite variable, produced the large variation in Q_T. In the east, a föhn sometimes occurred (Kobayashi and Saito, 1985b), showing a positive correlation between the wind speed and air temperature. Consequently a large variation of Q_T was produced.

This paper describes the first heat balance study on the icefield of the Northern Patagonia Icefield. The observation period and the instrumentation are insufficient, due to the logistic difficulties of getting to the area and the lack of the meteorological and glaciological informations. We make brief discussions on the accuracy of the present heat balance measurements.

In the calculation by eqs. (1) and (2), we assumed the logarithmic profiles of the turbulent elements. Since the air temperature was positive almost all of the observation period, the atmosphere near the surface was stable. But we consider that the effect of the stability on wind profile near the surface is substantially small, because the roughness length of the surface is small. We could not measure frequently the depth-density profile and the percentage of the free-water in the snow layer. Possible change of the percentage of the free-water introduces the estimating error of the amount of the melting of snow in the calculating method of this paper. However, the good agreements between independently calculated total heat flux to the glacier and heat sink suggests that the change of the percentage of the free-water is small. The result of the present heat balance analysis showed the slightly possitive value of daily mean effective longwave radiation (Q_{LW}) in Period I. Ohata et al. (1985a) also obtained the possitive value of Q_{LW} at the lower area of San Rafael Glacier. But this result must be treated carefully, because the value was obtained as the residue of net radiation and effective shortwave radiation, and the absolute value is small.

In the further study of the heat balance on the icefield of Patagonia, the above points should also be solved.

Acknowledgments

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