Heat Balance Study on Glacier No. 1 at Head of Urumqi River, Tianshan Mountains, China[1]

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Abstract Ablation and heat balance study were made on the ablation area of No. 1 Glacier at head of Urumqi River, Tianshan Mountains, Western China. The height of the observation site was 3895 m a. s. l. which was approximately in the middle of ablation area and the observation lasted from July 5 to 25. The firn snow at the site during this period consisted of two different layer, upper one of clean granular snow and lower layer of dirty granular snow containing desert origin dusts. The surface albedo changed drastically when the lower layer appeared at the surface. The calculation of heat balance components show that in the heat source part, net radiation contributed 71.6% and sensible heat 28.4%. In the heat sink part melting contributed 94.8% and latent heat 5.0%. Latent heat in the heat sink part means that evaporation overwhelmed condensation. This is due to the relatively low temperature and low humidity in this region. Mass loss due to evaporation in summer does not seem to be important in the annual mass balance but it seems to be an important factor in determining the glacier distribution in this area.

1. Introduction

Annual accumulation is small at the glaciers in the head of Urumqi River, Tianshan Mountains, China due to the dry climate there. Annual ablation amount is considered to be also small. The study of the variability of glaciers in response to the climatic change in such a region can be made through the investigation of the mass balance in relation to the climate condition. The part of mass loss, that is, ablation can be investigated through the study of heat balance at the surface. Climatological conditions will mostly determine the types and intensity of heat sources and sinks, and melting of snow and ice.

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The north and south side of eastern Tianshan Mountains which is running west to east are dry desert regions. It is characterized by low humudity and existence of dust of desert origin in the air. The climate in the mountains are similar but the air temperature is low and show a little different characteristics compared with the surrounding lowlands in some meteorological aspects (Ohata et al., 1989). These factors will modificate the pattern of heat balance here.

Previous works on the heat balance of the glacier in this region has been done by Bai and Xie (1965) on the same glacier. They calculated heat balance components from several cases of observation in the ablation season, and they cited the importance of the radiation terms for ablation.

During the summer of 1983, continuous observation of the heat balance were made in the ablation area of No. 1 Glacier at the head of Urumqi River. The present paper will report on the heat balance study at one site in the ablation area of the glacier. The study of extending this result to the whole glacier will be done in an another paper.

2. Site and method of observation

Observations were made on No. 1 glacier which is situated at the head of the Urumqi River. The site of observation was HB–1 (3895 m a.s.l.) shown in Fig. 1. It was a flat surface less than 5 ° in the ablation area. The annual equilibrium line of this glacier is usually around the height of 4000 m a.s.l. The photograph of the observation site is shown in Fig. 2. The measured elements are shown in Table 1, along with the instruments used. Ablation at the surface was measured by a star ablatometer.

Table 1 The type and amount of sensors used for heat balance measurements

Elements	Type of sensors	Number of sensors
Air temperature (dry bulb and wet bulb)	Platinum resistance thermometer	3
Wind speed	Photoelectric type anemometer	3
Wind direction	Photoelectric type wind vane	1
Snow temperature	Platinum resistance thermometer	3
Downward and upward shortwave radiation	Neotype pyranometer	2
Net longwave radiation	Net radiometer	1

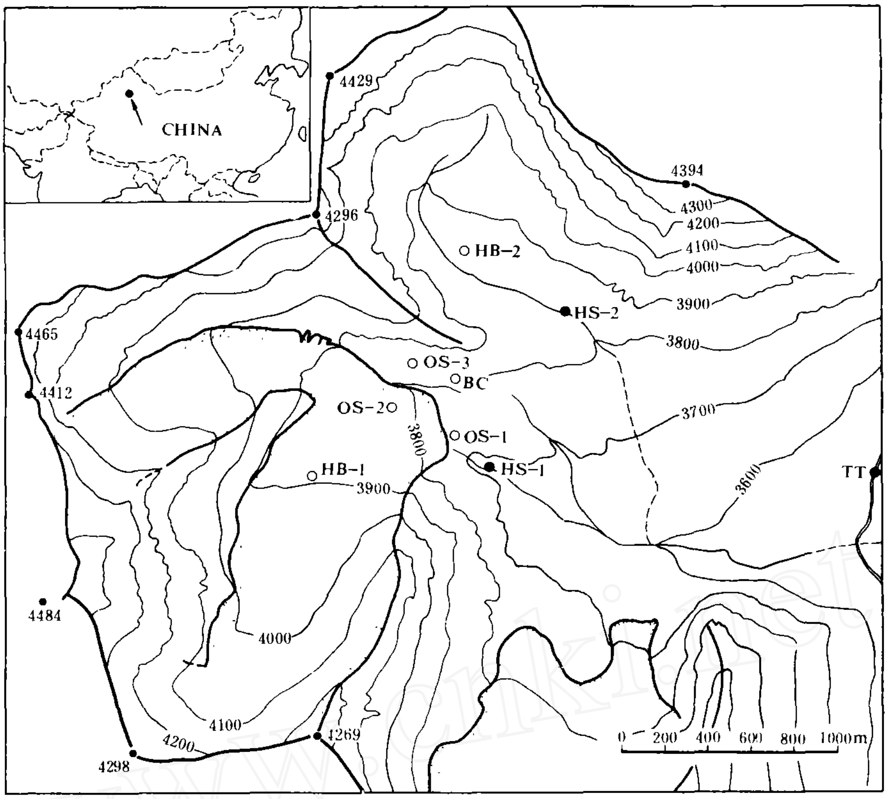

Fig. 1 The map of the observation area

3. Derivation of each heat flux components

The heat balance equation can be written as below

$$Q_{NR} + Q_S + Q_L + Q_P + Q_C = Q_M \tag{1}$$

$$Q_{NR} = Q_{SW} + Q_{LW} \tag{2}$$

$$Q_{SW} = Q_{SW}\downarrow + Q_{SW}\uparrow \tag{3}$$

$$Q_{LW} = Q_{LW}\downarrow + Q_{LW}\uparrow \tag{4}$$

where

Q_{NR}: Net radiation

Q_{SW}: Net shortwave radiation

$Q_{SW}\downarrow$ $Q_{SW}\uparrow$: Downward and upward shortwave radiation

Q_{LW}: Net longwave radiation

$Q_{LW}\downarrow$ $Q_{LW}\uparrow$: Downward and upward longwave radiation

Q_S: Sensible heat flux

Q_L: Latent heat flux

Q_C: Heat conduction to sub-surface snow layer

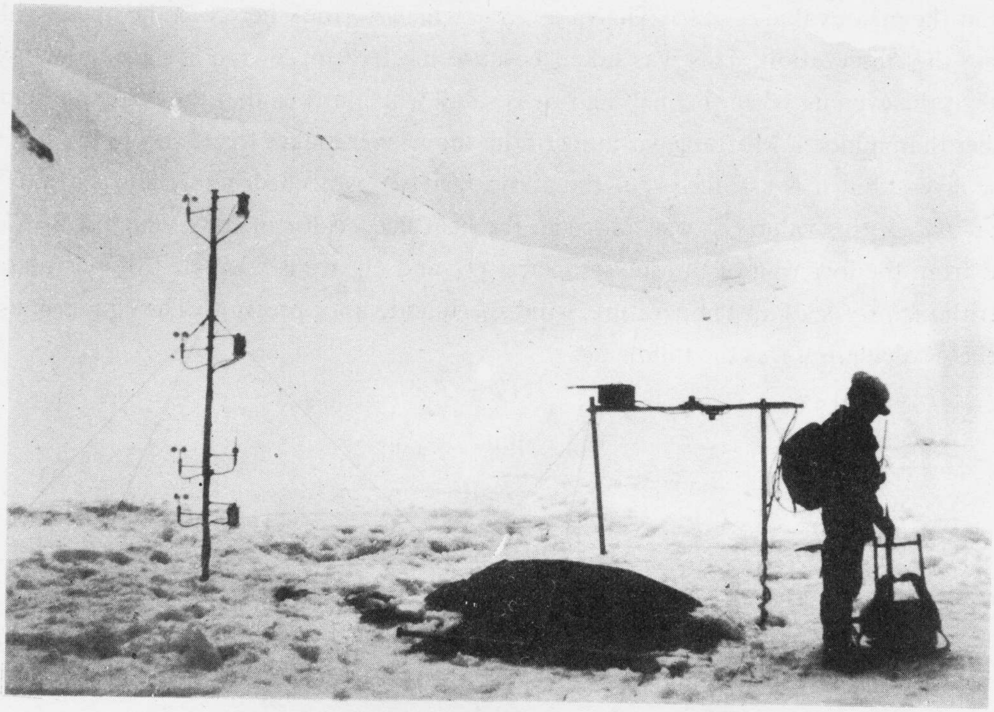

Fig. 2 Photograph of the heat balance site at HB−1. The instruments can be seen in the photo

Q_P: Heat used for phase change of ice / water and water / ice

a: albedo

Q_M: Heat used for melting of snow and ice

In the above equation, the heat coming into the surface will be denoted by "+" and heat going out by "−". Among the above terms direct measurements of Q_{NR}, $Q_{SW}\uparrow$ and $Q_{SW}\downarrow$ were made. From these values, Q_{LW} was calculated. Q_C was calculated from the temperature change in the snow layers. Q_M which stands for melting and freezing of ice is complicated in the present case. In a warm environment in the ablation season, there is only phase change from ice to water, but in cold environment near 0℃, there is also the change from water to ice in the nighttime for the free water sticking to the snow. This was the case for Tian Shan. Phase change from ice to water was calculated from the lowering of the snow surface. Freezing occurred during the night only on days of strong nocturnal radiative cooling. This heat Q_P was calculated by

$$Q_P = r \cdot m(d) \tag{5}$$

where r is the water content of snow and $m(d)$, the whole mass down to depth d, the lower limit of freezing. This d varied among nights. r was taken to be 12%. There were no measurements at each evening before freezing started. However, during the observation period, many measurements of water content of snow was made more than 10 times in various hours. Usually in the daytime when the melting was strong, water content was high at the mean value of 18%. The value 12% which we took here was the lowest value during the observation. This was taken because the freezing of the surface snow layer starts at the evening when the melting rate is small which means that the water content is smaller than midday. Morning warming of the snow layer makes free water in the surface snow layers, but it is assumed that the above heat Q_P is needed before surface start to lower. As so, this value Q_P was added to the heat needed for melting which was calculated from the lowering of the snow surface. Q_S and Q_L were calculated by postulating logarithmic profile of air temperature, wind speed and vapor pressure. The equation used for these calculation was the followings

$$Q_S = \rho C_P K^2 \frac{(T - T_o)U}{[\ln(z / z_o)]^2} \tag{6}$$

$$Q_L = \rho L K^2 \frac{(e - e_o)U}{[\ln(z / z_o)]^2} \cdot \frac{0.622}{P} \tag{7}$$

where

ρ: Density of air
C_P: Specific heat of air
K: Karman constant
L: Heat of sublimation
e, e_o: Vapor pressure at z and z_o
U: Wind speed at z
T, T_o: Air temperature at $z$and z_o
z_o: Roughness length
P: Atmospheric pressure

$z_o$was obtained from the vertical profile of the wind speed. Daily mean value of z_o varied from 0.007 to 0.084 cm. Q_S and Q_L were calculated from one hour mean values.

4. Meteorological conditions and lowering of snow surface

In Fig. 3, the daily value of four meteorological elements are shown for the period of July 11 to 25. The height of these sensors changed a little due to lowering of the snow surface during this period, wind speed from 190 to 235 cm above surface and dry and wet bulb air temperature from 100 to 180 cm. Daily mean wind speed at 1.5 m level varied from 2.0 to 4.0 m / s (mean 2.9 m / s), air temperature from −2.0 to 4.0℃ (mean 2.7℃), global radiation from 10.5 to 33.6 MJ / m^2 · d (250 to 800 ly / d) and mean value being 21.7 MJ / m^2 · d (516 ly / d) and vapor pressure 4.0 to 6.2 mb (mean 5.3 mb). The air temperature is relatively low but it is an average condition for this time of year. The mean air temperature at Tian Shan Station (3540 m a.s.l.) for July is 4.7℃ (Lanzhou Institute

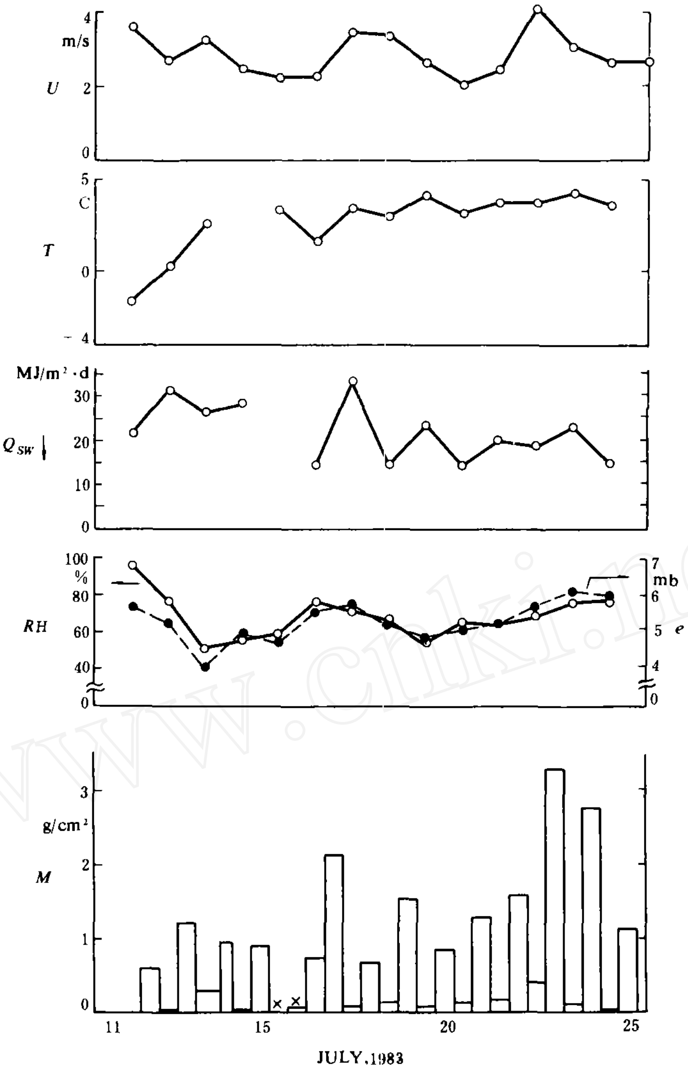

Fig. 3 Daily mean values of meteorological elements at HB−1. Wind speed (U, m / s), air temperature (T, ℃), global radiation ($Q_{SW}\downarrow$, MJ / m^2 · d), relative humidity (RH, %), vapor pressure (e, mb) and surface melting (M, g / cm^2) are shown

of Glaciology and Cryopedology, 1982), which means the temperature at the heat balance site is 2.9 ℃ assuming lapse rate of 6 ℃ / km. This value is approximately same with the present observation period.

Figure 4 shows the variation of snow surface level for the same period. In 15 days the surface lowered 52 cm. The observation of the vertical cross section of the firn layer on July 9 is shown in Fig. 5. On this day, firn layer above the glacier ice was 100 cm in depth. Top 9 cm were new snow, fallen on July 8, the preceding day. 84—91 cm were moist packed snow (layer A) and 68–84 cm were clean granular snow (layer B), and 0—68 cm were dirty granular snow (layer C) which depth hoar being developed partly, and

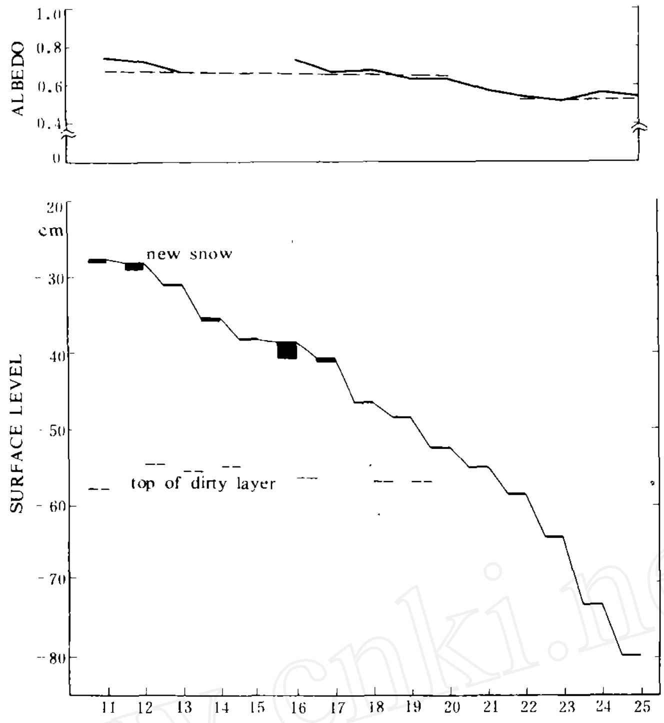

Fig. 4 The lowering of surface snow level at HB-1 and surface albedo

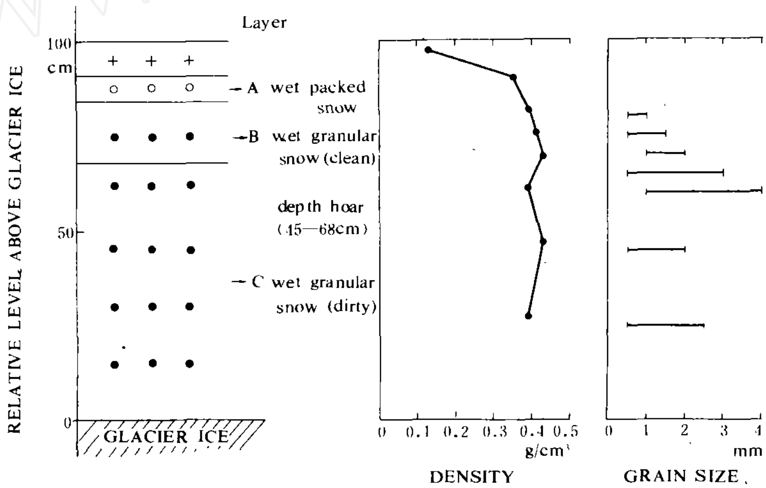

Fig. 5 The cross section of the firn layer on July 9 and vertical profile of density and grain size

also ice layer and ice lenses had formed in some places. Underlying ice was superimposed ice composed of fine grains. On the right side of Fig. 5, snow density and grain size are also shown. Depth hoar of large grain size can be seen in the upper part of layer C. The time of the snow deposition forming the firn layer is considered to be as follows. As the variation in the annual precipitation show high value from May to September (Lanzhou

Institute of Glaciology and Cryopedology Geocryology, 1982). These data show that solid precipitation here occurs before and after the ablation season. Considering that there are two distinct different layer (layers B and C), the lower layer C which contain much dust particle seems to be formed after the ablation season of the previous year, that is from September to probably April this year when the abundant snowfall before the ablation season starts. The highest dust content was observed at the upper part of layer C. The value was 118 mg / l, and this was higher compared with the value in layer B which was 4 mg / l.

In Fig. 4, the top of dirty layer is also shown. This dirty layer appeared partly on 20th and completely on 23rd around the observation site. Before this day the surface was clean granular snow. Surface albedo value at noon for each day is shown in Fig. 4. The average value of surface albedo before the dirty layer appeared was 0.67 excluding the days with new fresh snow on the top. After the dirty snow appeared it lowered to 0.52. This means that the absorption of the shortwave radiation increased by 47% in these few days.

The ablation amount was calculated from the lowering of this snow surface and the snow density value near the surface. Alternate observations were made by measuring the vertical density profile above the glacier ice every day, and obtaining the change in the water equivalent above glacier ice. This method will be useful in case when the snow layer densification is strong. The values obtained from the latter method showed more variation than the former method in the present case. The values obtained from the former method was taken in the present analysis as ablation amount.

5. Result of the heat balance

The heat balance for the main 7.5 day ablation period, July 17 to 24 is shown in Fig. 6 and the data is tabulated in Table 2. The other observation days did not have a complete fullday data. Daytime (08:00—20:00) and nighttime (20:00—08:00) are shown separately in the Figure. The total value for the whole period is shown at the right end. The result shows that heat sources and sinks balance quite well for each half day periods. When the value Q_P noted in section 3 was not taken into account the balance was worse. The most strong difference between the absolute value of heat sinks and heat sources occurred in the daytime of 21st and 22nd. The heat source part was 3.6 to 3.7 MJ / m^2 (86 to 90 ly) larger than the heat sink part. This was probably due to the fact that the dirty granular snow layer cited in section 4 appeared first at the site of radiation measurement making the Q_{SW} large. On the other hand at that time the site of star ablatometer was clean granular snow. On the 23rd, the surface of both sites became dirty granular snow, and as a result the balance was good on 23rd and 24th. The mean value at the right side

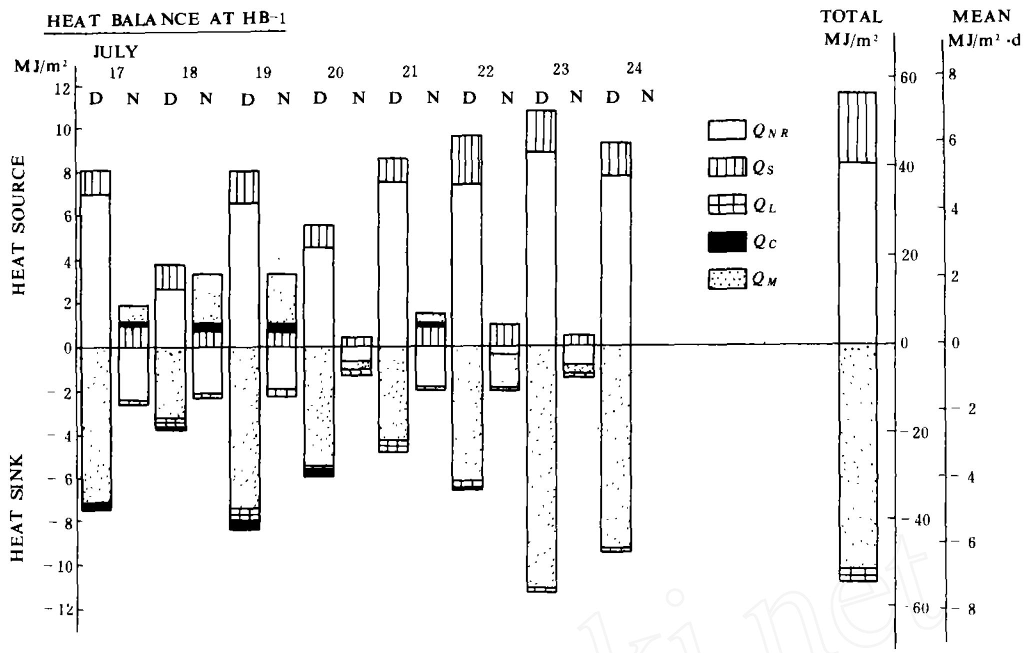

Fig. 6 Heat balance of all components for July 17–24 Each component was derived independently

of the figure shows that heat source is larger than heat sinks. This is mainly due to the difference on 21st and 22nd. Relative percentage is tabulated in Table 2. The heat source term is composed of Q_{NR} and Q_S, 71.6% and 28.4% respectively. This relative importance of Q_{NR} is little lower than the value obtained by Bai and Xie (1965). This is probably due to the type of the surface. If the present observation were made near the terminus where the surface is ice, Q_{SW} should have been lager. Another characteristics of the heat balance is that Q_L was in the heat sink, which means that the evaporation overwhelmed condensation. This can be easily recognized from the fact that mean vapor pressure at HB−1 was 5.31 mb (Fig. 3) and the glacier surface being little below 6.11 mb, that is the saturation vapor pressure for 0℃. This is approximately same as the result of Bai and Xie (1965) which condensation and evaporation contributed 5.3 and 11.9% to the total income and output, net value being 6.6% of evaporation.

Among the radiation term, Q_{NR} was 5.4 MJ / m^2 · d (129 ly / d) Q_{SW} was 8.9 MJ / m^2 · d (211 ly / d) and Q_{LW} being −3.5 MJ / m^2 · d (−82 ly / d). High Q_{LW} was due to low humidity and low air temperature. In Fig. 7, the relation between $Q_{SW}\downarrow$ and Q_{LW} is taken. Q_{LW} is probably almost constant due to near 0℃ surface temperature, Q_{LW} will show the variation in $Q_{LW}\downarrow$. So, the relation between Q_{SW} and Q_{LW} will show the total effect of topography and the cloud on the shortwave and longwave radiation balance at the surface. As can be seen from the figure, fairly good relation can be seen between the two. This relation should differ at glaciers in different climatic conditions and topographical settings.

Table 2 The result of heat balance for 7.5 days period

Date	D / n	Heatflux of Each Component in Heat Balance (unit MJ / m^2)						
		Q_{SW}	Q_{LW}	Q_{NR}	Q_S	Q_L	Q_C	Q_M
July 17	D	11.7	−4.8	6.9	1.0	0.0	−0.1	−7.1
	N	0.0	−2.5	−2.5	0.9	−0.2	0.1	−0.3
July 18	D	4.9	−2.3	2.6	1.1	−0.4	−0.1	−2.3
	N	0.0	−2.2	−2.2	0.7	−0.1	0.4	−0.4
July 19	D	8.8	−2.4	6.4	1.5	−0.5	−0.4	−5.2
	N	0.0	−2.1	−2.1	0.6	−0.3	0.3	−0.3
July 20	D	5.5	−1.1	4.4	1.0	−0.1	−0.3	−2.9
	N	0.0	−0.7	−0.7	0.4	−0.1	0.0	−0.4
July 21	D	8.7	−1.3	7.4	1.0	−0.5	0.0	−4.3
	N	0.0	−1.9	−1.9	0.9	0.0	0.1	−0.4
July 22	D	8.7	−1.5	7.2	2.2	−0.3	−0.1	−5.3
	N	0.0	−0.4	−0.4	1.0	−0.1	0.0	−1.4
July 23	D	11.4	−2.7	8.7	1.8	−0.1	0.0	−11.0
	N	0.0	−0.9	−0.9	0.5	0.1	0.0	−0.4
July 24	D	6.8	0.8	7.6	1.5	−0.1	0.0	−9.2
	N							
Total		66.5	−26.0	40.5	16.1	−2.7	−0.1	−50.9
Mean		8.87	−3.47	5.40	2.15	−0.36	−0.01	−6.79
Relative percentage				71.6	28.4	5.0	0.2	94.8

D: Daytime, 08:00–20:00; N: Nighttime, 20:00–08:00.

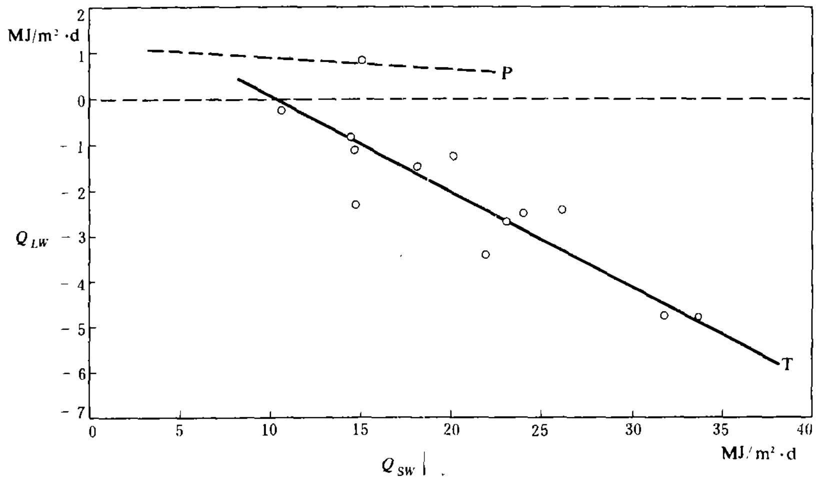

Fig. 7 Relation between daily total value of $Q_{SW}\downarrow$ and Q_W

6. Discussions

The summer climate at the observation site is characterized by relatively low air temperature and low humidity. The result of the heat balance in the summer time on the firn snow in the ablation area shows that Q_{NR} contribute 71.6% and Q_S is 28.4%. In the heat sink part Q_M is 94.8% and is Q_L 5.0%. Q_L is in the sink part meaning that evaporation overwhelms condensation. This shows that surface melting is mainly controlled by the variation in the radiation term. High contribution of the radiation term in the heat source part is usually said to be realized at the glaciers in the high altitude and high latitude regions (Andrews, 1975). Tian Shan lies in the former category which is similar to the Eastern Tianshan Mountains. However the continentality which is related to dry climate, and the size of the glacier which is small may be one important factor in determining the high radiation terms.

In the firn there existed two layers. One clean granular snow layer and underlying lower layer of dirty granular with partly depth hoar forming. The surface albedo changed abruptly when the surface lowered and reached this dirty lower layer. The existence of desert origin dust in the firn layer is quite important in the heat balance not only in the present summer balance but probably in the snow cover in general in this region at other seasons also.

The amount of evaporation overwhelmed condensation. The present result show that 0.013 g/cm^2 of snow and ice evaporates a day on the average. If this value is extrapolated to the length of one year, it will amount to 4.8 g/cm^2. The result Bai and Xie (1965) obtained was little larger than this result and was 0.038 g/cm^2 and 13.9 g/cm^2 respectively. As for the present observation of heat balance in the summer season, evaporation did not contribute so much to the heat balance nor mass balance. However this evaporation term may be important in the annual mass balance as the solid precipitation in one year should be less than 400 mm (Ohata et al., 1989). The observation of evaporation at Hintereisferner for 11 days in summer showed 0.025 g/cm^2 per day at the altitude of 3030 m (Kaser, 1982). At Mizuho Station in Antarctica (Fujii, 1979), the annual net sublimation was estimated to be 4.73 g/cm^2 from direct measurement, and distinct peak in the summer three months. This annual amount is similar to the value obtained here. At Mizuho the winter half season shows net radiation deficits and there is no potentiality for evaporation. On the other hand, at Tian Shan there is probably has continuous income of solar radiation at the surface throughout the year meaning possibility of continuous evaporation. It will be important to evaluate this amount as the annual solid precipitation amount is small.

The amount of evaporation should be different at differing slopes. For example, the southward facing slope should evaporate much more than the northward facing slope due to higher insolation. This tendency will be intensified by the existence of dust particles which will decrease the surface albedo, leading to more difference in the absorption of shortwave radiation at northward and southward facing slopes. If this is effective there will be a difference in the thickness of remained snow cover. This may be one important cause for the differential distribution of glaciers in the south and north side of the ridges in the Tianshan Mountains.

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中国天山乌鲁木齐河源1号冰川的热量平衡研究（摘要）[①]

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中国西部天山乌鲁木齐河源1号冰川上的消融和热量平衡研究是在冰川消融区中部海拔高度3895 m的平坦雪面上进行的。观测场中的粒雪由两个不同层次的清洁粒雪和包含来自沙漠地区尘暴的污化粒雪所组成。当下部污化层在表层出露时，冰川自然表面的反射率则产生急剧的变化。当反射率从0.67降低至0.52时，相应的吸收辐射量将随之增加47%。根据1983年7月5日至25日的观测资料，对具有代表性的各天气情势下的热量平衡各组成分量的计算表明，在热量收入部分中，净辐射供热占71.6%（5.40 MJ／m^2·d），感热供热占28.4%（2.15 MJ／m^2·d）。在热量支出部分中，消融耗热占94.8%（−6.79 MJ／m^2·d），潜热占5.0%（−0.36 MJ／m^2·d），其余0.2%（−0.013 MJ／m^2·d）的热量用于冰雪层中的热传导。以热量耗散形式出现的潜热意味着蒸发抑制了凝结作用。这是因为该区相对的低温和较低的湿度的缘故。在夏季，尽管平均日总量为0.013 g／cm^2的蒸发在年物质平衡中所造成的物质亏损似乎是不太重要的，然而它却是制约该区冰川分布的重要因子。

关键词 冰川辐射及热量平衡 冰雪消融 污化粒雪层 雪面蒸发 天山乌鲁木齐河源1号冰川

① 本文系中日合作《天山冰川对气候变化的响应研究》课题成果之二。