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Glaciological observations on July 1st glacier in Qilian Mountains of west China during summer 2002

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Abstract

Meteorological and glaciological observations on the July 1st (Qiyi) glacier in the Qilian Mountains were carried out from June to September 2002. Meteorological stations were installed near the glacier terminus and on the glacier. Glacier surface albedo, ice temperature profile and mass balance were also observed. Meteorological conditions around the July 1st glacier seem to fluctuate at intervals of about two weeks. The albedo decreased to below 0.2 due to mud-like material (cryoconite) covering the glacier surface. Observed refrozen water was very scarce compared with the potential refrozen water calculated from ice temperature changes or the water running off from the glacier surface. The altitudinal profile of the mass balance suggests that the July 1st glacier may be shrinking.

1. Introduction

Central Asia is an arid/semi-arid region. The amount of precipitation is much greater in the mountains than on the plains. However in the plains, evaporation and/or transpiration are significant, far higher than the amount of precipitation. The life of the inhabitants has been strongly affected by variations in the amount of available water. Many cities and towns have been established along the major rivers in order to ensure ready access to water. Glaciers play an important role in the hydrological cycle in such regions, since a considerable amount of solid water is stored in the glaciers and most of the rivers are replenished by them (*e.g.* Yang, 1992; Ujihashi *et al.*, 1998).

The Qilian Mountains in the northwestern Qinghai-Tibetan Plateau of west China are in such an arid/semi-arid region with summits higher than 5000 m a.s.l. Winter is the dry season in this region. On the other hand, the southeasterly and southwesterly monsoons supply the moisture in summer, and more than half of the annual precipitation occurs from June to August. The annual precipitation on the east side of the mountains is greater than on the west side, ranging from 200 to 900 mm (Ding and Kang, 1985; Yang, 1992).

The Qilian Mountains have 2815 glaciers, the whole area of which was 1390.49 km^2 in 1980, most of them facing north (Wu, 1985). The rivers nourished by these glaciers supply water to the plains. Yang (1992) estimated the glacier melt runoff in this range and concluded that it provides about 12.5% of the stream runoff to the Hexi region, north of the Qilian Mountains.

On the July 1st (Qiyi) glacier, located on the west side of the Qilian Mountains (Fig. 1) many observations have been carried out since 1958 (*e.g.* Lanzhou Institute of Glaciology and Geocryology, 1985, 1992; Shi *et al.*, 1988). A joint research team of Japanese and Chinese scientists started meteorological, hydrological and glaciological observations on this glacier in the middle of June 2002 to evaluate the melting processes of glaciers in this region in order to estimate their response to climate change and to measure the fluctuations in the effects of glacier variations on water resources.

We present the preliminary results of those observations from the middle of June to the beginning of September, 2002.

2. Location and observations

The July 1st (Qiyi) glacier (39°15′ N, 97°45′ E; Fig. 1) faces north and, according to Liu *et al.* (1992a), its length along the centerline and the area were 3.8 km and 2.98 km^2, respectively, in 1985.

Observation items, sites, periods and intervals are

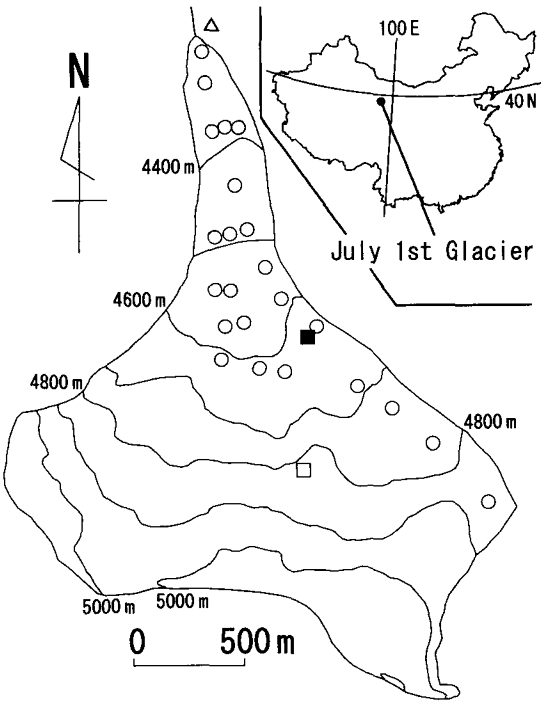

Fig. 1. Location map of stakes (open circles, solid and open squares). The three lost stakes are not plotted. Solid square, open square and triangle denote st8-2, st10 and AS, respectively.

summarized in Table 1, and Fig. 1 shows the topography of the July 1st glacier and the locations of observation sites. Figure 1 is based on a photo survey carried out in 1975 (Wang *et al.*, 1981) and on subsequent surveys by carrier-phase differential GPS conducted in June, 2002.

An automatic weather station (AWS) was installed, and the AWS site (AS, 4290 m a.s.l.) is near the terminus of the July 1st glacier. Air temperature, downward and upward shortwave radiation and ice temperature profile have been measured at the st8-2 (4619 m a.s.l.). It should be noted that the distances between the positions of the sensors and the glacier surface have been changing at st8-2 due to the glacier ablation. Twenty-eight stakes for mass balance measurements were installed on the glacier (Fig. 1) three of which were lost.

3. Results and discussions

3.1. Meteorological conditions

Daily mean meteorological values are shown in Fig. 2 and the average values measured by AWS from June 10 to September 3 are summarized in Table 2.

Figure 2 shows that the meteorological conditions around the July 1st glacier seem to fluctuate at intervals of about two weeks. Relatively cold and wet conditions continue for about two weeks while the following weeks are relatively warm and dry. After warm and dry days, cold and wet conditions return. When there was precipitation, the relative humidity was fairly high, and global solar radiation, wind speed and the lapse rate of air temperatures between AS and st8-2 were relatively small. The directions of daily vector mean wind showed that southerly winds, which are mountain winds here, prevailed, followed by northerly winds. Westerly and easterly winds were very rare.

Table 1. Observation items, sites, periods and intervals. The altitude of AS, st8-2 and st10 are 4290, 4619 and 4827 m a.s.l., respectively.

Items	Sites	Period	Interval
Automatic			
meteorological elements at AS	AS (4290 m a.s.l.)	Jun. 10 -	10 min. (average/sum)
wind velocity and direction	height: 298 cm		
air temperature	height: 184 cm		
relative humidity	height: 184 cm		
downward shortwave radiation	height: 221 cm		
upward shortwave radiation	height: 209 cm		
scattered radiation	height: 207 cm		
net radiation	height: 224 cm		
ground surface temperature			
precipitation			
meteorological elements at st8-2	st8-2 (4619 m a.s.l.)		30 min.
air temperature	height: 150 - 237cm	Jun. 15 -	
downward shortwave radiation	height: 91 - 186cm	Jun. 15 -	
upward shortwave radiation	height: 91 - 186cm	Jun. 15 -	
ice temperature	st8-2	Jun. 15 -	30 min.
	depth: 0, 1, 2, 4, 8 m (Jun. 15)		
Manual			
albedo	13 stakes	Jun. 21 - Aug. 25	about 5 days
surface level	25 stakes	Jun. 13 - Sept. 7	about 5 days
snow thickness	25 stakes	Jun. 13 - Sept. 7	about 5 days
snow density	several stakes	Jun. 16 - Aug. 15	occasionally
GPS survey	outline of glacier	June	(once)
	25 stakes	Jun. and Sept.	(twice)

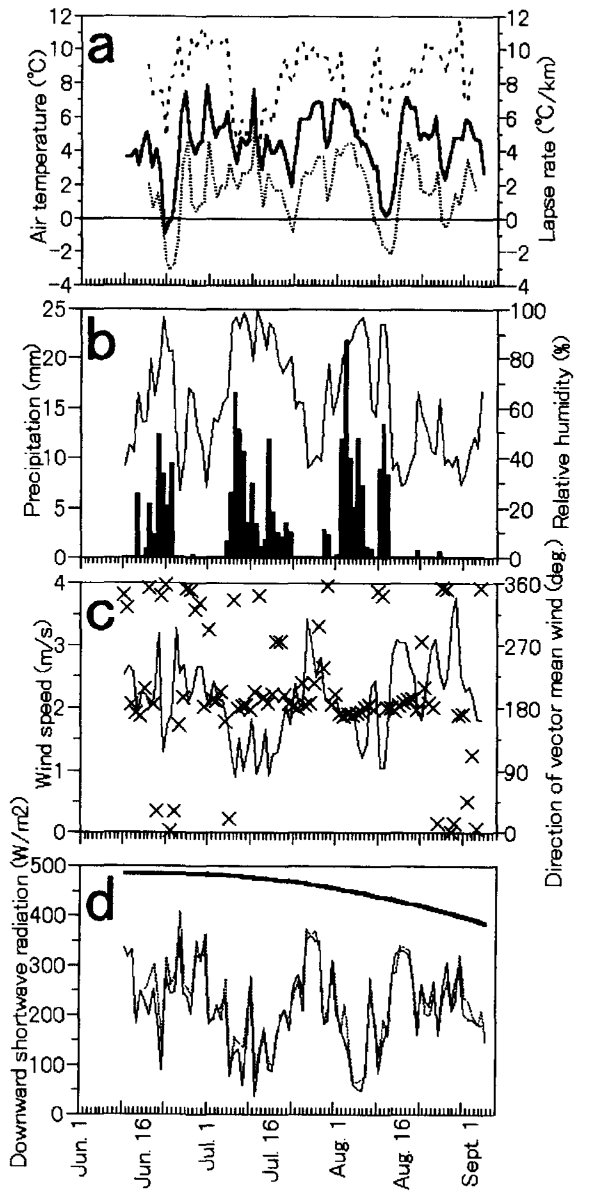

Fig. 2. a) Daily mean air temperature at AS (solid line) and st8-2 (dotted line), and daily mean lapse rate of air temperature between AS and st8-2 (broken line). b) Daily mean relative humidity (solid line) and daily precipitation (bar) at AS. c) Daily mean wind speed (solid line) and direction of daily vector mean wind (cross) at AS. d) Daily mean downward shortwave radiation at AS (solid line) and st8-2 (dotted line), and daily mean solar radiation at the top of the atmosphere (thick line).

3.2. *Albedo*

In the mid- and low-latitude regions where global solar radiation is relatively strong, the surface albedo is an important factor controlling the mass balances of glaciers, since dramatic changes in the albedo can drastically alter the amount of energy received on the glacier surface as a result of the remarkable change net shortwave radiation.

Figure 3 shows the daily albedo at st8-2. When observations were started, the glacier around st8-2 was covered with snow and the albedo value was relatively high. However, the albedo declined drastically until the beginning of July with the melting of surface snow and maintained low values except for short periods. Three albedo peaks were observed on or about June 22, July 20 and August 11. Air temperatures at st8-2 fell below 0℃ around then. These increases of albedo indicate the occurrence of snowfalls and accumulations of snow, but the snow on the glacier surface seemed to melt quickly and the albedo decreased rapidly.

Around July 12 and early in August, the albedo fell below 0.2, which is lower than the usual values on glacier ice. The dark-colored material called cryoconite (Takeuchi *et al.*, 2001) covering the glacier surface was observed during the observation period, and the low albedo was mainly due to it. Kohshima (1989) and Kohshima *et al.* (1993) reported that the albedo-reduction by cryoconite accelerates glacier melting. A similar phenomenon must occur on the July 1st glacier.

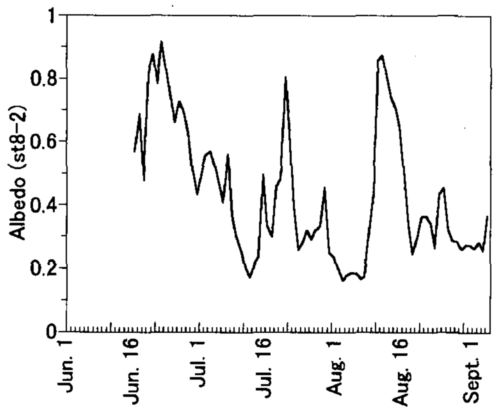

Fig. 3. Daily mean albedo measured at st8-2 (4619 m a.s.l.).

Table 2. Average meteorological values during summer 2002. Lapse rate of air temperature was calculated from the difference in air temperature between AS and st8-2.

Items	Average value	Site	Period
air temperature	4.5 ℃	AS	Jun. 11 - Sept. 3
precipitation	2.9 mm d^{-1}	AS	Jun. 11 - Sept. 3
wind speed	2.1 m s^{-1}	AS	Jun. 11 - Sept. 3
relative humidity	63 %	AS	Jun. 11 - Sept. 3
global solar radiation	215 W m^{-2}	AS	Jun. 11 - Sept. 3
	223 W m^{-2}	st8-2	Jun. 16 - Sept. 4
air temperature	1.8 ℃	st8-2	Jun. 16 - Sept. 1
lapse rate of air temperature	8.3 ℃ km^{-1}	(AS - st8-2)	Jun. 16 - Sept. 1
lapse rate of days with precipitation	7.1 ℃ km^{-1}	(AS - st8-2)	Jun. 16 - Sept. 1

3.3. *Ice temperature*

Figure 4 shows the daily mean ice temperature profiles on June 16, July 1, August 1 and September 31. Though the ice temperature gradually became warmer during the observation period, the temperature of the ice mass except that near the surface remained below 0℃ throughout the summer. Therefore, the July 1st glacier may be classified as a sub-polar glacier.

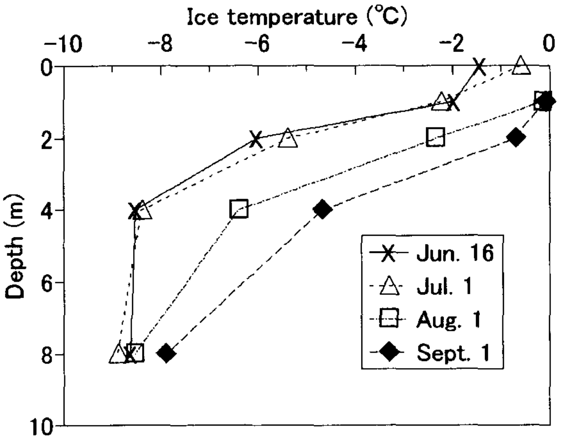

Fig. 4. Ice temperature profiles measured at st8-2 (4619 m a.s.l.). Depth 0 m corresponds to the surface on June 16, 2002.

According to Huang *et al.* (1982) the heat conduction always occurs in one direction and the annual temperature change is less than 0.2℃ at the depth of 16 m in Chinese glaciers, and Huang *et al.* (1982) and Huang (1990) showed the ice temperatures of Chinese glaciers at the depth of 16 m. Therefore, the ice temperature of that depth is useful to compare the ice temperatures of Chinese glaciers. However, the deepest ice temperature sensor installed in June 2002 was at a depth of 8 m, therefore there is no data of the ice temperature at the depth of 16m. As the ice temperature at the depth of 16 m at 4600 m a.s.l. on the July 1st glacier in 1975 was −9.0℃ (Huang, 1990) and the observed ice temperature at the depth of 8 m from June to September 2002 has been about −8 ℃ during the observation period, it is supposed that the ice temperature at the depth of 16 m might have been about −8 or −9℃ recently. Since, according to Huang *et al.* (1982) and Huang (1990) the ice temperature of −8 or −9℃ is comparatively very low in Chinese glaciers, the idea of Huang *et al.* (1982) that the western section of the Qilian Mountains may be where the temperature of the alpine glaciers is at its lowest in the middle and low latitudes, may be still acceptable.

3.4. *Surface levels*

Figure 5 shows surface-level variations calculated from the observed stake length at several points on the July 1st glacier. Glacier surface levels declined

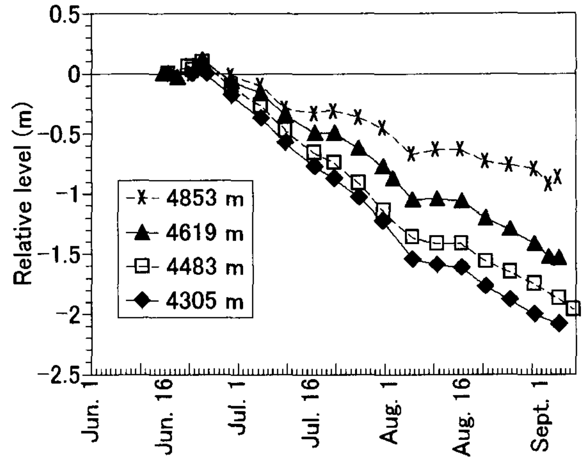

Fig. 5. Variations of relative surface levels. The dates of the reference surface levels are June 16, June 16, June 15 and June 21 at 4305 m a.s.l., at 4483 m a.s.l., at 4619 m a.s.l. (st8-2) and 4853 m a.s.l., respectively.

even at the higher glacier sites during the observation period. The surface level on September 4 was about 90 cm lower than that on June 21 even at 4853 m a.s.l., which is the upper part of the glacier. When snow accumulates on the glacier, the surface-levels decline stops. The variations in surface levels indicate that the snow accumulated on or about June 23 and August 10 on the whole glacier. Surface declines stopped above 4619 m a.s.l. (st8-2) for several days around July 20, but they persisted at the lower part of the glacier during this period.

3.5. *Mass balance*

Specific mass balance is calculated from the observed stake length, the snow thickness of the stake site, and the density of ice and snow. The density of ice is assumed to be 900 kg m^{-3}, and the average snow density measured at several points on July 1st glacier (449 kg m^{-3}) is used for the calculation.

Solid precipitation is calculated based on the relation between the probability of solid precipitation and air temperature observed in the Qilian Mountains (Ding and Kang, 1985) and the assumption that there was no variation in precipitation on the glacier. According to Ding and Kang (1985) the relation between the probability of solid precipitation (*Ps*) and air temperature (*Ta*) is expressed as follows:

$$Ps = -13.4\,Ta + 98.6 \quad (-0.1 \leq Ta \leq 7.3), \tag{1}$$

where *Ps* and *Ta* are the percent and degree Celsius, respectively. The amount of solid precipitation *cs* is calculated from the product of precipitation (*p*) and *Ps* as follows:

$$cs = Ps \cdot p. \tag{2}$$

Air temperature was estimated from that measured by AWS and the mean lapse rate on the day precipitation is observed by AWS (7.1℃ km^{-1}). Figure

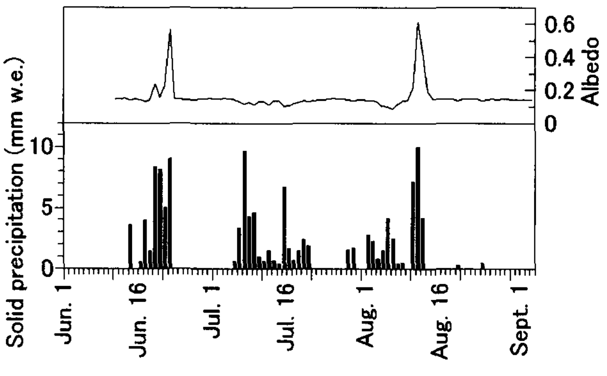

Fig. 6. Daily albedo and calculated solid precipitation at AS.

6 shows the daily albedo and solid precipitation calculated by equation (1) at AS. When the albedo value was high, so were the amounts of calculated solid precipitation. However, despite the considerable calculated solid precipitation, the albedo remained at a low value during July. Air temperature during July was relatively higher than that around June 22 and August 11, when the albedo is about 0.6, suggesting that *Ta* from which *Ps* becomes zero may be lower than 7.3℃ and that the calculated solid precipitation by equation (1) may be overestimated.

Meltwater refreezing plays an important role in the mass balance of sub-polar glaciers (Fujita *et al.*, 1996). The amount of observed refrozen water (rf) is calculated from the increase of ice surface as follows:

$$rf=(\rho i-\rho s)\cdot\Delta h, \qquad (3)$$

where ρi and ρs are the density of ice (900 kg m^{-3}) and snow (449 kg m^{-3}) respectively, and Δh is the change in ice surface level during the observation interval. On the other hand, according to Fujita *et al.* (1996) the potential amount of refrozen water (Rf) representing the maximum ability of ice body to refreeze meltwater is calculated assuming that the warming of the underlying glacier ice is caused only by the latent heat released at the ice surface associated with the refreezing of meltwater as follows:

$$Rf=\int_0^{zc}\frac{\rho iCi}{L}\cdot\Delta Ti(z)\cdot dz, \qquad (4)$$

where Ci is the specific heat capacity of ice (2009J kg^{-1} ℃$^{-1}$) L is the latent heat of fusion for ice (3.35× 10 J kg^{-1}) $\Delta Ti(z)$ is the change in ice temperature (℃) at depth z (m), and the unit of Rf is kg m^{-2} (numerically equal to mm w.e.). The Rf at st8-2 during July and August calculated by equation (4) is about 100mm, though the rf is only 4.5 mm. Though there was much glacier meltwater at st8-2, rf is much less than Rf, possibly because liquid water has run out before becoming cold enough to freeze.

The surface ablation (a), *i.e.*, the amount of meltwater and evaporation, is calculated as follows:

$$a=b-(cs+rf), \qquad (5)$$

where b is the approximated mass balance obtained from stake measurements.

Figure 7 shows mass balance, solid precipitation, the amount of refrozen water, and the surface ablation from June 29 to September 4, 2002. Figure 7 denotes that the specific balance during summer 2002 was possibly negative even at the summit of the July 1st glacier.

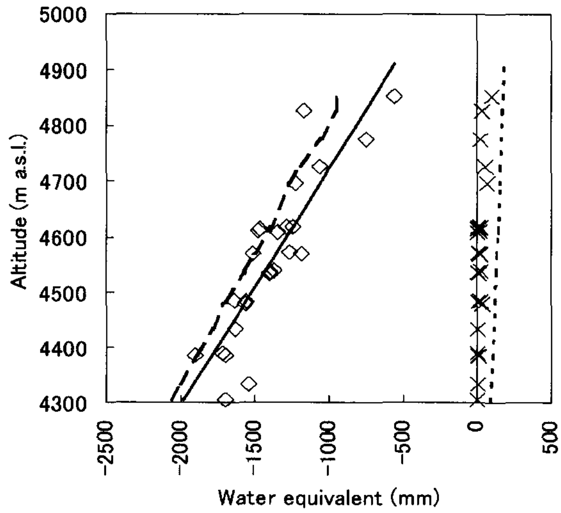

Fig. 7. Altitudinal profiles of observed mass balance (square), the amount of observed refrozen water (cross), approximated mass balance (solid line), calculated solid precipitation (dotted line), and the surface ablation (broken line) on July 1st glacier from June 29 to September 4, 2002.

Assuming that the annual precipitation was 500 mm (Yang, 1992) and considering observed precipitation from June 29 to September 3, 2002 (197.1 mm), the total precipitation from September 5, 2001 to June 28, 2002 was about 300mm. And if all of the precipitation occurred as the solid phase and there was no glacier melt during this period, the mass balance from September 5, 2001 to June 28, 2002 was 300 mm w.e. Equilibrium line altitude (ELA) is where annual balance is zero, therefore, if mass balance during September 5, 2001 to June 28, 2002 was 300 mm w.e. at any place on the July 1st glacier, mass balance at ELA during June 29 to September 4 was −300 mm w.e. And ELA of the year from September 5, 2001 to September 4, 2002 is supposed as about 5020 m a.s.l. from the approximated mass balance from June 29 to September 4, 2002 (b). Liu *et al.* (1992b) show the relation between ELA and the annual total mass balance on the whole of the July 1st glacier as follows:

$$B=3186.25-0.68H, \qquad (6)$$

where B and H are the annual total mass balance (× 10^4 m^3 w.e.) and ELA (m), respectively. Equation (6) suggests that the July 1st glacier is in the equilibrium state when ELA is 4686 m a.s.l. According to Wang *et al.* (1985) and Liu *et al.* (1992b), ELA in 1958/59, the 70's and 80's were from 4550 m to 4810 m a.s.l., and the July 1st glacier fluctuated around the equilibrium state. The supposed ELA of 5020 m a.s.l. is obviously higher than that in the equilibrium state and that observed in the past.

The actual mass balance during September 5, 2001 to June 28, 2002 can have been less than 300 mm w.e., because glacier melt may have occurred from September 5, 2001 to June 28, 2002 and precipitation may have often occurred as the liquid phase. Therefore, ELA of 2001/2002 may be indeed higher than 5020 m a.s.l. The ELA at present would be the highest in the last half-century and, considering equation (6) the glacier may be shrinking in size.

Acknowledgments

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