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Characteristics of melt water discharge in the Glacier No. 1 basin, headwater of Urumqi River

Gao Mingjie, Han Tianding *, Ye Baisheng, Jiao Keqin

State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, Gansu 730000, China

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ABSTRACT

Characteristics of the daily melt water discharge cycle and the relation between melt water discharge, air temperature, and precipitation are analyzed based on observation data during 2001–2005 in the Glacier No. 1 basin at the headwater of the Urumqi River, Tianshan Mountains (hereafter, Glacier No. 1). The results indicate that the daytime and nighttime discharges were less during the preliminary stage of melting in May, and became strong following the ablation period (July–August). The daytime and nighttime discharges in the same month varied year-over-year, and the daily discharge cycles in different months of the summer were dissimilar.

The mean daytime/nighttime discharges were somewhat related to the mean nighttime air temperature (T_n), but were not significantly related to the amount of precipitation. In the daily cycle of average discharges in the summer months during 2001–2005, the maximum discharges occurred in the afternoons and evenings, and the minimum discharges occurred in the mornings. The daily discharge peaks lagged behind the time of maximum melting (maximum air temperature) on selected clear-weather days in different months in different years. This was related to the melt water flow distance inside and underneath the glacier and the structure of the internal drainage net, and may also have been influenced by the weather prior to and after the observed consecutive clear-weather days.

The monthly mean daytime discharge was generally greater than the nighttime discharge, primarily because cloudy and rainy weather and lower air temperatures led to less melt water, and precipitation could not make up the loss of discharge from melt water. Daytime melt water contributed only slightly to nighttime discharge due to the short time lag caused by melt water flow distance.

1. Introduction

Global warming has resulted in loss of mass and volume of most alpine glaciers. Small glaciers are highly sensitive to changes in air temperature and precipitation, and their runoff has contributed to approximately one-quarter to one-third of the 7 cm rise in sea level that took place during the last century (IPCC, 2007). Consequently, detailed individual glacial runoff observation is imperative for the evaluation of glacier recession and changes in water resources on regional. Mountain regions play a critical role in the water cycle, storing water in the form of snow and ice mainly during the cold/wet season, and releasing it as melt water during the dry/warm season when it is greatly needed (Gino et al., 2009). Glaciers, especially mountain glaciers, are sensitive to climatic change (Li et al., 2007; Zhou et al., 2010). Since the 20th century, most of the global mountain glaciers have begun to retreat with climate warming, and the trend of retreating has sped up in the past 20 years. These influences melt water discharge and much research has shown that this is indirectly affected by air temperature.

In Glacier No. 1, the delay characteristics of melt water discharge were studied by Kang (1991) with the dye tracer method. The long-term characteristics, extremum discharge, and the causes of discharge change have also been discussed (Han et al., 2003, 2005, 2010). The relationship between the 0 °C layer height and the stream flow of the Urumqi River in the period of spring snowmelt was researched by Guang et al. (2010). Yang et al. (2012) applied the HBV model to simulate the runoff the Glacier No.1 at the Headwater of Urumqi River, while the degree-day model was used to calculate ice and snow melt. Using measured hydro-meteorological data during 1980–2006 and five glacier area topographic maps as the model input, the daily runoff of the watershed were simulated. The results showed that the degree-day factor and the glacier ice volume and area affected the melt runoff. In other regions the characteristics of runoff in the Tarim River basin and Yarkand River basin were analyzed by Gao et al. (2010a,b). Peter et al. (2003) discussed the effect of different processes and time-scales on the glacier melt drainage and concluded that short-term storage concerns

* Corresponding author. Address: Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Donggangxi Road 320, Lanzhou, Gansu 730000, China. Tel.: +86 931 4967395; fax: +86 931 8271448.

E-mail address: tdhan@lzb.ac.cn (H. Tianding).

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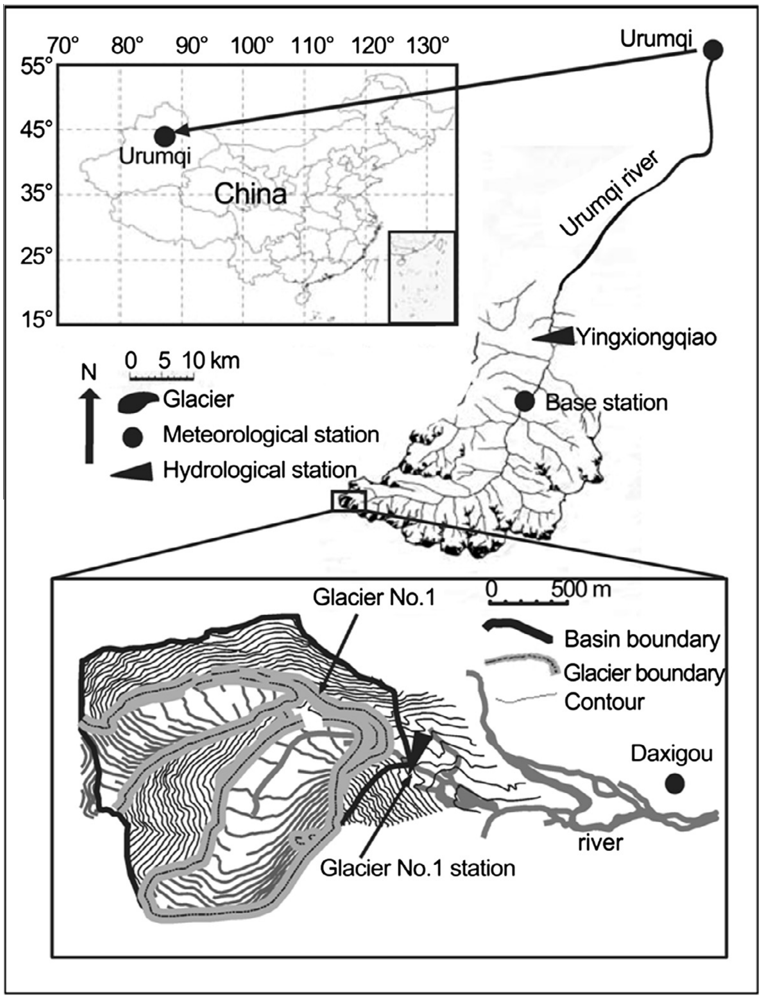

Fig. 1. Schematic map of Glacier No. 1 at the headwater of the Urumqi River, Tianshan Mountains.

diurnal effects of drainage through the glacier including routing through snow, firn and en- and subglacial pathways. Hock (1998, 1999, 2003) modeled glacier melt and discharge, then simulated the distributed temperature-index ice and snow melt model, and analyzed the advantages and disadvantages of different temperature-index model. However, the studies on change characteristics and delaying characteristics of daytime and nighttime average discharge are few. This paper aims to study the characteristics of daytime and nighttime average discharge and the relation between discharge and air temperature and precipitation with a high time resolution so that it can make it clear which factor is dominated.

2. Site description, data sets and method

Glacier No. 1 has an elevation range of 3730–4486 m a.s.l. and is located in the headwater of the Urumqi River, Tianshan, China (43°05′N, 86°49′E) (Fig. 1). It is a small valley glacier with two branches, the east and west branches. These two branches became separated into two small dependent glaciers in 1994 due to continued glacier shrinkage. The length and area in 2000 (length 2.2 km; area 1.733 km^2) decreased compared with that in 1962 (length 2.4 km; area 1.950 km^2) (Jiao et al., 2004). The hydrological station at Glacier No. 1, with a 3.34-km^2 drainage area and 1.71 km^2 glacier area, is located at 3,659 m a.s.l., about 300 m downstream from the tongue of Glacier No. 1. The station is used to observe the glacier melt runoff. The runoff components in the catchment are mainly melt runoff and precipitation. Before 1995, the runoff was determined by both melt runoff and precipitation; however, since 1996 the melt runoff has dominated. The runoff during May–September takes up about 90% of the yearly runoff. For the yearly runoff, the glacier melt runoff is 70% and the rainfall runoff is about 30%.

For hydro-meteorological study of any glacier, the primary requirement is availability of continuous and reliable flow data from at least the ablation period every year. This study analyzes the hydro-meteorological data at the Glacier No. 1 gauging site and precipitation data from the Daxigou meteorological station (elevation 3539 m a.s.l.), which is 1 km from Glacier No. 1, during the ablation period (May–August) from 2001 to 2005. The discharges were obtained by developing a stage–discharge relationship (rating curve) for each ablation season (2001–2005) to convert water levels into discharges. The time step for discharges as well as for air temperature was 1 h. For analysis, the daily discharge data were divided into daytime discharge (09:00–20:00) and nighttime discharge (21:00–08:00), and the air temperature data were divided into similar daytime temperature (09:00–20:00) and nighttime temperature (21:00–08:00).

3. Characteristics of daytime and nighttime average discharges in Glacier No. 1

As displayed in Fig. 2a–c, the variation of discharge generally had trends similar to air temperature. Interestingly, during times of considerable of precipitation the discharge did not increase

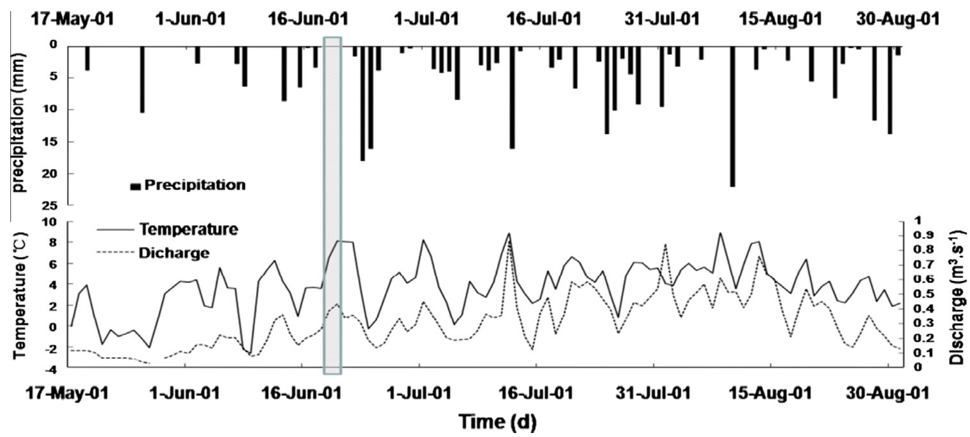

Fig. 2a. The variation in discharge (dashed line) and air temperature (solid line) together with the daily precipitation (bars) during the melt season of 2001. The area covered by the gray bar is the specific period selected for diurnal analysis.

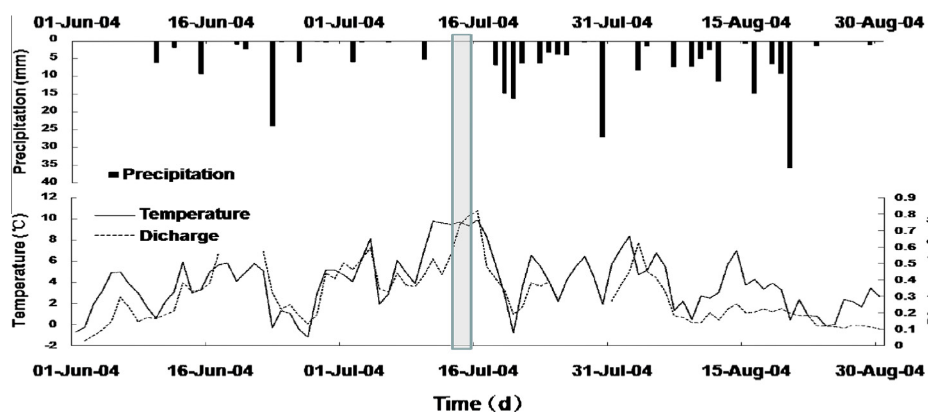

Fig. 2b. The variation in discharge (dashed line) and air temperature (solid line) together with the daily precipitation (bars) during the melt season of 2004. The area covered by the gray bar is the specific period selected for diurnal analysis.

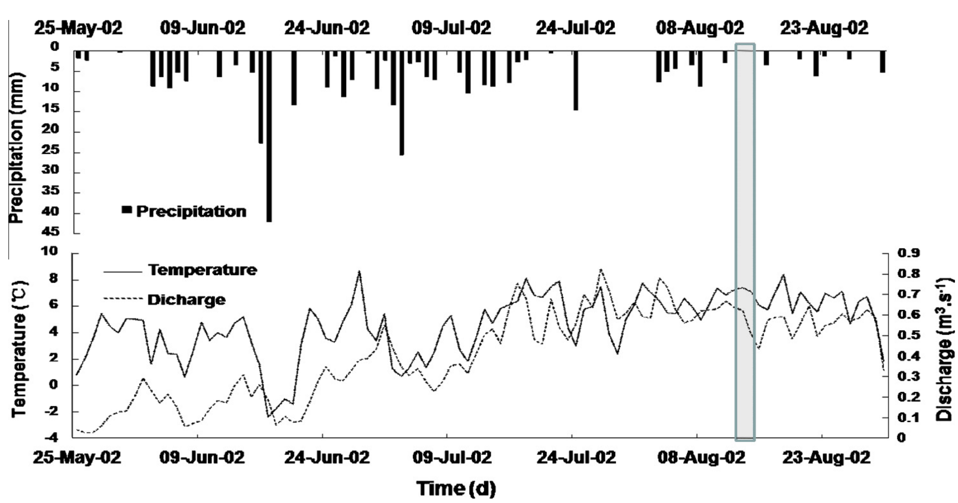

Fig. 2c. The variation in discharge (dashed line) and air temperature (solid line) together with the daily precipitation (bars) during the melt season of 2002. The area covered by the gray bar is the specific period selected for diurnal analysis.

obviously; on the contrary, the mean daily discharge declined sharply due to the reduced temperature on the overcast days. Section 3.4 discusses the diurnal variation in discharge on clear-weather days as it offsets the effect of precipitation.

3.1. Variation of monthly mean daytime/nighttime discharges

The monthly mean daytime and nighttime discharges in the summer ablation periods (2001–2005) are shown in Fig. 3, and

Table 1
Variation in ratio of monthly mean daytime discharge to monthly mean nighttime discharge in summer ablation periods (2001–2005).

Month/Year	2001	2002	2003	2004	2005
May	1.151	0.997	0.949		
June	1.263	0.875	1.268	1.181	1.281
July	1.301	1.137	1.116	2.147	1.523
August	1.617	1.685	1.338	1.340	1.634

the ratios of monthly mean daytime discharge to monthly mean nighttime discharge are shown in Table 1. The monthly mean daytime discharges were all greater than nighttime discharges in the summer ablation period in 2001. The reason why the monthly mean daytime discharge and the nighttime discharge both increased may be that as air temperature rose incrementally, ice and snow melted intensely and the discharge became greater. The ratio increase from 1.15 in May to 1.62 in August might have been due to different levels of influence of air temperature and precipitation.

The ratio in June 2002 was less than 1; this was related to the monthly mean air temperature, which was lower than that in 2001 and 2003 but higher than that in 2004. The daily mean air temperatures from June 18 to June 21 in 2002 were all below 0 °C. However, the ratio in June 2002 was less than that in 2001, 2002, and 2004, while the ratio in June 2004 was less than that in 2001 and 2002. This may be related to the fact that in June 2002 there was a snowfall incident which delayed the release of melting water. The ratio in June 2004 was relatively small because the small amount of melt water needed to be observed for a longer time due to the air temperature being lower.

The monthly mean daytime and nighttime discharges in July and August 2002 increased rapidly. Compared with June 2002, the monthly mean daytime discharge and nighttime discharges in July were 1.73 and 1.10 times greater than that in June, respectively, and in August were 3.85 and 2 times greater than that in June, respectively. The ratio of monthly mean daytime discharge to monthly mean nighttime discharge in August was larger than that in July.

Monthly mean daytime discharges in June, July, and August 2003 were all greater than the monthly mean nighttime discharges, but the ratios all became smaller. Compared with 2001 and 2002, the monthly mean daytime/nighttime discharges in June were larger, but the monthly mean daytime/nighttime discharges in July and August were less. The reason may be that in July–August overcast and rainy weather occurred frequently and there was more precipitation (87.7 mm in August 2001; 51 mm in August 2002; 100.6 mm in August 2003). This type of weather lessens ice and snow melt, and discharge from precipitation cannot make up this decrement of discharge.

The monthly mean daytime/nighttime discharges in 2004 were unexpected. The monthly mean daytime and nighttime discharges in August were both less than in July (42% and 67% less than the July levels, respectively) and were significantly lower than in June (97% and 85% less than the June levels, respectively). The cause may be the considerable precipitation (112.5 mm) in August, but it still could not make up the decrement of discharge from melt water. This will be further discussed in Section 4.

Compared with the Gangotri Glacier in the Indian Himalayas (Singh et al., 2006, 2011), both the mean daytime discharges and the mean nighttime discharges increased month by month from May to August. However, the ratios of monthly daytime discharge to nighttime discharge for the different months (May–August) during the ablation period varied. The ratio in Glacier No. 1 ranged from 0.95 to 2.15 (except for 0.88 in June 2002), while it only ranged from 0.96 to 1.08 in the Gangotri Glacier. In other words, the diurnal amplitude of discharge was small in Glacier No. 1 while it was large in the Gangotri Glacier. The reason may be that the Gangotri Glacier has a strong melt water storage characteristic due to its large size. Very little or no melting takes place during the nighttime, but there is sufficient flow in the river during nighttime coming from melt water in the snow or the firn area of the glacier during the daytime and from several days previous. Glacier No. 1 is much smaller in size than the Gangotri Glacier and its the storage capacity is less. In the daytime, melt water flows out from the glacier snout for only a few hours; the nighttime discharge is closely related to the nighttime air temperature and also some occasional precipitation. Thus, the daytime discharge is much larger than the nighttime discharge from Glacier No. 1.

3.2. Characteristics of daytime/nighttime discharges in the same month in different years

Because of missing data, this study does not assess the discharges in May of 2004, 2005 (Fig. 3). The monthly mean daytime discharge in June 2002 was much less than in the other years but was greatest in June 2003. However, differences in the monthly mean nighttime discharges during 2001–2005 were negligible. In addition, the monthly mean daytime discharge in June 2002 was less than that in June 2001, but the nighttime discharge was the opposite (greater). For the monthly mean nighttime discharge in July, 2003 was the least and 2004 was the largest (2.20 times greater than 2003). The monthly mean daytime discharge in July 2003 was the lowest, while July 2002 was the largest. Moreover, the ratio in July 2003 was 1.12 but was 2.15 in July 2004. The trend in August was the same as that in July but the amplitude was larger. The monthly mean daytime discharge in August 2002 was the largest during the entire period of 2001–2005.

3.3. Monthly mean daytime and nighttime discharges in summer months during 2001–2005

In different months, the monthly mean daytime and nighttime discharges during 2001–2005 were dissimilar (Fig. 4). For example,

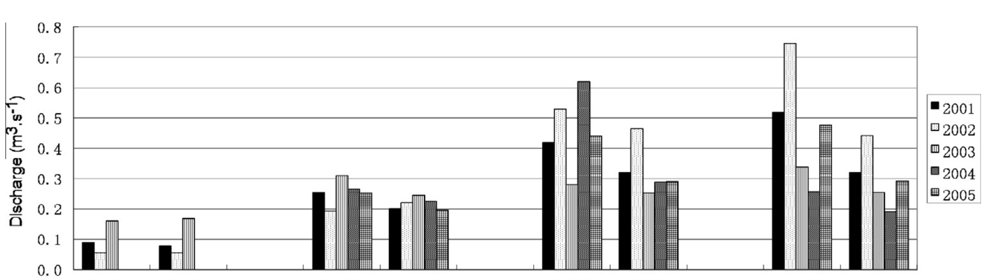

Fig. 3. Monthly mean daytime (d) and nighttime (n) discharges in summer during 2001–2005.

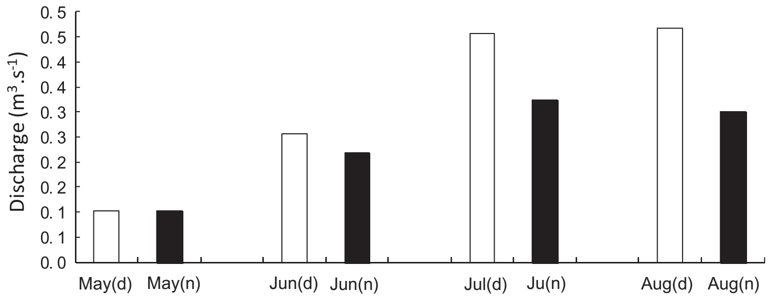

Fig. 4. The monthly mean daytime and nighttime discharges in summer months during 2001–2005.

in June the monthly mean daytime discharges during 2001–2005 were slightly more than the nighttime discharges, and the monthly mean daytime discharges in July/August during 2001–2005 were much larger than the nighttime discharges. This indicates that as time passed, the ratio of monthly mean daytime discharge to nighttime discharge in the summer months during 2001–2005 increased. The monthly mean daytime discharges in the summer months during 2001–2005 presented the same trend. However, the monthly mean nighttime discharges during 2001–2005 increased gradually from May to July but decreased slightly in August.

3.4. Daily cycle of average discharges in summer months during 2001–2005

Because variation in air temperature occurs on annual, seasonal, monthly, and daily cycles, there are corresponding changes in discharge levels. Mean changes in discharge on the diurnal scale for different months are depicted in Fig. 5. It is observed that the daytime discharge started rising from June onward and reached its maximum in August, while the nighttime discharge started rising from June onward, reached its maximum in July, and then started to decline in August. The maximum discharges for different months ($0.319\,m^3\,s^{-1}$ in June, $0.581\,m^3\,s^{-1}$ in July, and $0.626\,m^3\,s^{-1}$ in August) occurred at 18:00, 17:00, and 16:00, respectively, and the minimum discharges ($0.157\,m^3\,s^{-1}$ in June, $0.240\,m^3\,s^{-1}$ in July, and $0.227\,m^3\,s^{-1}$ in August) occurred at 10:00, 09:00, and 09:00, respectively.

Both limbs of the hydrograph are almost flat during early part of melt season. Rising and falling limbs of the hydrograph become steeper with advancement of the melt season, but the rising limb of the hydrograph is always steeper than the recession limb. In the beginning of the melt season (May), the less pronounced diurnal fluctuation in discharge from the glacierized basin may be due to the depth and broad extent of seasonal snow over the glacier, which can have a dampening effect on the melt runoff. Under such conditions, the runoff can have a significantly delayed response because melt water passes through the snowpack and flows as interflow after reaching the ice surface. In addition, it is so cold in May that there is little or no melting, or else the melt water refreezes before it reaches the ice surface, so there is no discharge. However, during the middle part of the melt season (July–early August), intense melting takes place due to stronger solar radiation and the larger extent of exposed glacier ice. This results in melt water producing well distinguished diurnal changes in discharge levels. At this stage there is no significant storage of melt water at the glacier surface, so the melting follows strong diurnal patterns. As shown in Fig. 5, the maximum discharge was observed in the evening (16:00–18:00), which was earlier than that (17:00–19:00) in the Gangotri Glacier discussed above. This may be because the distance (300 m) from the Glacier No. 1 gauging site to the snout of the glacier is shorter than that in the Gangotri Glacier. The time range of minimum discharge in the morning (09:00–10:00) is smaller than that (07:00–10:00) in the Gangotri Glacier (Singh et al., 2006).

3.5. Delay characteristics of daytime and nighttime discharges

There is a time lag between melt water generation over the glacier and the appearance of this melt water as runoff at the snout of the glacier. In order to understand the variations in this time lag, the data collected near the snout of glacier during the 2001–2005 observation period were used. Other factors such as precipitation and overcast and rainy weather were not considered in this analysis (Fig. 2a–c), because solar radiation directly influences the melting.

Another important factor in such an analysis is that the measurement of discharge be as close as possible to the snout to minimize the impact of time taken by the water to travel from the snout to gauging site, and to eliminate the possible contribution from any other sources within the reach from the snout to gauging site. Therefore, the gauging site was located at the watercourse about 300 m downstream of the snout of the glacier. Year-to-year

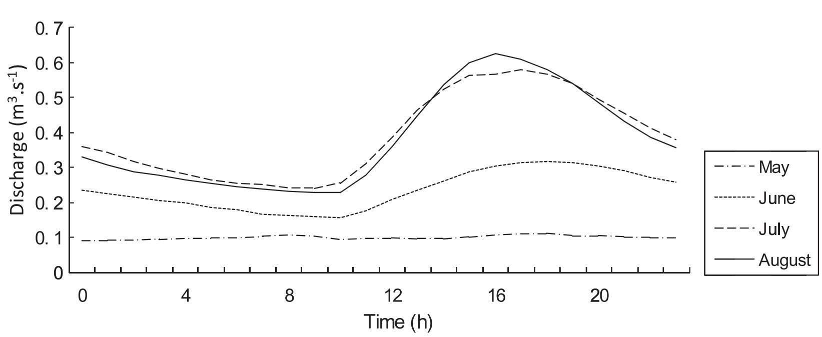

Fig. 5. The daily cycle of average discharges in summer months during 2001–2005.

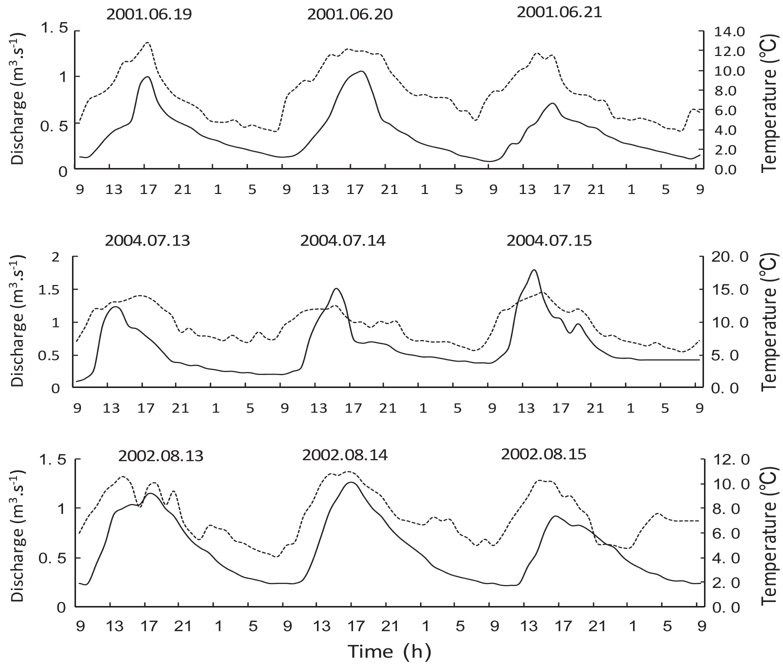

Fig. 6. Diurnal variation in discharge (solid line) and air temperature (dashed line) for selected clear-weather days in different months in different years.

variation in discharge was not obvious, so this study does not consider the distinction of years.

Hydrographs of three consecutive clear-weather days were selected in June, July, and August, and the comparison between air temperature and hourly discharge is shown in Fig. 6. The maximum air temperature occurred between 14:00 and 17:00, while the daily discharge peak varied between 16:00 and 18:00 in June. The daily discharge peak lagged behind the time of maximum melting (maximum temperature) on the glacier by 1–2 h. In July the daily discharge peak did not lag and both the daily discharge peak and maximum melting occurred between 14:00 and 15:00. The maximum melting in August was lower than that in July and also occurred between 14:00 and 15:00, but the daily discharge peak varied between 17:00 and 18:00 and lagged behind the time of maximum melting by 2–3 h. Thus, the time lag varied between 1 and 3 h. However, in the Gangotri Glacier it varied between 4 and 7.5 h (Singh et al., 2006) or between 2 and 6 h (Singh et al., 2011) in these years.

Generally, the magnitude of runoff delay depends on the distance the water has to travel through and below the glacier, and the configuration of the internal drainage network. The distance for melt water travel in the Gangotri Glacier is much longer than in Glacier No. 1, and the area of the Gangotri Glacier is much larger than Glacier No. 1, so there was a longer time lag due to the greater storage characteristics of the Gangotri Glacier.

Also, at Glacier No. 1 the time of the least daily discharge and the minimum air temperature varied in different months. The time of minimum air temperature varied from 07:00 to 08:00, 05:00 to 07:00, and 07:00 to 08:00 in June, July, and August, respectively. The time of the least daily discharge was from 08:00 to 10:00, 06:00 to 09:00, and 08:00 to 09:00 for the corresponding months.

Based on the above analysis, the time lag between the daily discharge peak and the time of maximum melting varied in different months. In general, in the early part of a melt season the seasonal snow cover in the catchment is so large that there is little melt water and thus there are no significant water pressure perturbations above steady-state values, so the distributed linked-cavity systems cannot collapse into channelized systems. The melt water has to travel a longer distance to reach the glacier snout, so the time lag is greater. The time lag is reduced with the advancement of the melt season because of glacier melting and the efficient, well-developed drainage network. Toward the end of the melt season, the lag time of the daily discharge peak after the time of maximum melting becomes longer because there is less available energy for melting due to lower air temperature, which results in less melt water.

4. The causes of variation in mean daytime and nighttime discharge

To determine the factors that influence mean daytime and nighttime discharge levels, we selected the mean daytime and nighttime discharges in particular months that had certain remarkable characteristics.

4.1. Causes of mean daytime discharge being less than nighttime discharge

In June 2002 the mean daytime discharge was less than the nighttime discharge compared with June 2001. The mean daytime temperature (T_d), mean nighttime temperature (T_n), mean daily temperature (T_{avg}), mean maximum daily temperature (T_{max}), and mean minimum daily temperature (T_{min}) in June 2002 were 0.2 °C, 0.7 °C, 0.5 °C, 0.5 °C, and 0.6 °C lower than those in June 2001, respectively (Table 2). In addition, the mean minimum daily temperature (T_{min}) was also lower than 0 °C. The precipitation (P) in June 2002 (157.7 mm) was more than twice that in June 2001, and the number of days with precipitation (D) in June 2002 was twice as many as in June 2001. However, the mean daytime discharge (Q_d) in June 2002 was less than that in June 2001. The reasons are as follows.

The discharge here is mainly dominated by melt water from the glacier after 1995 (Han et al., 2010). As we know, on the basis of temperature-index model, there is a strong relationship between melt water and air temperature: the higher the air temperature,

Table 2
Comparison of air temperature, runoff, and precipitation between June 2001 and June 2002.

Year	T_d (°C)	T_n (°C)	T_{avg} (°C)	T_{max} (°C)	T_{min} (°C)	Q_d (m^3 s^{-1})	Q_n (m^3 s^{-1})	P (mm)	D (d)
2001	5.2	2.2	3.7	7.9	0.3	0.255	0.202	70.7	14
2002	5.0	1.5	3.2	7.4	−0.3	0.194	0.221	157.7	16

T_d, mean daytime air temperature; T_n, mean nighttime air temperature; T_{avg}, mean daily air temperature; T_{max}, mean maximum daily air temperature; T_{min}, mean minimum daily air temperature; Q_d, mean daytime discharge; Q_n, mean nighttime discharge; P, precipitation; D, number of days with precipitation.

the more melt water. In this study, the degree-day factor computed was 2.36 mm/(°C d) in June 2001 and 2.06 mm/(°C d) in June 2002, and meanwhile, the mean daytime temperature (5.0 °C) in June 2002 was lower than that (5.2 °C) in June 2001, so the mean daytime glacier melt runoff in June 2002 which was calculated with a simple degree-day formulation was less than that in June 2001. Correspondingly, the mean daytime discharge (Q_d) in June 2002 observed from the hydrological station of the Glacier No. 1 was less than that in June 2001.

However, the mean daytime discharge (Q_d) was less than the mean nighttime discharge (Q_n) in June 2002 observed from the hydrological station of the Glacier No. 1, while the mean daytime temperature (T_d) (5.0 °C) was higher than the mean nighttime temperature (T_n) (1.5 °C) in June 2002. It was due to low air temperature during overcast days as well as to the precipitation in the night. In part before, it was mentioned that the discharge observed from the hydrological station of the Glacier No. 1 consisted of glacier melt runoff and rainfall. According to temperature-index model, the mean daytime temperature (T_d) being higher than the mean nighttime temperature (T_n) in June 2002 meant that the mean daytime glacier melt runoff was larger the mean nighttime glacier melt runoff in June 2002. So the mean daytime discharge (Q_d) being less than the mean nighttime discharge (Q_n) in June 2002 observed from the hydrological station of the Glacier No. 1 was due to more rainfall in the night during overcast days.

Generally, the nighttime discharge mainly comes from melt water on clear-weather days, but the nighttime discharge is made up of melt water together with precipitation on overcast days. The maximum daily temperature was about 2 °C during the overcast days, while it was about 10 °C during clear-weather days. As for the minimum daily temperature, it was below 0 °C (even −4 °C) during the overcast days, while it was always above 0 °C on the clear-weather days.

The diurnal amplitude of air temperature during overcast days was reduced by 2 °C compared with that on the clear-weather days. Thus, the glacier melt water decreased sharply in the daytime and decreased slightly in the nighttime. The discharge in the daytime should be greater than that in the nighttime if both of them came from melt water. However, the observed discharge in the daytime was less than that in the nighttime, and the variation trend of the discharge was not the same as the nighttime air temperature trend on the overcast days. The mean nighttime temperature declined while the mean nighttime discharge rose to some extent. At the same time, there was considerable precipitation on the study days and nights. Precipitation can partly contribute to the nighttime discharge, so the mean nighttime discharge (Q_n) was slightly more than the mean daytime discharge (Q_d).

4.2. Cause of the mean daytime discharge being larger than nighttime discharge

The mean daytime temperature (T_d) and mean daily temperature (T_{avg}) in July 2004 were 3 °C and 2.6 °C higher than those in July 2003, respectively (Table 3). The mean temperature difference in July 2004 was 3.6 °C, while it was 2.7 °C in July 2003. The precipitation events in those years were dissimilar. The amount of precipitation (P) in July 2003 was 85.5 mm for 14 days and there were no more than two consecutive clear-weather days in that month. By comparison, the amount of precipitation (P) in July 2004 was only 65.7 mm for 10 days, and July 13 to July 18 were consecutive clear-weather days.

As for discharges, the mean daytime discharge (Q_d) in July 2004 was 1.13 times more than that in July 2003, but the mean nighttime discharge (Q_n) in July 2004 was slightly more than that in July 2003. In addition, the ratio of monthly mean daytime discharge to monthly mean nighttime discharge in July 2004 was 2.147, whereas it was only 1.097 in July 2003.

Based on these facts, the phenomenon of the mean daytime discharge (Q_d), the mean nighttime discharge (Q_n), and the ratio all being larger in July 2004 mainly resulted from less precipitation (P), fewer days with precipitation (D), more clear-weather days, the air temperature rise on clear-weather days, and most especially, the number of consecutive clear-weather days and the melt water increase.

On the basis of mass balance observation data, the degree-day factor was calculated (Yuhuan et al., 2010). The value is 4.42 mm/(°C d) in July 2003 and 6.97 mm/(°C d) in July 2004. It is also found that the higher the temperature is, the bigger the degree-day factor is and the factor rises faster with temperature increasing. As we know, the mean daytime temperature was larger than mean nighttime temperature, and the range from mean daytime temperature to mean nighttime temperature in July 2004 was larger than that in July 2003. So the daytime mean glacier-melt runoff was more than the nighttime mean glacier-melt runoff. In addition, the rainfall in July 2003 and 2004 was similar. Hence, the mean daytime discharge (Q_d), the mean nighttime discharge (Q_n) and the ratio are all larger in July 2004.

Taking 14 July 2004 for example (Fig. 7), a heavy rainfall occurred and reached 36.2 mm, which led to the air temperature going down and the mean daytime discharge (Q_d) and mean nighttime discharge (Q_n) decreasing. When the rainfall stopped on 15 July 2004, the temperature went up and the discharges increased. This indicates that although the amount of precipitation (P) was large in one precipitation event, the melting was weak and discharges were small due to low air temperature. By analyzing the

Table 3
Comparison of air temperature, runoff, and precipitation between July 2003 and July 2004.

Year	T_d (°C)	T_n (°C)	T_{avg} (°C)	T_{max} (°C)	T_{min} (°C)	Q_d (m^3 s^{-1})	Q_n (m^3 s^{-1})	P (mm)	D (d)
2003	4.7	2.0	3.3	7.2	0.2	0.290	0.265	85.5	14
2004	7.7	4.1	5.9	10.0	2.4	0.619	0.288	65.7	10

T_d, mean daytime air temperature; T_n, mean nighttime air temperature; T_{avg}, mean daily air temperature; T_{max}, mean maximum daily air temperature; T_{min}, mean minimum daily air temperature; Q_d, mean daytime discharge; Q_n, mean nighttime discharge; P, precipitation; D, number of days with precipitation.

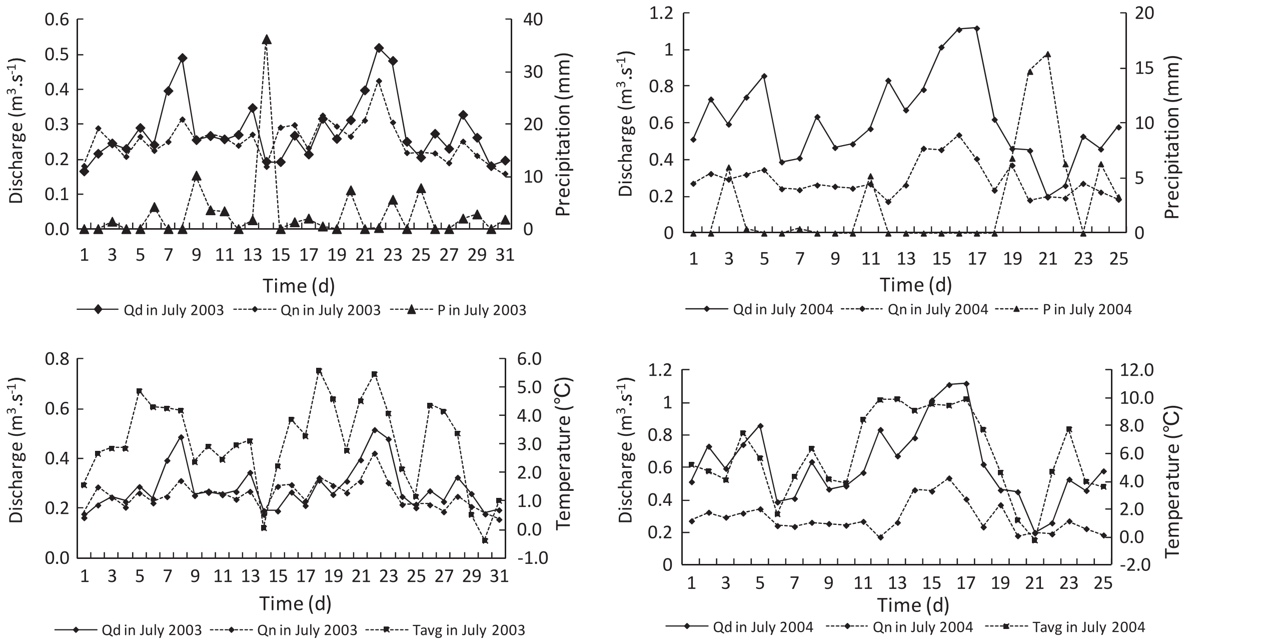

Fig. 7. The daytime and nighttime discharge, air temperature, and precipitation in July 2003 and July 2004. Q_d, mean daytime discharge; Q_n, mean nighttime discharge; T_{avg}, mean daily air temperature; P, precipitation.

mean daytime discharge (Q_d), mean nighttime discharge (Q_n), the amount of precipitation (P), and air temperature, we found that during the precipitation event the temperature descended and the discharge decreased. However, the less amount of precipitation (P) and the more consecutive clear-weather days in July 2004 maintained the air temperature at a higher level and the glacier produced more melt water.

By analyzing these same factors, we found that the reason for less discharge in July 2003 was that overcast and rainy weather made the air temperature go down and the melt water decrease. This suggests that the discharge level may be less related to the amount of precipitation and more related to the number of days with precipitation (D). The more days with precipitation, the less discharge there is.

The ratio of monthly mean daytime discharge to monthly mean nighttime discharge in July 2004 was large for the following reasons. On the one hand, during clear-weather days, high air temperature leads to faster melting and more melt water, producing larger daytime discharges. On the other hand, there is more nighttime discharge than daytime discharge because the melt water produced in the daytime contributes somewhat to nighttime discharge. In addition, from 18 July 2004 to 23 July 2004, the weather was overcast and rainy. The mean daytime discharge (Q_d) and mean nighttime discharge (Q_n) both consisted of base flow and precipitation, and the ratio was small. This demonstrates that the small ratio in July 2003 was mainly due to the preponderance of overcast and rainy weather.

4.3. The relation between air temperature and mean daytime / nighttime discharge

The correlation coefficients of mean daytime and nighttime discharges and mean daytime air temperature (T_d) were 0.6722 and 0.5604, respectively, at the 0.01 confidence level. However, the discharges and the daily amount of precipitation had no correlation. This suggests that the daytime and nighttime discharges were both influenced by mean daytime air temperature rather than the amount of precipitation. The discharges increased with the rise of daytime air temperature. Furthermore, the impact of the daytime air temperature on the mean daytime discharge was greater than on the mean nighttime discharge.

5. Conclusion and discussion

Changes in the monthly mean daytime and nighttime discharges at Glacier No. 1 during the summer months of 2001–2005 are obvious. They both increased during that time, with the melting becoming strong (except in 2004, when the mean nighttime discharge decreased in August). In addition, the monthly mean daytime discharges were all greater than the monthly mean nighttime discharges from June to August (except in June 2002).

As for the monthly mean daytime and nighttime discharges in the same mouth over different years, in June 2002 the monthly mean daytime discharge was the least and the ratio was less than 1 (0.875), while the ratios in other years were all greater than 1. The largest was 1.281 in June 2005. Generally the ratios in July were greater than those in June.

The daily cycle of average discharges in the summer months during 2001–2005 is also obvious. The maximum discharges for different months (0.319 $m^3 s^{-1}$ in June, 0.58 1 $m^3 s^{-1}$ in July, and 0.626 $m^3 s^{-1}$ in August) occurred in the evenings (at 18:00, 17:00, and 16:00, respectively), and the minimum discharges (0.157 $m^3 s^{-1}$ in June, 0.240 $m^3 s^{-1}$ in July, and 0.227 $m^3 s^{-1}$ in August) occurred in the mornings (at 10:00, 09:00, and 09:00, respectively). The daily discharge peaks lagged behind the time of maximum melting (maximum air temperature) on selected clear-weather days in different months in different years. However, that characteristic was not obvious in July. This was related to the flow distance inside and underneath the glacier and the structure of the internal drainage net. In addition, because there were so few consecutive clear-weather days, the time lag may have also been influenced by the weather prior to and after the consecutive clear-weather days; this possibility needs further study.

The monthly mean daytime discharge was generally greater than the nighttime discharge, primarily because more cloudy and rainy weather and lower nighttime air temperatures led to less melt water, and precipitation could not make up the loss of discharge from melt water. However, in July 2004 there were several consecutive clear-weather days and higher air temperatures which led to more melt water, so the monthly mean daytime discharge was greater than usual. The nighttime discharge was also became larger, but the daytime melt water contributed only slightly to nighttime discharge due to the short time lag.

The mean daytime/nighttime discharges were related to the mean nighttime temperature (T_n); the coefficients were 0.6722 and 0.5604, respectively, at the 0.01 confidence level. The mean daytime/nighttime discharges were not significantly related to the amount of precipitation.

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