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Response of glacial-lake outburst floods to climate change in the Yarkant River basin on northern slope of Karakoram Mountains, China

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A B S T R A C T

Based on the glacial flood events and climate change in the Yarkant River basin during the past 50 years, the study investigated the long-term change of temperature and precipitation, the characteristics of glacial floods, the origin of sudden flood release, the suggested flood mechanism of glacial lakes and the relationship between glacial floods and climate change. Results showed that there was an obvious increase in the temperature of the basin since 1987. Specifically in the mountainous area, the significantly increasing temperature in the summer and autumn seasons accelerated the melting rate of glaciers and caused glacial-lake burst. Sudden flood release occurred frequently. The frequency of glacial-lake outburst floods was 0.4 times/a during the period 1959–1986 and increased to 0.7 times/a during 1997–2006. Peak discharge also increased. There were seven floods with peak discharge over 4000 m^3/s from 1959–2006, and three occurred after 1997. The increasing frequency and magnitude of glacial outburst floods mirrored the effect of climate warming on glaciers.

1. Introduction

Water is one part of the environment. Its availability is irreplaceable for the effective operation of the biosphere, but can also be destructive. Floods, extreme hydrological events, are threatening the safety of human beings and society. With climate warming, unstable weather occurs frequently and glacier melt accelerates. Glacial lake outburst floods (GLOFs) increased and have received widespread attention, causing disasters in Iceland, Peru, Switzerland, Canada, Russia, USA, Nepal and Bhutan (Bjornsson, 1974, 2002; Ives, 1986; Vuichard and Zimmermann, 1986; Clague and Evans, 2000; Chikita et al., 2001; Yabuki, 2003; Jordan and James, 2008). The Himalayas is an area where GLOFs frequently occurred (Xu, 1988; Mool, 1995; Walder and Costa, 1996; Sakai et al., 2000; Iwata et al., 2002; Komori et al., 2004; Wang et al., 2008). Research on GLOFs mainly involves assessments and simulations (Walder et al., 2003; Huggel et al., 2004; Carey, 2005), and also some empirical formulae (Huggel et al., 2002; McKillop and Clague, 2007) and physically based process models, such as DAMBRK, BREACH, and SOBEK (Carrivick, 2006). In recent years, the integration of remote sensing data with GIS and hydrodynamic modeling has become an increasingly important means of simulating GLOFs (Carrivick, 2006; Birendra et al., 2007; Jiro, 2008; Wang et al., 2008).

GLOFs in the Shaksgam valley on the northern slope of the Karakoram Mountains are common natural hazards. Recent statistics for the past 5 decades showed that about 21 glacial flood events occurred in the valley. Previous studies have been done on the causes, the possible peak discharge and prediction of GLOFs (Chen et al., 1989; Wang and Chen, 1989; Wang et al., 1989; Wang, 1990; Chen, 1994). This paper, based on the detailed analysis on the sudden floods and temperature and precipitation change, investigates the long-term change of climate, the characteristics of glacial floods and the relationship between glacial floods and climate change.

2. Study area

Yarkant River, one of the tributaries of Tarim River, originates from the north slope of the Karakoram Mountains. The watershed area is 50,248 km^2. Typical annual runoff amounts to 65.8×10^8 m^3, which is composed of glacier meltwater (64%), snow meltwater (13.4%) and base flow (22.6%). Glacier resources are abundant in the Yarkant River basin. There are five glaciers in the Shaksgam valley, one of the largest tributaries of the Yarkant River (Fig. 1). Isolated rocks covered by moraine gravels

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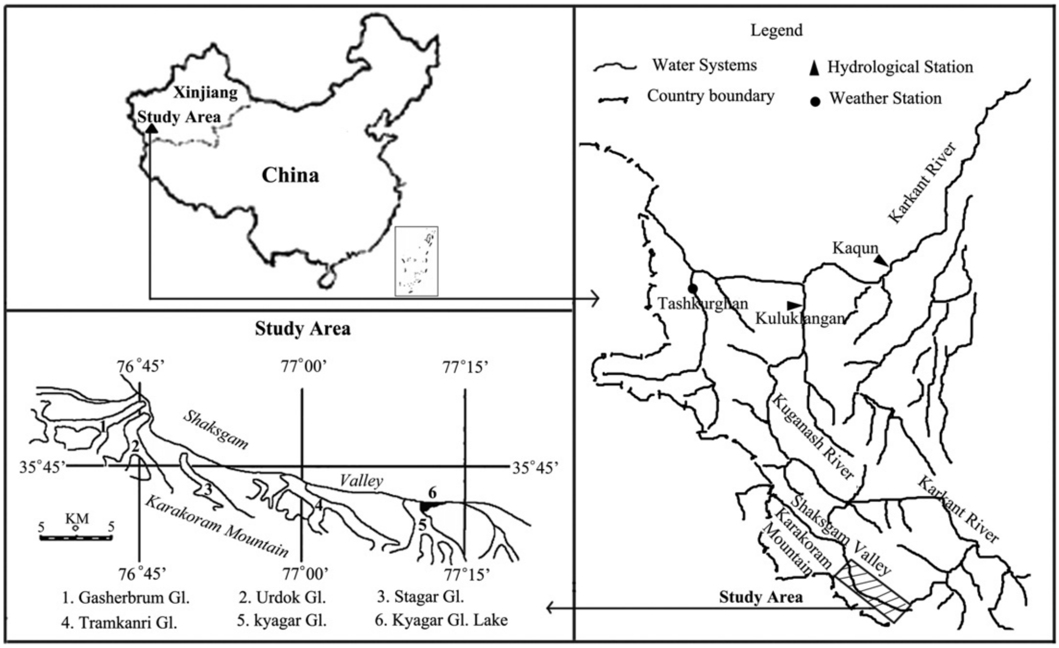

Fig. 1. The glaciers in Shaksgam Valley, northern slope of the Karakoram Mts.

along the Shakegam Valley are present in front of the Gasherbrum, Urdok and Stagar Glaciers. Gravels beyond the fronts of these glaciers, testify that these glaciers had at some time barred the valley. However, these glaciers could not have formed dammed-lakes, for there are no lacustrine traces, terraces, or deposits. However, dammed rivers and lakes are distributed at the upper end of the Shaksgam Valley, at the Tramkanri and Kyagar Glaciers. These are more pronounced at the Kyagar Glacier, some 19 km upstream from Tramkanri Glacier. The Kyagar Glacial Lake is located at the junction of Kyagar Glacier and Shaksgam Valley. Whether a lake is formed or a river becomes blocked depends on the location of a glacier in the river. Distribution of lakes in the Shakegam River shows that lakes are more readily formed in the upper reaches, barred by glaciers. At present, the Tramkanri Glacier may not fully dam the lake, as the glacier terminus has partly separated from the right bank of the river, so melting water can drain away.

The Kaqun hydrometric station (1420 m a.s.1.) established in 1953 is located at the mountain pass. The average annual discharge for the station since 1953 is 202 $m^3 s^{-1}$, with an equivalent runoff depth of 132.6 mm for the basin.

3. Results and analysis

3.1. Local climate change

The characteristics of air temperature and precipitation in the plain and mountainous area are different. Two observation stations, Kaqun hydrological station (1420 m a.s.l., at the mountain pass) and Tashkurghan meteorological station (3093.7 m a.s.l., on the high mountain), were chosen to investigate the characteristics of air temperature and precipitation in the different sections of the Yarkant River. The average annual temperature both in Kaqun station and Tashkurghan station showed increasing trends. However, at Kaqun, the growth rate was only 0.03 °C/10a. At Tashkurghan, the latter was significant with a rate of 0.25 C°/10a (Fig. 2), indicating that the temperature change in mountainous area was more obvious than that in the plain. An M-K test showed that the air temperature in the Tashkurghan station had a significant jump in 1987. The average annual temperature during the period 1961–1986 was 3.30 °C, and that during 1987–2000 was 3.87 °C.

The decadal change of seasonal air temperature in the Tashkurghan station consistently showed an upward tendency (Table 1).

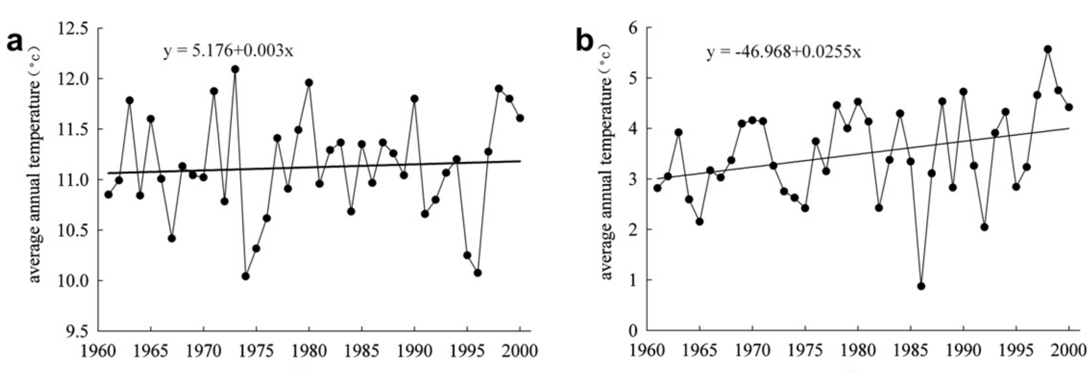

Fig. 2. Average annual temperature changes in (a) Kaqun station and (b) Tashkurghan station during the period 1961–2000.

Table 1
Decadal variation of seasonal air temperature in Kaqun and Tashkurghan stations in the Yarkant River basin during 1961–2000.

Decade	Kaqun station (°C)					Tashkurghan station (°C)				
	Spring	Summer	Autumn	Winter	Annual	Spring	Summer	Autumn	Winter	Annual
1961–1970	14.22	23.19	12.03	−3.92	11.07	4.68	14.73	3.29	−9.91	3.23
1971–1980	14.00	23.31	11.60	−4.38	11.15	5.22	15.35	3.59	−10.09	3.51
1981–1990	13.72	22.83	11.11	−2.75	11.21	5.07	14.94	4.00	−10.51	3.36
1991–2000	13.56	22.40	11.04	−2.74	11.06	5.09	15.49	4.46	−9.49	3.90

Specifically, the average annual temperature increased by 0.67 °C. The autumn season contributed most, increasing by 1.17 °C from the 1960s to the 1990s, summer season by 0.76 °C, and spring and winter seasons by about 0.4 °C. Increasing temperature accelerated the melting and hindered the formation and maintenance of glaciers.

For the Kaqun station, however, the air temperature exhibited a downward tendency except in winter. The average annual temperature showed an inconspicuous change from the 1960s to the 1990s, while the winter temperature increased significantly by 1.18 °C. The different trends of air temperature changes at Tashkurghan and Kaqun stations revealed the thermal differences between the mountainous and near-plain areas.

Interannual variation of precipitation in Tashkurghan and Kaqun stations (Fig. 3) suggested that the plain had a greater increase in precipitation than did the mountainous area. The threshold occurred in 1986. The decadal annual precipitation (Table 2) increased since the 1960s at the Kaqun station. By the 1990s it reached about 85 mm, increasing by 25.23% and 38.29% over the 1980s and 1960s, respectively, which could be attributed to the change in summer. At the Tashkurghan station, however, annual precipitation did not change significantly compared to that in the 1980s, but spring precipitation increased significantly from 10.77 mm in the 1980s to 19.55 mm in the 1990s. The data indicate that since the 1980s, both the mountainous and near-plain area had an obvious increase in precipitation, mostly in summer season for the near-plain area and in spring for the mountainous area.

3.2. Glacial flood characteristics

During the last 50 years, about 21 flood releases linked to glaciers have taken place in Yarkant River (Fig. 4). From 1959 to 1986, floods were frequent and steady. The average peak discharge was 2685 m^3/s and volume was 0.67×10^8 m^3. From 1987 to 1996, there were no outburst floods because the glacier drainage had been opened due to a glacial-lake outburst in 1986. Since 1997, however, seven extra-large glacial outburst floods occurred, with an average peak discharge of 3293 m^3/s and volume 0.72×10^8 m^3. The flood frequency of the first thirty years is 0.4 times/a and that of the latter ten years is 0.7 times/a. Sudden flood releases mainly occur from June to November, being quite different from snow-melt or storm floods. They are characterized by a rapid rise, high peak discharge, small volume compared to peak discharge, and are of short duration with a single peak hydrograph. Discharge also falls suddenly. Fig. 5 shows the four flood hydrographs that have comparable shapes and might be formed by the same mechanism.

Peak flood discharges in excess of 4500 m^3/s have occurred six times, with a further six events in the range 2000–4500 m^3/s. Other events include flows of 800–2000 m^3/s. Peak flood discharges are over six times the base flow on average, with a maximum of over ten times. Most flood durations are about 20 hours, the shortest being 12 hours. Some of these floods only take half an hour to reach the flood peak. The 1961 sudden flood release took only half an hour to rise to a flow of 6270 m^3/s from a base flow of 806 m^3/s. The 1984 sudden flood release is another example, taking only 18 minutes from initiation to reaching the flood peak. The rate of increase of flood flow was 203 m^3/min.

Flood peak discharges exceeding 4500 m^3/s have appeared between August and early September, while discharges of 800 m^3/s are typical during fall and at the beginning of winter. Whilst sudden floods arising in different seasons have peak discharges varying by a factor of eight, nevertheless they have a similar pattern. Discharges are quite large, but volumes are relatively small. Flood discharges are 10–25 times larger than mean annual flow rate. However, flood volumes are only 0.2–1.7% of mean cumulative flow. The 1961 outburst discharge was 6270 m^3/s, or 25 times the annual average flow, but the related runoff volume was 1.5×10^8 m^3, less than 2% of the annual cumulative flow. Nearly all the flood volumes were below 1.0×10^8 m^3, except for the 1961, 1978, 1984, 1999, and 2002 floods.

3.3. Specific flood event details

Peak discharge for the 1984 flood release was 10,480 m^3/s, based on flood profile marks near the leading edge of the Tramkanri Glacier in the upper Shakegam Valley. This declined to 8300 m^3/s at Stagar Gorger, 18.5 km downstream, then further declined to 4940 m^3/s at the Kuluklangan Hydrometric Station, 324 km downstream from the last measuring section. It was only 4570 m^3/s at the Kaqun Hydrometric station, a further 112 km downstream.

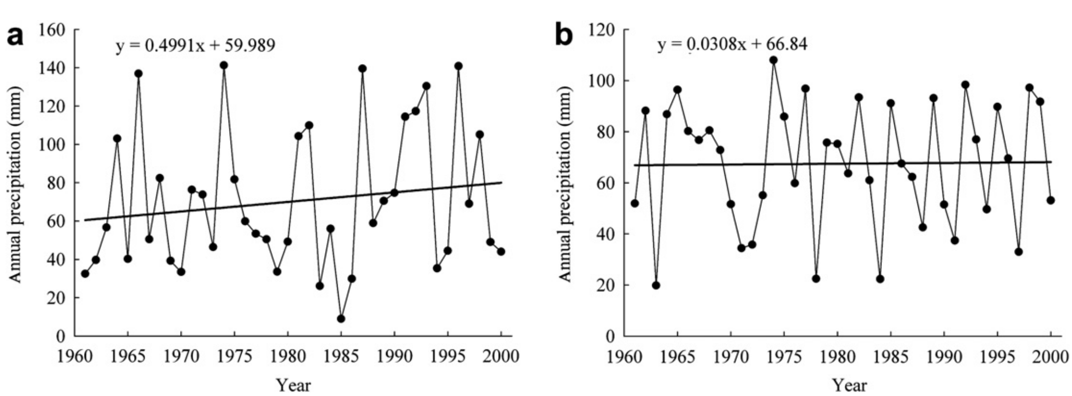

Fig. 3. Annual precipitation changes in (a) Kaqun station and (b) Tashkurghan station during the period 1961–2000.

Table 2
Decadal variation of seasonal precipitation in Kaqun and Tashkurghan stations in the Yarkant River basin during 1961–2000.

Decade	Kaqun station (mm)					Tashkurghan station (mm)				
	Spring	Summer	Autumn	Winter	Annual	Spring	Summer	Autumn	Winter	Annual
1961–1970	23.39	22.50	9.36	6.20	61.45	21.57	35.21	9.45	5.05	70.49
1971–1980	16.63	19.55	13.63	16.78	66.59	15.30	27.87	9.97	12.27	64.91
1981–1990	17.05	32.98	11.11	5.60	67.86	10.77	41.01	9.66	6.38	64.84
1991–2000	23.19	44.93	7.65	10.33	84.98	19.55	38.00	7.28	7.06	69.65

While there were some tributaries flowing into the main channel during this flooding, it was evident that the flood discharge was simply declining (Fig. 6). In addition, propagation velocities of flood discharges were nearly equal. Along the reach, average propagation velocities were about 12.9 km/h from Lan Gan Station to Kaqun Station. Propagation velocities of some large sudden floods occurring in summer were even higher, at about 14 to 16 km/h. For example, in the 1971 sudden flood occurring on August 2nd, discharge was 4570 m^3/s with a velocity of up to 16 km/h.

Glacial-lake outburst floods in 1997, 1999, and 2002 recorded at Kaqun station are typical, exceeding 4000 m^3/s, and shown in Fig. 7. They all had an obvious peak, rising and falling rapidly with various durations. The flood in 1997 started at 22:00 on August 2, reached peak value at 05:30 on August 3, and ended at 00:00 on August 4. The duration for the fluctuation was 26 hours. It took 7.5 hours to reach peak value from 984 m^3/s to 4040 m^3/s. The flood volume was 0.879×10^8 m^3. The flood in 1999 started at 12:00 on August 10, reached peak value at 12:12 on August 11 and ended at 20:00 on August 12. The duration for the fluctuation was 56 hours. It took 24 hours to reach peak value from 1050 m^3/s to 6070 m^3/s. The flood volume was 1.702×10^8 m^3. The flood in 2002 started at 18:00 on August 12, reached peak value at 10:00 on August 13 and ended at 14:00 on August 15. The duration for the fluctuation was 68 hours. It took 16 hours to reach peak value from 1330 m^3/s to 4610 m^3/s. The flood volume was 1.248×10^8 m^3.

3.4. Origin of sudden flood releases

Reasons for the sudden floods on the Yarkant River have been debated for many years and remained unanswered. Two hypotheses have been considered. One is that this kind of flood is caused by precipitation, while the other links them to glaciation processes. Now, a three-year field investigation suggests that sudden floods on the Yarkant River were not caused by precipitation.

The basic reasons for discarding the rainfall hypothesis include consideration of the Yarkant River's location at the southwest edge of the Taklamagan Desert, far from any ocean. In addition, southern basins of the Himalaya Mountains and Karakoram Mountain divert air currents containing moisture from the Indian Ocean away from the area. The annual precipitation there is only 350–400 mm. A further reason is that the air temperature falls about 2–4 °C during precipitation in mountain regions above 4000 m a.s.l. Forms of precipitation change with change of altitude. New snow falling at different altitudes cannot melt simultaneously to form such a large discharge. Finally, air temperatures fall in the high mountain regions after the end of August and precipitation is almost always in the solid form. So, precipitation cannot explain the sudden floods occurring after that time.

Detailed analysis of meteorological data and satellite cloud pictures prior to sudden floods also cannot substantiate the precipitation hypothesis for the event on August 30th, 1984. The air temperature at 600 hPa in the K2 region shows that when this is at the maximum value of 10.3 °C, then the height of the zero layer is around 5500 m a.s.l, and the last ten day period in August is mainly pyro-temperature weather without any precipitation and cloud activity. Investigations of sudden floods on the upper Yarkant River also suggest that such floods originate from the upper end of the Shaksgam Valley, a large tributary of the Yarkant River, and are related to glaciers.

It appears possible that some sudden floods are caused by releases from two lakes formed by the damming action of the Kyagar and Tram Kanri Glaciers, located on the northern slope of the Karakoram Mountain. The geomorphic survey indicates that the width of the Shaksgam Valley is from 0.5 to 1.5 km. The valley is so wide that the glacial moraine lakes and subglacial or interglacial lakes could not cause havoc when they drain into the Yarkant River. Only glacier-dammed lakes can store sufficient water for an outburst flood. Both Kyagar and Tram Kanri glaciers are aligned

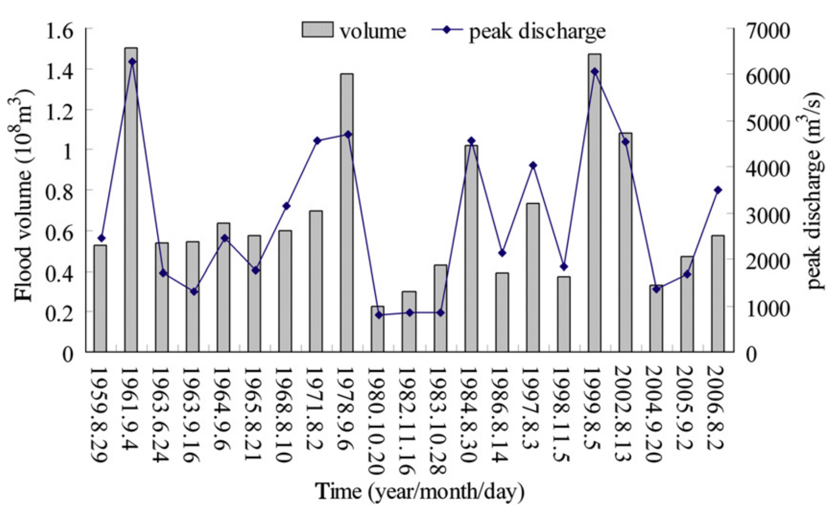

Fig. 4. Volume and peak discharge of glacial outburst floods in the Yarkant River during 1959–2006.

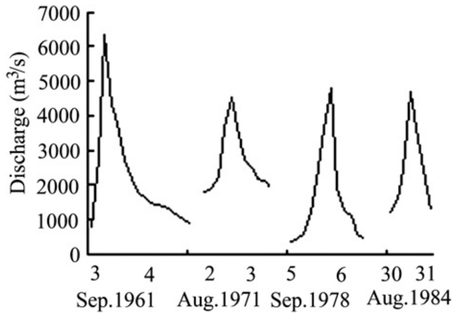

Fig. 5. Flood hydrograph in Kaqun hydrometric station.

nearly N–S, damming the Shaksgam Valley to form the two lakes, which extend in an E–W direction. One of them, Kyagar Lake, currently one of the largest active glacier-dammed lakes in the Yarkant River, is the original site of flooding in the basin.

3.5. *Suggested flood mechanism for Kyagar lake*

It is difficult to positively identify the mechanism of dammed water release. Usually there are three main ways in which glacier-dammed water bodies might drain. The dam might be overtopped, there might be flow underneath the glacier dam, or the dam might collapse. Complete and well-documented observations of the sudden floods do not exist. Fortunately, a survey team met twice at the Kyagar glacier-dammed lake area during 1996–1998. Some direct evidence and facts about the mode of emptying of the Kyagar glacier-dammed lake were obtained by detailed field observations of the glacier dam and lake area both before and after flooding.

Detailed analysis of the relative process of the flash flood occurrence time in the area of investigation as well as of intensity and interannual temperature change shows that most glacier outburst floods occur in the years and periods with positive anomalous air temperature. The necessary condition of occurrence of the g1acier outburst flood in the Yarkant River is positive anomalous air temperature at the 600 hPa height of Hotian, where is near the basin. Using data from Taskurghan Metrological Station situated near the middle reaches of the Yarkant River and the air temperature at the 600 hPa height of Hotian, it can be seen clearly that nearly 70% of glacier lake outburst floods occurred at the crest value of annual change of ≥ 5 °C accumulated temperature. Four floods of more than 4500 m^3/s occurred in the crest value year, but the annual cumulative temperature value of the next year descended, and it was a year without floods. Fig. 4 shows that flash floods also occurred in 1964 and 1965. The cumulative temperature in 1964 and 1965 was low, but the interannual variation of summer (from Jun. to Aug.) air temperatures at the 600 hPa height showed that the summer air temperature at that height during the period of 1964–1965 was rather high. Glacier flash flooding is closely

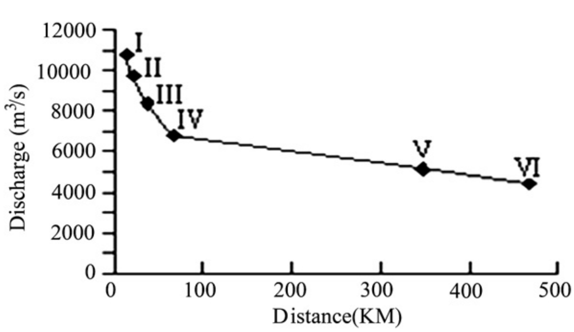

Fig. 6. Decline of flood peak discharge in 1984.

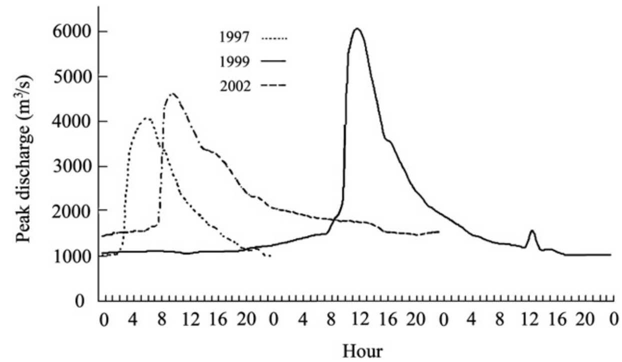

Fig. 7. Hydrograph of glacial-lake outburst floods in 1997, 1999 and 2002 recorded at Kaqun hydrological station in the Yarkant River. Dotted line (left) denotes the flood in 1997, dashed line (middle) denotes the flood in 2002, and solid line (right) denotes the flood in 1999. Their starting times were 00:00 Aug. 3, 1997; 12:00 Aug. 10, 1999; and 00:00 Aug. 13, 2002, respectively.

associated with annual cumulative temperature and variation of summer air temperature at the 600 hPa height.

3.6. *Relationship between glacial-lake outburst flood and climate change*

Analysis of local climate change showed that since 1987 the air temperature in the mountainous area has increased significantly, which would have a vital effect on the glacial sudden flood events. There were three times outburst floods after 1987, 37.5% of all flood events since 1959. Moreover the peak discharges of these three times

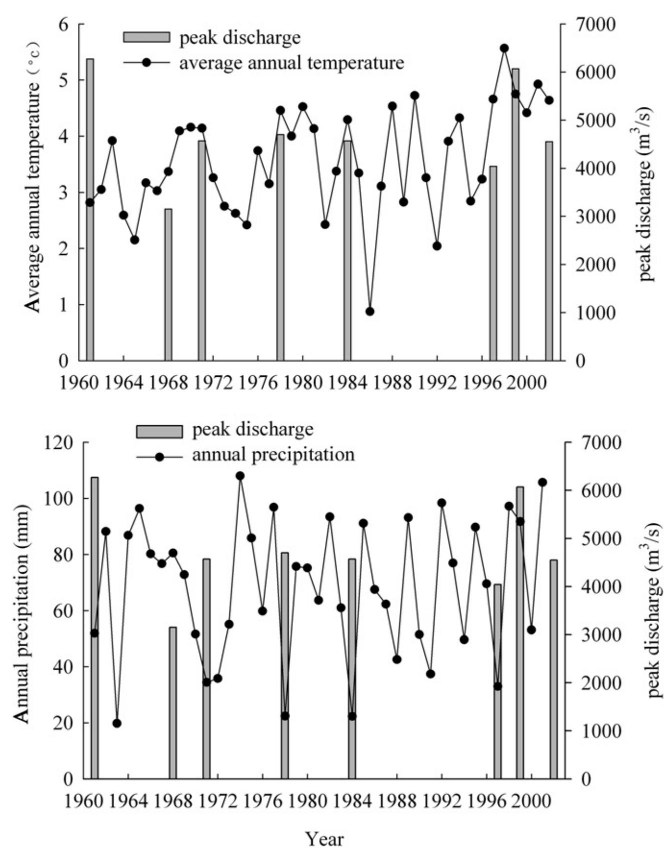

Fig. 8. Peak discharge >3000 m^3/s and the average annual temperature and annual precipitation in Tashkurghan station during 1959–2002.

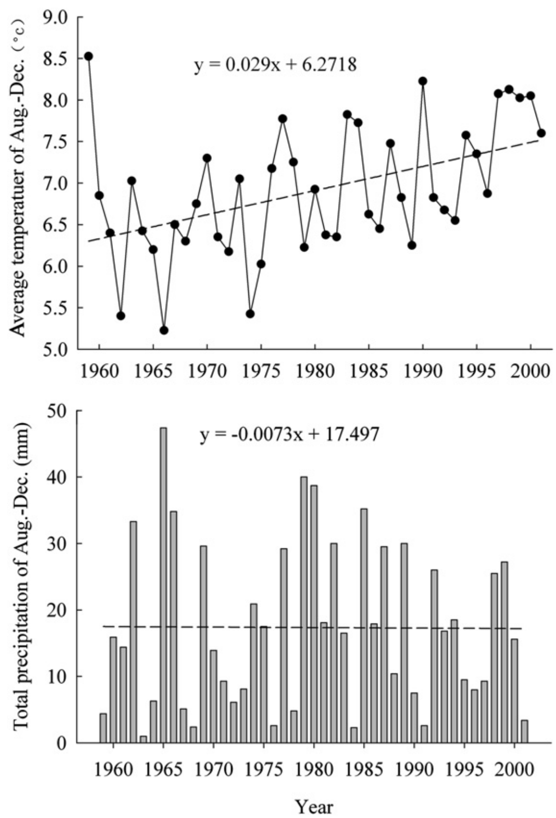

Fig. 9. Average annual temperature of August-December in Tashkurghan station during 1959-2001.

floods were all higher than 4000 m^3/s, representing 42.9% of all flood events with this magnitude. It suggested that the frequency and magnitude of outburst floods were increasing with climate warming.

Fig. 8 shows the peak discharge >3000 m^3/s and the average annual temperature and annual precipitation at Tashkurghan station. Peak discharges >3000 m^3/s almost occurred in warmer periods when the three years average temperature showed a positive anomaly, representing 87.5% of all events. Comparatively, lower peak discharges generally appeared in dry periods when annual precipitation was lower than the average annual precipitation, representing 75% of all events.

Outburst flood release mainly occurred in summer and autumn, especially from August to November (Fig. 4). The average annual temperature of these four months exhibited an increasing trend, while the contemporary annual precipitation did not show any obvious trend (Fig. 9), in some degree indicating that the glacial outburst floods were more related to the increasing temperature than precipitation.

4. Conclusions and discussion

The Yarkant River basin on the northern slope of Karakoram Mountains has experienced the warming climate since 1987, which is synchronized with global warming. However, changes of climate in the mountainous and plain areas are different. Temperature increase was more obvious in the mountainous area in summer and autumn, while precipitation increase was evident in the plain area in summer. For the mountainous area all four seasons' temperatures increased, especially in autumn and summer, which was not conductive to the formation and maintenance of glaciers. During the last 40 years, glacier loss in the Yarkant River basin amounted to 111 km^2 (Liu et al., 2006). This could result in water resources increasing in a certain period, but in the long run it would decrease and weaken the regulating action of glacier meltwater for runoff. Potential disasters, such as floods, will increase. The inconspicuous increasing precipitation will aggravate the water shortage.

With temperature increase, about 21 flood releases linked to glaciers have taken place in the Yarkant River basin during the last 50 years. The frequency and magnitude of glacial outburst floods increased. From 1959 to 1986 there were fourteen floods and four peak discharges >4000 m^3/s; the flood frequency was 0.4 times/a. From 1997 to 2006 there were seven floods and three peak discharges >4000 m^3/s; the flood frequency was 0.7 times/a. Peak flood discharges in excess of 4500 m^3/s have occurred six times and appeared between August and early September, and discharges of 800 m^3/s are typical during fall and at the beginning of winter. They were characterized by a rapid rise, high peak discharge, and sudden fall.

There were once different hypotheses on flood origin (Wang and Chen, 1989): heavy storms, snowmelt runoff, and the strong melting of surface ice under high temperature. The relationship between floods and climate change indicates that glacial outburst floods were more attributed to increasing temperature rather than precipitation. The sharply increasing temperature accelerated the glacier melting, increased the glacial meltwater, raised ice temperature and enhanced the glacier flow rate, resulting in glacial damming of the drainage and formation of glacial lakes, which burst to produce floods.

With climate warming, glacial-lake outburst floods will be more frequent and threaten the water safety of the area. Research on glacial flood activities and early warning should be enhanced. Making the most of increasing water resources induced by climate change, active defense measures are required to serve the local agricultural production and for water security maintenance.

Acknowledgments

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