Recent change and prediction of glacier-dammed lake outburst floods from Kunmalik River in southern Tien Shan, China

LIU JINGSHI & YOSHIHIRO FUKUSHIMA

Institute for Hydrospheric– Atmospheric Sciences, Nagoya University, Nagoya 464-8601, Japan

e-mail: liu@hydro.hagaokaut.ac.jp

Abstract Glacier Lake Outburst Flood (GLOF) from a glacier-dammed lake in the Central Tien Shan has occurred during almost 100 years. Recent records of the GLOF events in the 1990s has indicated that the lake volume and peak discharge are becoming larger and larger corresponding to a warming and wetting of the inner Asian continent. Two extraordinary events of GLOF in summer 1994 and winter 1996 are investigated and described. There is evidence of a change in the magnitude and frequency of floods and in the extension of the glacier and the lake systems. A possible change of the GLOF for next 50 years is predicted by reviewing the history of GLOF events combined with water and heat indices of the current climate. The maximum peak discharge and the flood volume will be enlarged by 50% and 20% respectively, and the date of GLOF occurrence will be shifted to early summer and/or winter. The spring flow will be enlarged due to base flow originating from meltwater.

INTRODUCTION

The Kunmalik River, an international river, is located in one headwater of the Tarim River from the glacier covered central Tien Shan Mountains at the borders between China, Kazakstan and Kirgistan, with sources from the western slope of Mount Tomur (Pedobe in Russian)—Han Tengri (Fig. 1).

Hydrologic records from both the former Soviet Union and China indicated that Glacier Lake Outburst Floods (GLOF), being catastrophic floods with loss of life and property, have occurred frequently almost every year, even twice per year, in the Kunmalik River since 1955. The source of the GLOF is a huge glacier lake, Merzbacher, dammed by the largest glacier, Inylchek, in Tien Shan. The outbursts are caused by shrinking and retreating of the lake's northern branch (Fig. 2) (Kalesnic, 1963; Golubev, 1976).

Figure 3 shows examples of GLOF hydrographs. The first author summarized major characteristics of the GLOF observed at the streamgauge about 200 km away from the lake downstream in China, and proposed an empirical formula to forecast the flood processes at the streamgauge (Liu, 1991).

Due to larger and larger GLOF and the fact that some abnormal phenomena were observed in the Chinese part recently, the aim herein is to make a prediction of the future development of the GLOF based on a few events that occurred in the 1990s, and on changes in the glacier, and changes of the climatic and the river regime.

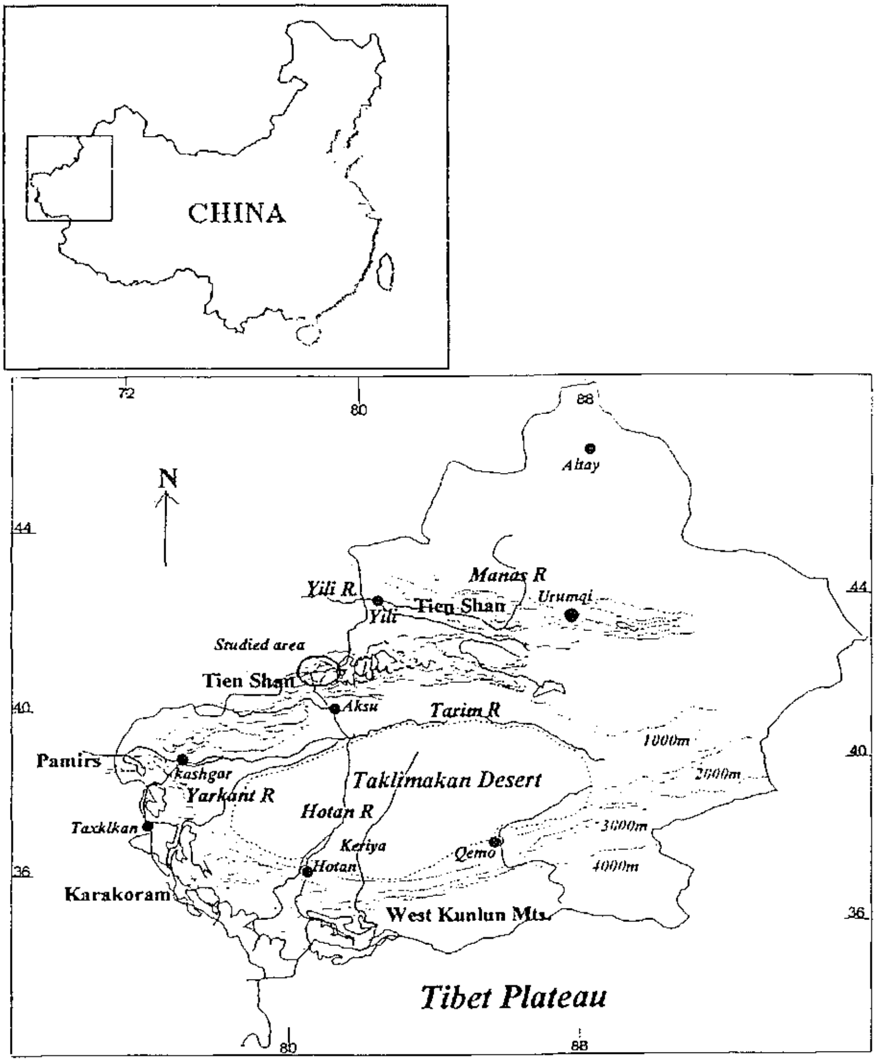

Fig. 1 Location map of the studied area in west China.

RELATIONSHIP BETWEEN THE GLOF AND THE GLACIER-DAMMED LAKE

Glacier Inylchek is the largest valley glacier in the Tien Shan Mountains. It is composed of two branches named the South and the North Inylchek, the former being 65 km in length with an area of 574.4 km^2, and the latter 41.0 km with an area of 247.2 km^2. The altitude of snow line of the glacier is around 4450 m a.s.l. (Liu, 1986). The glacier-dammed lake Merzbacher is formed at 3600 m a.s.l. within an emptied valley of the North Inylchek, the ice dam and the lake bed being frontal parts of the glacier (Golubev, 1976). The lake was found by G. Merzbacher and named in 1902 (Merzbacher, 1905). Currently the lake is made up of two parts, called the upper and

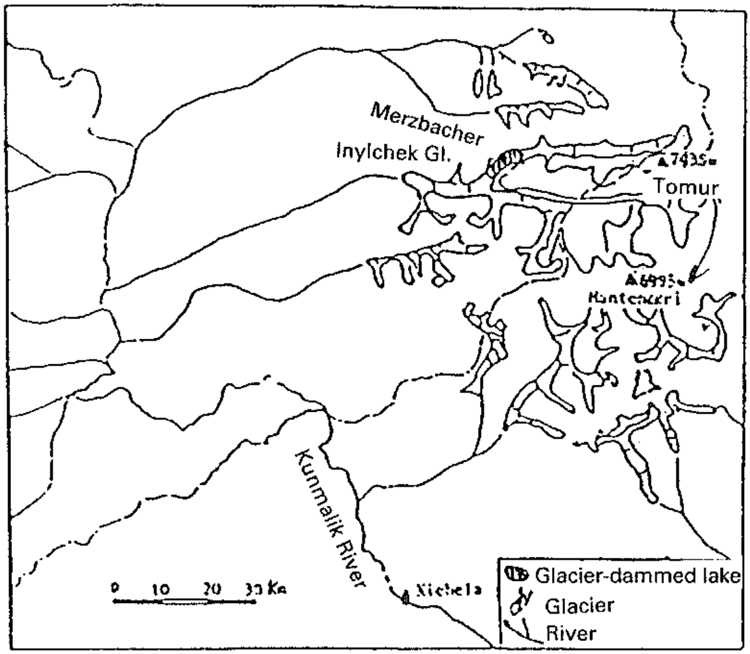

Fig. 2 Location map of Kunmalik River and glacier-dammed Lake Merzbacher.

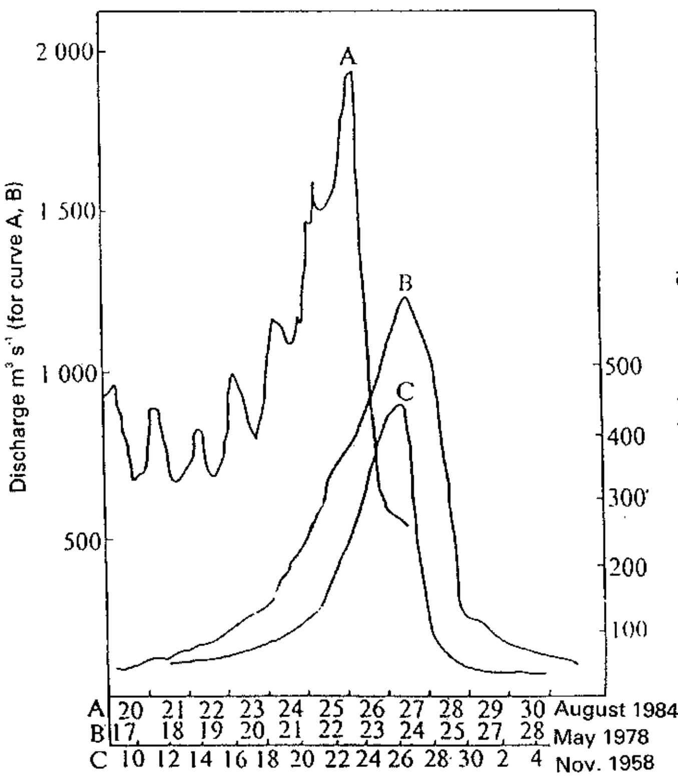

Fig. 3 Hydrographs of GLOFs at the Xichela streamgauge in the River Kunmalik.

lower lake, linked by an end moraine at the front of the North Inylchek (Fig. 4). The upper lake with area of 4.0 km^2 and a volume about 300 × 10^6 m^3 was formed in the 1950s when the glacier began to retreat again. The lower lake is the original one with an area of 3.8 km^2 and a volume of 165–200 × 10^6 m^3 (Vinogradov, 1977; Mavlyudov, 1991). The lake has a total area of 7.8 km^2 and maximum reserve capacity of meltwater of 4.65 × 10^8 m^3.

To be able to predict and design the probable maximum flood from Merzbacher Lake and to prevent a greater catastrophic outburst to the downstream areas, it is necessary to review the history of the lake development and the GLOF events. From Tables 1 and 2 it can be seen that there is a close relationship between appearance of

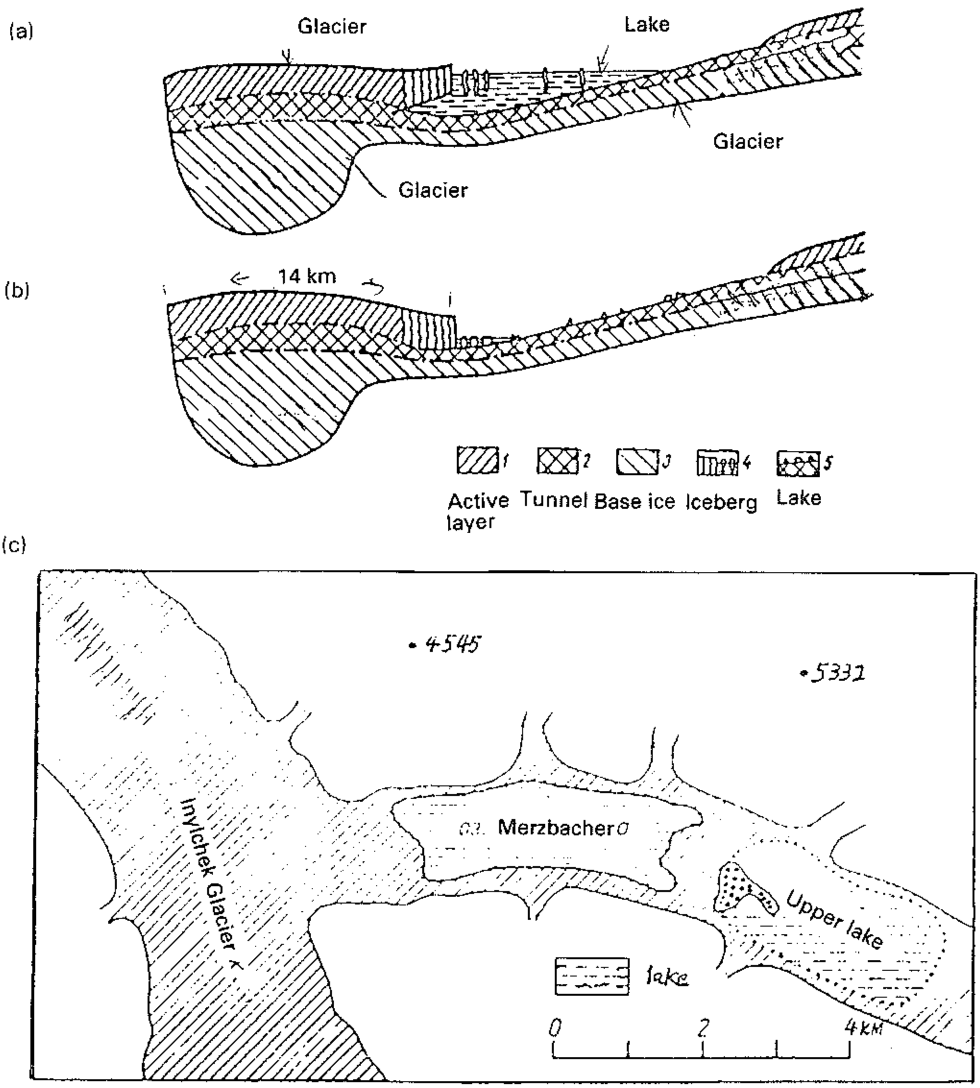

Fig. 4 (a) and (b) Vertical outline of the glacier dam, and (c) the Lake Merzbacher system (after Vinogradov, 1977).

Table 1 Recorded the GLOF events at termini of Inylchek Glacier (from Vinogradov, 1977).

GLOF event	GLOF event
8–12 September 1932	End of August 1933
Beginning of September 1935	Beginning of October 1936
Beginning of October 1937	End of October 1938
September–October 1940	Beginning of October 1941
Beginning of October 1942	22 September–2 October 1943
No lake on the air photos 1946–1947	1–3 August 1949
End of July–beginning of August 1953	24–31 August 1954
4 September 1956	9 September 1961
August 1963	September 1965
Beginning of August 1963	September 1965
4 July & 27 November 1966	7–14 September 1967
Beginning of September 1970	

Table 2 The GLOF events in winter recorded at the gauge in China.

Date	Discharge ($m^3 s^{-1}$)	Volume* (10^6 m^3)	Baseflow ($m^3 s^{-1}$)
24 November 1958	448	189.5	51.2
13 December 1966	132	5.36	36.8
4 October 1972	703	160.2	63.0
12 October 1988	584	207.0	41.0
5 December 1996	817	272.9	38.0

* estimated by the authors in the separation of the flood hydrographs.

the lake, glacial change and GLOF events. The major fluctuations of glacial advance and retreat in Central Asia and the historical records of the lake during the last hundred years are as follows:

(a) The glaciers advanced during the 1870s–1880s; no ice lake was observed by Ignajev in 1876 (Kalesnic, 1963).

(b) The glaciers retreated during the 1890s–1910s; the ice lake was found (Merzbacher, 1905) and the largest flood occurred in 1906, a catastrophic flood with extraordinary discharge in the downstream area and a unique record at the Chinese side before 1940 (Aksu Branch of Hydrology and Water Resources).

(c) The glaciers advanced or were in a stable state during the 1920s–1930s; there was no lake and no large flood recorded (Kalesnic, 1963; Vinogradov, 1977).

(d) The glaciers retreated during the 1930s to the middle of the 1940s. The record of the lake and the GLOF events are listed in Table 2 (Vinogradov, 1977).

(e) Due to the glaciers' retreat, the upper lake appeared in the beginning of the 1950s, and developed 2–3 km in length and 1.0–1.2 km in width in 1965 (Vinogradov, 1977).

(f) The glaciers retreated, became thinner, and frequent GLOF events were recorded after the 1950s both on the Chinese and the Russian sides (Su *et al.*, 1986; Liu, 1991).

Although there are no discharge observations of the GLOF before the 1950s as shown in Table 2, the relationship between the glacier activity, the appearance of the lake and the GLOF events noted both before and after the 1950s can be used to make the following statements:

(a) The glacier lake was small, and the GLOF did not occur as frequently before as after the 1950s.
(b) The date of occurrence of the GLOF before the 1950s is comparatively late in the year, usually late summer/early autumn.
(c) The periods of an existing lake became longer after the 1950s than before and the date of the GLOF occurrence was generally shifted to an earlier month.
(d) Not only did the peak discharge of the GLOF become larger, but also its frequency became higher with an occurrence even twice a year after the 1950s.

To determine the probable maximum flood (PMF), its frequency of occurrence under the current climate warming, particularly the associated glacial change is a necessary and difficult task for hydrologists. The first author has forecast that the GLOF would become larger and larger in the recent decade (Liu, 1993), and unfortunately, this has been confirmed by two extraordinary GLOFs in 1994 and 1996.

EXTRAORDINARY GLOF EVENTS IN THE 1990s

The flood in summer 1994

By monitoring downstream from the glacier, the authors obtained data of an extraordinary GLOF occurring 18–24 July 1994. Its observed peak discharge at the streamgauge was 2300 $m^3 s^{-1}$ with a water volume of $324 \times 10^6 m^3$. This GLOF caused great economical loss along the river: a reservoir with a volumetric capacity of $90.0 \times 10^6 m^3$ had to be blown up as the inflow from the upper stream was too large to be drained, and many hydraulic constructions and bridges were flooded.

Poor design of hydraulic structures, which took into consideration only normal release of glacier meltwater from the watershed and not from the glacier lake Merzbacher, was a cause of the greatest damage. The critical discharges for issuing warnings and for flooding at the mountain outlet of the river were 1500 $m^3 s^{-1}$ and 1800 $m^3 s^{-1}$, respectively, before this event. Furthermore, according to an investigation of historical floods, the maximum historical flood at the gauge was 2560 $m^3 s^{-1}$ in 1906 (Wang *et al.*, 1994). The maximum annual flood with a frequency of once per 100 years has been designated based on data from the in past 50 years, and the observed maximum flood in 1994 at the gauge was very close to this value.

The abnormal GLOF winter 1996

There have been at least five GLOF events recorded during winter, i.e. in October or later (Table 2). Their peak discharges were not as big as those occurring in summer. However, an abnormal GLOF with peak discharge 817 $m^3 s^{-1}$ occurred 27 November–8 December 1996. It released about $280 \times 10^6 m^3$ of water to the downstream hydrological section in China. Attention should be paid not only to the magnitude of the peak discharge and the water volume but also to the fact that a lot of icebergs were observed during the beginning of the outburst release from 28 November to 3 December. The large ones were of a size 2 × 1.5 m above the water surface and consequently much bigger under the water. This was the first time that glacier icebergs were transported by a GLOF in winter. It is clear that there is a serious problem with the ice dam of the lake, which seems to have entered into a non-stable state and is now more easily broken under the huge water pressure from the lake.

RECENT CHANGE IN CLIMATE AND RIVER REGIME

The hydrometeorological records observed throughout Tien Shan give evidence that the climate in Central Asia is warming and getting wetter since the 1940s (Aizen & Aizen, 1997), and particularly since the 1980s (Ren & Ji, 1992). The rise in temperature has occurred with an average rate of 0.01°C per year in central Tien Shan and was particularly pronounced at high altitudes above 2000 m. The changes in precipitation have a positive, statistically significant, trend in the Tien Shan. The change in stream and glacier runoff corresponds to a negative mass balance in Tien Shan and the snowmelt flow in basins with large glaciers has increased.

The hydrologic response to the climate change obviously appears as an increase in the annual runoff and in maximum floods including GLOFs, not only in Kunmalik River but also in neighbouring rivers. The average discharge in the Kunmalik River increased about 9% in the 1980s compared to the 1950s–1970s (Table 3). The increase in water volume is mainly observed in spring and summer with an increase in May, July and August of 21.5, 14.3 and 12.6%, respectively. Generally for the region, both peak discharge and volume are much bigger in the 1980s than before.

Table 3 Change in the GLOF, climate and stream flow in Kunmalik River during the last 40 years.

Period	Annual temperature* (°C)	Annual precipitation (mm)	Annual runoff (10^8 m^3)	GLOF discharge (m^3 s^{-1})	GLOF volume (10^8 m^3)	GLOF frequency (>1500 m^3 s^{-1})
1955-69	9.77	110.9	44.82	1086	1.631	3
1970s	9.84	122.3	45.61	972	1.679	0
1980-97	10.3	134.8	47.95	1580	1.932	8

* Aksu meteorological station.

PROBABLE MAXIMUM FLOOD

The first author has proposed an empirical formula for forecasting the diurnal discharge, Q_t, (m^3 s^{-1}) of the GLOF at the streamgauge based on statistical analysis (Liu, 1991):

$$Q_t = Q_0 \exp(bt) \quad (1)$$

Q_t is calculated for the ascending phase of the GLOF from an initial base discharge Q_0 m^3 s^{-1}, t is time in hours from this initial value, and b is a statistical coefficient. The value of b differs between two groups—the summer and non-summer GLOF mainly determined by the drainage rate

The released maximum water volume from the lake rises to 373×10^6 m^3, about 80% of the capacity of the lake. The flood duration is within 168 h (7 days) as in 1994,

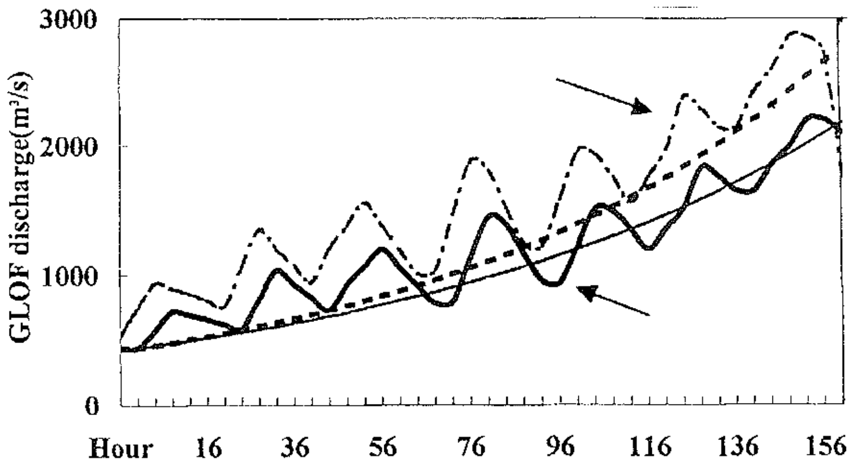

Fig. 5 Hydrographs for GLOFs in 1994 (solid line) and the forecast probable maximum flood (dotted line). Daily melt fluctuations are added.

when the ascending and descending phases were 156 and 2 h, respectively. An averaged coefficient of the ascending rate for the five biggest GLOF events is $b = 0.0115$. The GLOF in 1994 is regarded as the design flood. The probable maximum GLOF for summer is 2860 m^3 s^{-1} and related to a value $b = 0.0105$. Figure 5 shows the probable maximum GLOF development by the formula based on the GLOF event in 1994. It can exceed 3000 m^3 s^{-1} if a summer melt flood is added to the GLOF.

CONCLUSION

The GLOF is more sensitive to climatic change than other hydrological elements from the cryosphere, which is exemplified for the meltwater River Kunmalik. Rising temperature and negative mass balance of glaciers result in a shrinking glacier area and increase in glacier runoff. In other words, the area and volume of the glacier lake Merzbacher will be enlarged. Consequently the GLOF will be significantly enlarged and its date of occurrence will change to an earlier month with a higher frequency and/or to a later winter month. For these changed future conditions the probable maximum flood is estimated to reach 3000 m^3 s^{-1}. The increased GLOF events, not only in summer but also in winter during the 1990s provide good evidence for this change in conditions.

Acknowledgements The authors wish to express our gratitude to Mr Shunde Wang in the Aksu Branch of Xinjiang Bureau of Hydrology & Water Resources in China for providing new data, and to the Japanese Monbusho for supporting this work through the IHP (International Hydrological Program) funding in Japan.

REFERENCES

Aizen, V. & Aizen, H. (1997) Climatic and hydrological changes in the Tien Shan, Central Asia. *J. Climate* **10**, 1393–1404.

Golubev, N. G. (1976) *Hydrology of Glaciers* (original book in Russian translated into Chinese by Zhang Zhizhong *et al.* in 1987 at Lanzhou Institute of Glaciology & Geocryology, Chinese Academy of Science).

Liu, C. *et al.* (1986) Tien Shan Mountains (Interior drainage area of Tarim basin). *Glacier Inventory of China*, vol. 3. Science Press, Peking, China.

Liu, J. (1991) Jokulhlaups in Kunmalike River, the Southern Tien Shan Mountains, China. *Ann. Glaciol.* **16**, 85–88.

Kalesnic, T. (1963) *General Glaciology* (in Russian, Chinese version in 1984).

Merzbacher, G. (1905) The central Tien Shan Mountains. *J. Geogr.* 1902–1903.

Mavlyudov, B. (1991) New data about the Glacier Dammed Lake Merzbacher in central Tien Shan, Russia (in Chinese). *No. 35 Abstracts of Proc. Int. Symp. on Glacier change and Human Activity.* Science Press, Lanzhou, China.

Ren, Y. & Ji, Z.-Y. (1992) Climate warming in recent decade and its implications in Xinjiang Region (in Chinese with English abstract). *Arid Land Geogr.* **14**(4), 42–46.

Su Z., Zhang, W.-J. & Ding, L.-F. (1985) *Modern Glacier on Mt Tomur Glacier and Weather in Mount Tomur, Tien Shan*, 33–98 (in Chinese with English abstract). The People's Publisher of Xinjiang, Urumqi, China.

Vinogradov, Y. (1977) *Glacier Floods and Debris Flow* (in Russian), 32–36. Hydro-Meteorological Press, Leningrad, Russia.

Wang, S. *et al.* (1994) Hydrological handbook of Aksu. Unpublished document of the Xinjiang Bureau of Hydrology and Water Resources, Aksu, China.