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Response of the Melting Ürümqi Glacier No. 1 in Eastern Tianshan to Climate Change

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Abstract: Current glacier recession under the global warming has aroused world-wide attention. Initiated from 1958, the observations of Ürümqi Glacier No. 1 at the headwaters of Ürümqi River in eastern Tianshan promise the best datasets of the glacier and the climate changes in China. Taking Ürümqi Glacier No. 1 as an example, we analyzed the response of the glacier to the climate change. The results show that over the past 50 years, the glacier has changed remarkably in the aspects of snow-firn stratigraphy, ice formation zone, ice temperature, area and terminus position, etc. These changes are apparently the results of temperature rise in this area. The glacier recession continued throughout the entire observed time period, and showed an accelerated tendency since 1985. Meltwater runoff also increased 84.2% over the last 20 years.

Key words: glacier melting; climate warming; Tianshan; Ürümqi Glacier No. 1

Introduction

Under the global warming, the sensitivity of alpine glaciers to temperature change is found to be largely amplified. The number of retreating glaciers has increased significantly. For a number of glaciers, the rate of shrinkage appears to have accelerated since the 1990s [1]. Accelerated melting of glaciers can lead to sea level rise and submerging of some coastal areas. Moreover, it induces snow and ice related disasters, for example, glacier flood and avalanche, which not only menace the living environment of human beings and wild animals, but also change the habits and characteristics of many species. On the other hand, the disappearance of ice-covered regions on the Earth will in turn change the global climate regime significantly. Ice covers, especially those in the Polar regions, can reflect a great deal of solar energy back to the outer space, which helps to keep the Earth cool. However, with the ice cover melting, the underlain land and the water will expose to the air, and thus certainly absorb much more solar radiation and cause more ice melting. Through this feedback process, declining ice strengthens global warming. Hence, the United Nations Environment Programme (UNEP) decided that the World Environment Day slogan selected for 2007 is Melting Ice—a Hot Topic. Working Group II of the Fourth Assessment Report of IPCC pointed out that impacts of climate warming on many phenomena are remarkable [2], such as shrinkage of the Arctic ice cap, acceleration of sea level rise, recession of glacier terminus all over the world, thawing of permafrost, earlier breaking up of ice in the rivers and lakes, prolongation of crop growing season in the mid-high latitudes, and changes in the distribution and behavior of animals and plants. The accelerated glacier recession in China is also very obvious [3−4], especially in Northwest China where glacier meltwater runoff greatly increases, area of glacier decreases, terminus retreats, snow line elevates and many small glaciers are disappearing. Glacier is known as the solid reservoir and the cradle of oasis in the arid regions in Northwest China. It is the major water source for human living and development. All these changes of the glaciers during the recent years have aroused wide attention.

Glacier monitoring is a major component in the global climate change research. A number of glaciers in the world are regularly reported and evaluated by the World Glacier Monitoring Service (WGMS) which is located in Zurich

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and operates a glacier monitoring network cross the whole world. Ürümqi Glacier No. 1 (43°06′N, 86°49′E) at the headwaters of Ürümqi River is a representative glacier in Central Asia in this network. This glacier has been monitored for nearly 50 years. It is the only glacier in China that a glaciological station is based to be responsible for the glacier observation and research. The observations were initiated in 1958, including the observations of glacier, glacial hydrology and meteorology, etc. Many previous studies have summarized these observation data of different periods [5−7]. The key point of this research is to report the response of the glacier melting to the climate change.

1 Observation data and climate background at the headwaters of Ürümqi River

1.1 *Observation data sets*

The data of this research come from the long-term field observation datasets of Tianshan Glaciological Station, including the snow-firn stratigraphy, ice temperature (borehole temperature), glacier mass balance, glacier hydrology, glacier area and glacier terminus position, etc. The meteorological datasets, within a time period from 1958 to 2004, are from three hydro-meteorological stations in the headwaters region, as well as Daxigou Meteorological Station and Houxia Meteorological Station along the Ürümqi River basin.

1.2 *Climate background at the headwaters of Ürümqi River*

The main drive forces to the glacier change are the heat and water conditions of the glacierized region. Glacier melting is tightly related to the temperature variation. According to the records of meteorological stations in the headwaters region, overally, the air temperature has been rising since 1985, and the tendency of rise has accelerated since 1995. From 1997 up to present, the average temperature has increased by 1 ℃, as the largest rise extent in recent 50 years. The observation of Daxigou Meteorological Station shows that the average annual temperature increased by 0.8 ℃ (0.017 ℃/a) during 1958−2004 with obvious temperature rises especially in autumn and winter.

Cumulative temperature is a major factor affecting glacier ablation. Cumulative temperature, namely, the sum of daily mean air temperature above the melting point during ablation season is closely related to the area of glacier ablation zone. According to the previous studies [8], the annual cumulative temperature in the headwaters region of Ürümqi River rose by 133 ℃ · d during 1960−2004. Its tendency is coincident with that of average annual temperature, i.e. since the late 1980s the cumulative temperature has risen remarkably, and meanwhile the climate warming showed a accelerated tendency (see Fig.1).

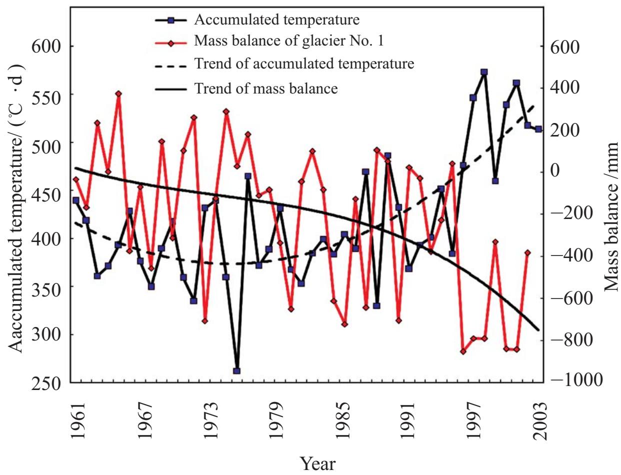

Fig. 1 Mass balance of Ürümqi Glacier No. 1, accumulated temperature ($T > 0$ ℃) and their trends during 1958−2003

2 Changes in basic features of the glacier

2.1 *Changes in snow-firn stratigraphy and glacial zone*

The characteristics of snow-firn stratigraphy and ice formation zone of the glacier are sensitive to the climate change. The climate warming greatly promotes the glacier melting, which consequently alters the properties of snow pack stratigraphy and ice formation zones. According to the analyses of 60 vertical profiles of snowpits obtained from the accumulation zone of Glacier No. 1 (4130 m a.s.l.) during the period of 1961−2005, the structure of snow-firn stratigraphy had a remarkable change. The proportion of coarse firn in the snowpits increased from 40% to 65%, and fine firn decreased from 25% to 7%. This indicates that snow pack is severely affected by meltwater, which accelerates the process of transformation from fine firn to coarse firn. Compared with the snow-firn stratigraphic constituents and its structure in the 1960s and 1980s, current specimens show remarkable changes, such as reduction of snow-pack depth, simplification of structure, blurred boundaries of snow layers, and mergence of dust layers within snow pack.

In 1962, Xie *et al.* [9] classified the Glacier No. 1 as four ice formation zones from bottom to top, ablation zone, infiltration congelation zone, infiltration zone, and recrystallization-infiltration zone. Twenty six years later in 1988, Wang *et al.* [10] and Liu *et al.* [11] found that the recrystallization -infiltration zone had disappeared due to the climate warming and been replaced by infiltration zone. From 2002 up to present, ice formation zones of Glacier No. 1 have shown a transformation tendency from a cold pattern to a warm pattern, i.e., the area of ablation region keeps expanding, the boundaries of neighboring zones move upwards, and the constitution of snow-firn stratigraphy becomes simpler [12−15]. In particular, we found a meltwater pool at the head of the east branch of the glacier in the late summer of 2004, which indicates that the melting occurred both on the head and on the tongue of the glacier [16]. The changes in snow-firn stratigraphic characteristics and ice formation zones can lead to the decrease of the new snow and the increase of the impurity in snow pack, which will reduce the albedo of the glacier surface, and thus enhance the absorption of solar radiation. As a result, this accelerates the retreat of the glacier in recent years.

2.2 *Glacial temperature rise*

Glacial temperature, especially the temperature of the ice below active layers, determines many physical characteristics of the glacier. The change of ice temperature indicates the change in cold reserve of the glacier, which can lead to the change of the sensitivity of the glacier in response to climate warming. Comparing with three vertical profiles of ice temperature at the altitude of 3840 m in the years of 1986, 2001 and 2006 (Fig. 2), we found that the lower boundary of the active layer of the glacier is about 10 m in depth, below which the ice temperature is little affected by the seasonal variation of air temperature. If ignoring the change of the ice temperature in active layer, the ice temperature from 10 to 22 m in depth had a remarkable rise during 1986−2001. The rise range decreased with the largest value of 0.9 ℃ (10%) at 10 m depth below ice surface and a negligible change at 22 m depth. Similarly, compared with the ice temperature in 2001, the ice temperature in 2006 had an obvious rise, with an increase of 0.4 ℃ at 10 m depth (Fig. 2). Usually, the ice temperature at the lower boundary of active layer is identical with the annual average air temperature. Therefore, the rise of ice temperature is undoubtedly the result of progressively climate warming.

2.3 *Changes in glacier area and terminus position*

Under the climate warming, glacier shrinkage generally follows the law of terminus recession and ice thickness reduction. The changes of glacier area and terminus position result from short- and long-term climate changes. Glacier No. 1 has an overall shrinkage since the year 1959 when

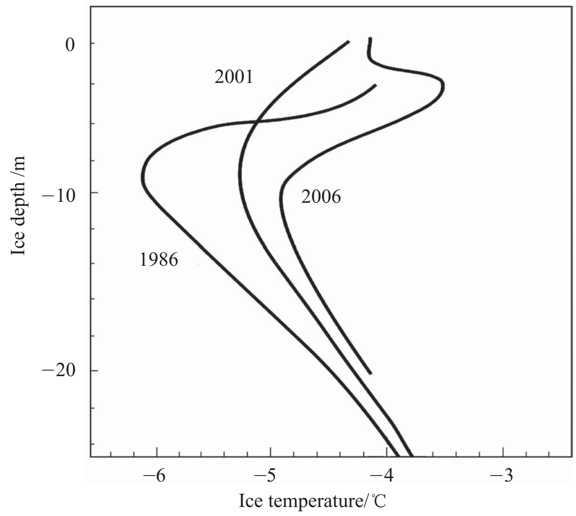

Fig. 2 Comparison of ice temperature profiles obtained in 1986, 2001 and 2006 at a site around 3840 m a.s.l on Glacier No. 1 in Tianshan Mountain

the observation initiated. The east and west branches of Glacier No. 1 separated into two independent glaciers in 1993 due to melting, during this period (1959−1993) the total terminus retreat was observed as 139.72 m at an average retreat rate of 4.5 m per year. From 1993 to 2004, the east branch of Glacier No. 1 retreated at an average rate of 3.5 m per year (a total of 38.7 m), and the west branch retreated at a rate of 5.8 m per year (a total of 64.1 m). The recession rate (the ratio of receded length to the original glacier length) of Glacier No. 1 was 7.8% in the period of 1962−2004 for the east branch and 10.5% for the west

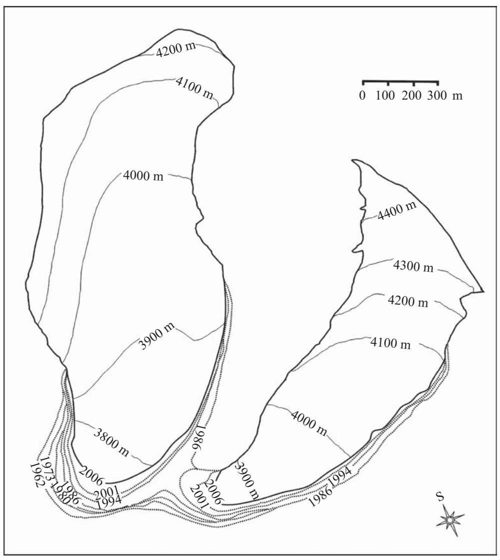

Fig. 3 Morphological change of Glacier No. 1 over time. (Dashed lines represent the glacial boundaries of 1962, 1973, 1980, 1984, 1986, 1994 and 2001; solid lines represent the glacial boundary of 2006)

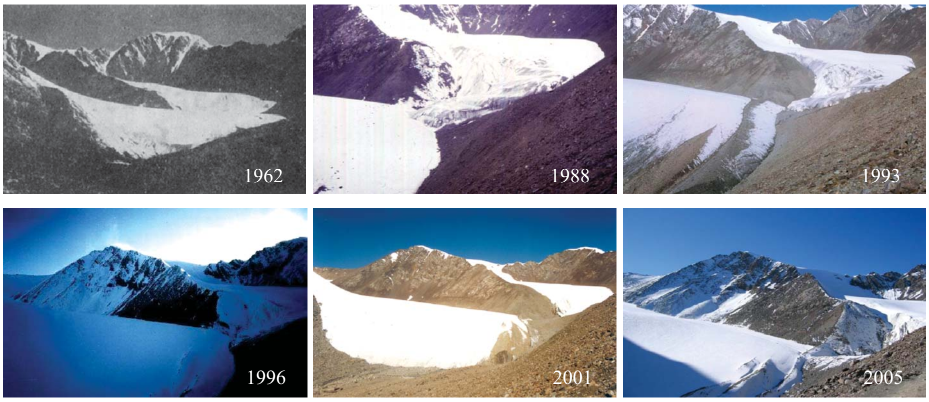

Fig. 4 Morphological changes of Ürümqi Glacier No. 1 in the years of 1962, 1988, 1993, 1996, 2001, and 2005

branch, respectively. The west branch terminus retreated 6.92 m in 1999 and 6.95 m in 2000, respectively, which are the highest records in the observation records. Since the ice flow velocities in corresponding years were observed stable at terminus, it is unlikely that the significant retreats were caused by the reduction of ice flux from upper parts of the glacier, and thus, it is obviously due to the intense ice melting. With terminus receding, its altitude simultaneously elevated from 3736 m a.s.l in 1962 to 3746 m a.s.l in 1980, and the east branch terminus altitude in 2005 was 3777 m a.s.l, 31 m higher than that in 1980.

During the period of 1962–2006, the area of Glacier No. 1 reduced by 0.27 km^2. From 1992 to 2006, the glacier area decreased by 0.16 km^2, which is 0.04 km^2 more than that from 1962 to 1992. Based on the observation over the past 43 years, we found that the decrease of glacier area has accelerated since 1986. Figure 3 shows the recession process of the glacier terminus, and Fig. 4 displays the morphological shapes of Glacier No. 1 in different years.

3 Glacier mass balance and meltwater changes and their responses to climate change

3.1 *Mass balance change*

Different from the changes of glacier area, depth and terminus, the mass balance change is an undelayed response of the glacier to climate change, and it is a sensitive indicator for climate change. The mass balance characteristics of Glacier No.1 have been reported in some previous researches [5–6, 17]. Here we sum up the major observation results. For the mass balance of Ürümqi Glacier No. 1, both annual value and cumulative value have shown negative increases since 1958, indicating severe mass losses. During 1958–2004, there were 31 negative mass balance years against 15 positive years. From 1997 to today, the negative mass balance has lasted for 10 years, which never happened ever before. The average annual mass balance during 1958–2004 was −233.6 mm water equivalent (weq) and the cumulative mass balance added up to −10746.5 mm weq, which means that the average thickness of the glacier nearly reduced 12 m and the volume loss was about 20.62×10^6 m^3 weq.

3.2 *Response of mass balance to temperature rise and precipitation increase*

Unlike the glaciers in Europe and mid-America, which accumulate in winter and lose mass in summer, Glacier No. 1 has both accumulation and ablation in summer, and there is little snowfall in winter. Previous researches on Ürümqi Glacier No.1 have shown that the mass balance was positively correlated with the precipitation, and negatively correlated with air temperature in summer (May to August). However, with the increase in both current temperature and precipitation, mass balance has different responses to them. Figure 5 shows the variations of mass balance, summer temperature, annual temperature and precipitation during 1959–2004, from which we found that during 1960–1986 the mass balance had a weak negative correlation with temperature, while a clear positive correlation with precipitation ($R^2 = 0.51$, $N = 27$, $P < 0.01$), indicating that the mass balance is controlled by both temperature and precipitation, with precipitation as the main factor. During this period, the annual average temperature and precipitation were −5.4 ℃ and 425.8 mm, respectively. However, the correlation has altered since 1986. The mass balance showed a negative correlation with temperature and no correlation with precipitation, indicating that the mass balance was mainly controlled by temperature. During this period, average annual temperature and precipitation were −4.9 ℃ and 491.6 mm, respectively. The above results show that mass balance is usually controlled by both temperature and precipitation, but it is controlled mainly by temperature when temperature rises to a certain level, though with high precipitation.

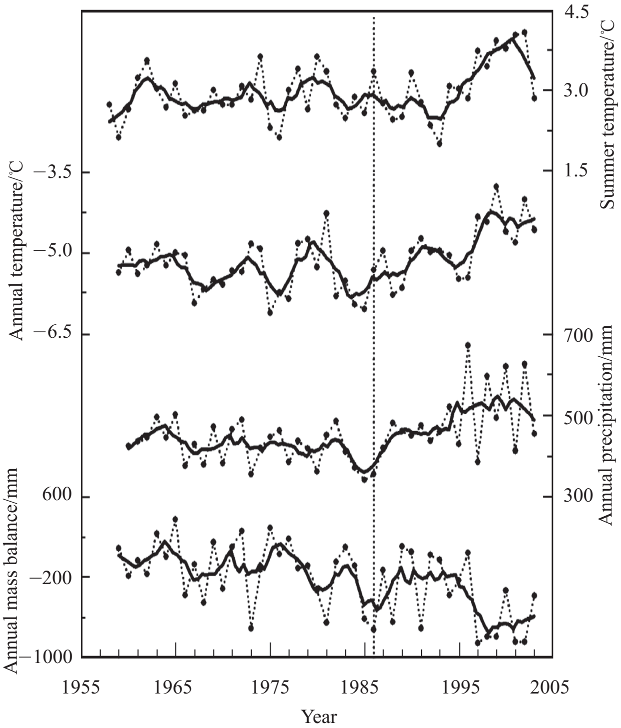

Fig. 5 Annual mass balance of Glacier No. 1 against summer temperature (May−August), annual temperature and annual precipitation at Daxigou Meteorological Station (The annual values are smoothed by negative exponential smoother with sampling proportion 0.1 and polynomial degree 1)

3.3 *Glacier meltwater change*

The change of glacier meltwater is an integrated index for glacier response to climate change. Li *et al*. [4] analyzed the meltwater runoff of Glacier No. 1 during 1958−2001, using the water balance model. The results show that the runoff has increased significantly since 1986. The average runoff depth was 508.4 mm per year during 1958−1985, and 936.6 mm per year during 1986−2001, with an increase of 84.2%. It is logically deduced that the stage rise of temperature led to the significant increase of glacier meltwater runoff from the mid-1980s (Fig. 6).

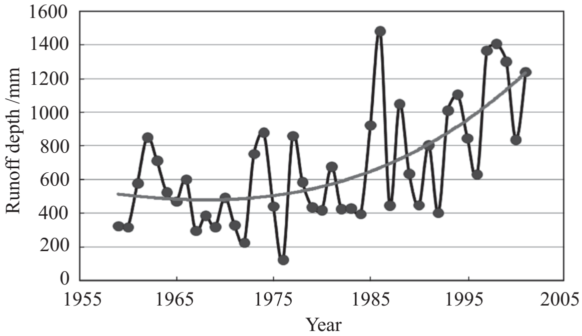

Fig. 6 Changes in annual meltwater runoff depth of Glacier No.1

4 Conclusions

Taking Ürümqi Glacier No. 1 as an example, this research analyzed the response of glacier to current climate warming based on the observation dataset of recent 50 years. The conclusion was drawn as follows:

(1) Since the1960s, snow-firn stratigraphic constituents and structure have shown remarkable changes, including decreasing snow pack depth, simplifying structure, and obscuring boundaries of snow layers with different characteristics. The area of glacier ablation zone keeps expanding, the positions of ice formation zones move upwards, and the top of east branch has already shown the characteristic of ablation zone.

(2) During 1962−2006, the area of Glacier No. 1 reduced by 0.27 km^2 (14%). The shrinking tendency has accelerated in recent years. At the altitude of 3840 m a.s.l, a significant rise in the ice temperature was observed during 1986−2001, with the highest rise value of 0.9 ℃ at depth of 10 m. From 2001 to 2006, the ice temperature rose by 0.4 ℃ at depth of 10 m.

(3) Average annual mass balance during 1958−2004 was −233.6 mm weq, with the cumulative mass balance of −10746.5 mm weq, which indicates that the thickness of Glacier No. 1 reduced nearly 12 m and volume loss came to about 20.62×10^6 m^3. Mass balance is controlled by both temperature and precipitation before 1986, with precipitation as the main factor. But after 1986, mass balance is controlled mainly by temperature, though with high precipitation.

Acknowledgments

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References

[1] Shen Yongping, Liang Hong. Accelerated global ice melting would threaten human environmental safety. Journal of Glaciology and Geocryology, 2001, 23 (2): 208−211(in Chinese)

[2] IPCC. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth

Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA: Cambridge University Press, 2007

[3] Yao Tandong, Wang Youqing, Liu Shiyin, *et al.* Recent glacial retreat in High Asia in China and its impact on water resource in Northwest China. Science in China (Series D), 2004, 47: 1065−1075

[4] Li Zhongqin, Han Tianding, Jing Zhefan, *et al*. A summary of 40-year observed variation facts of climate and Glacier No. 1 at the headwaters of Ürümqi River, Tianshan, China. Journal of Glaciology and Geocryology, 2003, 25 (2): 117−123 (in Chinese)

[5] Jing Z F, Jiao K Q, Yao T D, *et al*. Mass balance and recession of Ürümqi Glacier No. 1, Tianshan, China over the last 45 years. Annals of Glaciology, 2006, 43: 214−217

[6] Han T D, Ding Y J, Ye B S, *et al*. Mass-balance characteristics of Ürümqi Glacier No. 1, Tianshan, China. Annals of Glaciology, 2006, 43: 323−328

[7] Ye B S, Yang D Q, Jiao K Q, *et al.* The Ürümqi River source Ürümqi Glacier No. 1, Tianshan, China: changes over the past 45 years. Geophysical Research Letters, 2005, 32, L21504, doi:10.1029/2005GL024178

[8] Wang Guoya, Shen Yongping, Mao Weiyi. Climate warming at headwater of Ürümqi River, Xinjiang in past 44 years and its impact on glacier shrinking. Journal of Glaciology and Geocryology, 2005, 27 (6): 813−819 (in Chinese)

[9] Xie Zichu, Huang Maohuan. An evolution of the snow-snowgrains layer and ice formation in the Glacier No. 1 at the headwater of Ürümqi River, Tianshan. In: An Study of Glaciology and Hydrology on the Ürümqi River, Tianshan. Beijing: Science Press, 1965: 1−14 (in Chinese)

[10] Wang Xiaojun, Wang Zhongxiang, Xie Zichu. A recent trend of climate change on the Tianshan regions from the change of the past 28 years of the Glacier No. 1 at the Ürümqi River headwater, Tianshn. Chinese Science Bulletin, 1988 (9): 693−696

[11] Liu Chaohai, Xie Zichu, Wang Chunzu. A research on the mass balance processes of Glacier No. 1 at the headwaters of the Ürümqi River, Tianshan. Journal of Glaciology and Geocryology, 1997, 19 (1): 18−24 (in Chinese)

[12] Li Chuanjin, Li Zhongqin, Wang Feiteng, *et al*. A contrast of the ice formation time, ice formation zones and the stratigraphic profiles of snow pits in different time of the Glacier No. 1 at the headwaters of Ürümqi River, Tianshan Mountains. Journal of Glaciology and Geocryology, 2007, 29 (2): 169−175 (in Chinese)

[13] Wang Feiteng, Li Zhongqin, You Xiaoni, *et al*. Observation and study of the snow to ice transformation in the accumulation zone of Glacier No. 1 at the headwater of Ürümqi River. Journal of Glaciology and Geocryology, 2006, 28 (1): 45−53 (in Chinese)

[14] You Xiaoni, Li Zhongqin, Wang Feiteng. Study on time scale of snow-ice transformation through snow layer tracing method: take Glacier No. 1 at the headwater of Ürümqi River as an example. Journal of Glaciology and Geocryology, 2005, 27 (6): 853−860 (in Chinese)

[15] Li Xiangying, Li Zhongqin, You Xiaoni, *et al*. Study of the ice formation zones and stratigraphic profiles of snow pits on the Glacier No. 1 at the headwater of Ürümqi River. Journal of Glaciology and Geocryology, 2006, 28 (1): 37−44 (in Chinese)

[16] Li Zhongqin. A glacier meltwater pool was discovered at summit of east branch of Glacier No. 1 at Ürümqi River head, Tianshan, Xinjiang. Journal of Glaciology and Geocryology, 2005, 27 (1): 150−152 (in Chinese)

[17] Yang Huian, Li Zhongqin, Ye Baisheng, *et al*. Study on mass balance and process of Glacier No. 1 at the headwaters of the Ürümqi River in the past 44 years. Arid Land Geogr., 2005, 28 (1): 76−80