Recent Glacial Retreat and Its Impact on Hydrological Processes on the Tibetan Plateau, China, and Surrounding Regions

Authors: Yao, Tandong, Pu, Jianchen, Lu, Anxin, Wang, Youqing, and Yu, Wusheng

Source: Arctic, Antarctic, and Alpine Research, 39(4) : 642-650

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(07-510)[YAO]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 39, No. 4, 2007, pp. 642–650

Recent Glacial Retreat and Its Impact on Hydrological Processes on the Tibetan Plateau, China, and Surrounding Regions

Tandong Yao†‡
Jianchen Pu†
Anxin Lu†
Youqing Wang and*
*Wusheng Yu**

*Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100029, China
†Key Laboratory of Cryosphere and Environment, Chinese Academy of Sciences, Lanzhou 730000, China
‡Corresponding author: tdyao@itpcas.ac.cn

Abstract

Glacial retreat on the Tibetan Plateau and surrounding regions is characteristic since the 1960s and has intensified in the past 10 yr. The magnitude of glacial retreat is relatively small in the interior of the Tibetan Plateau and increases to the margins of the plateau, with the greatest retreat around the edges. Glacial retreat in this region is impacting the hydrological processes in the Tibetan Plateau and surrounding regions. The glacial retreat has caused an increase of more than 5.5% in river runoff from the plateau. In some areas, such as the Tarim River basin, the increase in river runoff is greater. Glacial retreat has also caused rising lake levels in the areas with large coverage of glaciers, such as the Nam Co Lake and Selin Co Lake areas. Rising lake levels are devastating grasslands and villages near the lakes.

Introduction

The Tibetan Plateau and surrounding regions contain about 46,300 glaciers, amounting to a total glacial area of about 59,400 km^2, and a total glacial volume of about 5600 km^3 (Table 1). These glaciers mainly concentrate around the Himalayan Mountains, Nyainqentanglha Mountains, Kunlun Mountains, Karakoram Mountains, and Tian Shan Mountains (Fig. 1, Table 1). The Tibetan Plateau itself contains 36,800 glaciers, with a total glacial area of 49,873 km^2, and a total glacial volume of 4561 km^3

The figures of glaciers and glacial area given above are based mainly on data obtained in the 1970s and 1980s referenced in the *Glacier Inventory of China* (Wang et al., 1991; Shi, 2005). Glacier volumes were estimated in the inventory from area and average depth for each glacier. The average depth was estimated by: $H = -11.32 + 53.21S^{0.3}$ (where H is the average depth and S the area for the given glacier) based on field observations (Wang et al., 1991; Shi, 2005). In the 1980s, most of these glaciers retreated severely because of climatic warming. Some previously advancing glaciers shifted to retreat with rapid climatic warming. In the 1990s, glaciers retreated even more rapidly (Yao et al., 2004). At the same time, the runoff of some rivers in these regions had increased, largely due to glacial melting (Shi, 2001). This paper reports the most recent studies on glacial retreat in the Tibetan Plateau and surrounding regions and its impact on the hydrological processes on the Tibetan Plateau and surrounding regions.

The Characteristics of Glacial Retreat in the Tibetan Plateau and Surrounding Regions

The glacial retreat in the Tibetan Plateau and surrounding regions started in the early 20th century and became more and more intensive with climatic warming. Before the 1950s, most glaciers advanced, although some glaciers shifted from advance to retreat. After the 1950s, a large percentage of glaciers retreated, which continued to the 1970s. Studies suggested that more than half of the glaciers were retreating and about one third advancing at that time (Zhang et al., 1981; Ren, 1988; Shi et al., 2002), and the remainder were stable. Between the 1970s and 1980s, glacial mass balances were somewhat positive and snowlines dropped. With more advancing glaciers, fewer glaciers retreated during this period. From the 1980s to the 1990s, glaciers retreated rapidly again and only 10% of glaciers were advancing. From the 1990s on, glacial retreat was more extensive than during any other period in the 20th century. There are still some glaciers advancing (Table 2) as inferred from some satellite images (Shi et al., 2006). However, all the field expeditions in recent years reported few advancing glaciers. A glaciological expedition in 1989 reported that glaciers of the southeast Tibetan Plateau were retreating rapidly (Yao et al., 1991). The Zepu Glacier and Kaqing Glacier were examples of retreating glaciers. But some glaciers, such as the Large Dongkemadi Glacier and the Small Dongkemadi Glacier, were still advancing in 1989. Detailed study of the Large Dongkemadi Glacier and the Small Dongkemadi Glacier in the Tanggula Mountains and the Meikuang Glacier in the Kunlun Mountains (Fig. 1) showed that these glaciers continued to advance during those years (Pu et al., 1998; Yao, 2002). However, all these glaciers have shifted from advance to retreat since the 1990s and all these glaciers are currently retreating.

Glacial retreat amplitude appears to be accelerating after the 1990s. There are two types of examples. The first example is more dramatic retreating of original retreating glaciers such as the Glacier No. 1, in the Urumqi River basin in the Tian Shan Mountains (Fig. 1). This glacier consists of two branches (east and west branches). Since the 1960s, Glacier No. 1 has been mapped nine times using large-scale cartography and plane table mapping (in 1962), ground photography (in 1973, 1980, 1986, and 1994) and GPS (in 2000 and 2002) by the Tian Shan Glaciological Station (Jiao et al., 2004), and using aerial photography (in 1964 and 1992) by Chen et al. (1996). Moreover, since 1986 the location of the glacier terminus has been measured every year. The ice tongues of east branch and west branch joined together in 1962, but the confluence area was thinning continuously as the two branches retreated. In 1993, the two branches were totally separated from each other and by 2001, the distance between the two branches

1523-0430/07 $7.00

TABLE 1

Glaciers in mountain ranges in the Tibetan Plateau and surrounding regions based on the data in the *Glacial Inventory of China* (Shi, 2005).

Mountains	Number of glaciers	Glacial area (km^2)	Glacial volume (km^3)
Altay	403	280	16
Sawuer	21	21	17
Tian Shan	9081	9236	1012
Parmir	1289	2696	248
Karokoram	3454	6231	686
Kunlun	7694	12266	1283
Altyn	235	275	16
Qilian	2815	1931	93
Qiangtang	958	1802	162
Tanggula	1530	2213	184
Gangdise	3538	1766	81
Nyainqentanglha	7080	10701	1002
Hengduan	1725	1580	97
Himalayas	6475	8412	709
Total	46298	59406	5590

exceeded 100 m. Glacier No. 1 retreated most rapidly from the early 1960s through the early 1970s (Fig. 2), with a retreat rate of 6.5 m yr^{-1}. The rate of glacial retreat decreased significantly in the mid-1970s and reached a minimum in the early 1980s. Afterwards the retreat rate increased again, and reached the maximum of 6.6 m yr^{-1} between 1990 and 1991.

The second example is the Large and Small Dongkemadi Glaciers in the Tanggula Mountains (Yao, 2002). These two glaciers were both advancing when they were first observed in 1991 (Fig. 3). The area of the Large Dongkemadi Glacier was about 14.6 km^2, and the area of the Small Dongkemadi Glacier was about 1.8 km^2. Based on glaciological theory, there is a time lag for a glacier to respond to climatic change that depends on glacial size: the larger the glacier, the longer the lag-time. Therefore, the Small Dongkemadi Glacier should shift from advance to retreat earlier than the Large Dongkemadi Glacier. The Small Dongkemadi Glacier advanced about 4 m in the summer of 1994, and then shifted to retreat in 1995, with a retreat rate of only 0.2 m yr^{-1} that year. After 1995, the Small Dongkemadi Glacier kept retreating at an increasing rate, reaching 2.9 m yr^{-1} in 2000. The Large Dongkemadi Glacier advanced 15.7 m yr^{-1} between 1989 and early 1994, then shifted to retreat after the summer of 1997. The annual retreat of the Large Dongkemadi Glacier also increased continuously and reached 4.6 m yr^{-1} in 2001.

More and more studies are confirming the accelerating glacial retreat in the Tibetan Plateau, Ren et al. (1998, 2004) has reported glacial retreat of the Rongbuk Glacier in Mt. Qomolanma which was interpreted as an impact of global warming. Others not only reported glacial retreat (Pu et al., 1998, 2001), but also mass-balance fluctuations (Pu et al., 1999; Liu et al., 2000). Glacial retreat varies from region to region (Chen et al., 1996; Su et al., 1996, 1999; Liu et al., 2000, 2002; Pu et al., 2001; Wang and Liu,

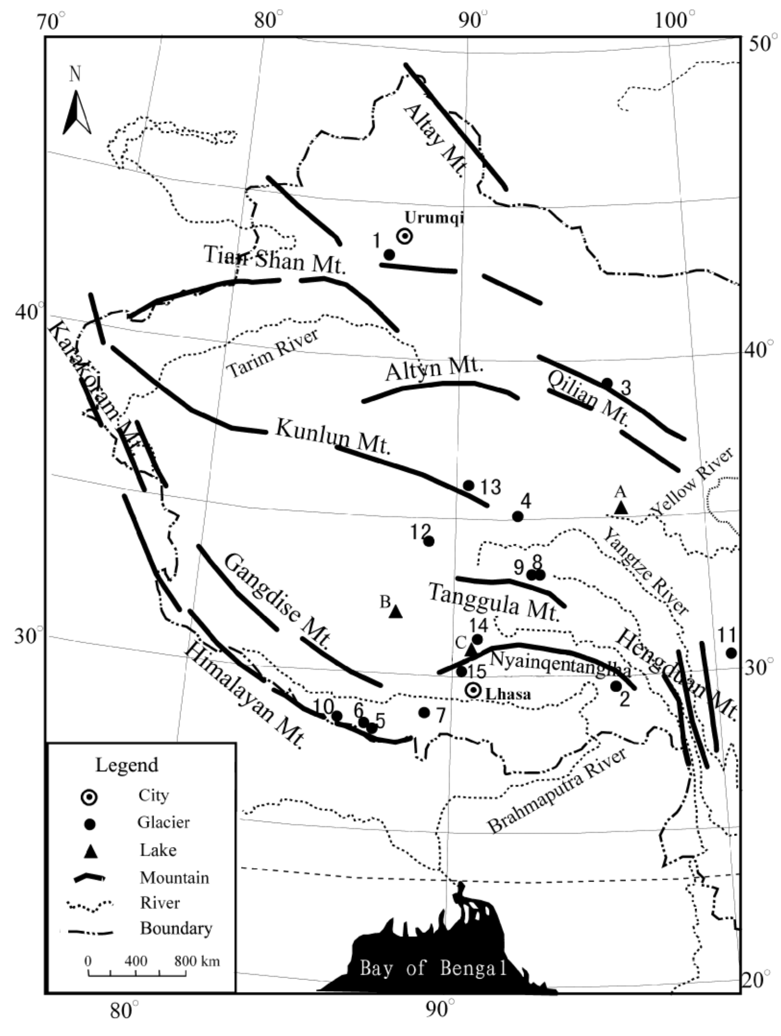

FIGURE 1. Map of the study area with the locations of glaciers and lakes studied in the present paper. The numbers are, respectively, for: 1. Glacier No. 1; 2. Basu Glacier; 3. Qiyi Glacier; 4. Meikuang Glacier; 5. Dasuopu Glacier; 6. Kangwure Glacier; 7. Qiangyong Glacier; 8. Large Dongkemadi Glacier; 9. Small Dongkemadi Glacier; 10. Rongbuk Glacier; 11. Hailuogou Glacier; 12. Puruogangri Glacier; 13. Malan Glacier; 14. Zhadang Glacier; 15. Gurenhekou Glacier. The triangles are, respectively, for: A. Xingxinghai Lake; B. Selin Co Lake; C. Nam Co Lake.

TABLE 2

Proportions of advancing and retreating glaciers on the Tibetan Plateau and surrounding regions at different times.

Stage	Number of glaciers analyzed	Retreating glaciers (%)	Advancing glaciers (%)	Stable glaciers (%)	References
Before 1950		Advancing glaciers shifting to retreating			Zhang et al., 1981; Ren, 1988
1950–1970	116	53.4	30.2	16.4	Zhang et al., 1981; Ren, 1988
1970–1980	224	44.2	26.3	29.5	Zhang et al., 1981; Ren, 1988
1980–1990	612	90	10	0	Yao et al., 1991, 2004
1990 to 2005	612	95	5	0	This paper

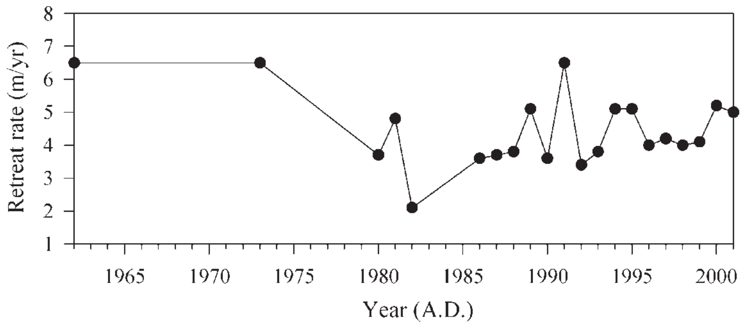

FIGURE 2. Retreat rate of Glacier No. 1 in the Urumqi River basin.

2001; Jing et al., 2002; Lu et al., 2002; Yao et al., 2004). Figure 4a demonstrates the retreat of the observed glaciers in different regions. These observations show that the magnitude of glacial retreat generally decreases from the margin to the interior of the plateau, and reaches its minimum in the central Tibetan Plateau. The magnitude of glacial retreat was the largest in the Karakorum Mountains and the southeastern Tibetan Plateau. The annual retreat rate is nearly 50 m yr^{-1} for the Basu Glacier in the Karakorum Mountains (Figs. 1, 4b). However, the glacial retreat in the interior of the Tibetan Plateau was small, no more than 10 m yr^{-1}. For example, the annual retreat rates of the Puruogangri Glacier and the Malan Ice Cap were less than 10 m yr^{-1}. As a lot of studies (Yao et al., 1990; Yang., 1991, 1995; Yang and Hu, 1992; Liu et al., 1999; Ye et al., 1999; Shen, 2003, Shen and Liu, 2003; Lu et al., 2005) pointed out, glacial melting water increase caused by more intensive glacial retreat has important influence on water resources or hydrological processes.

The Characteristics of Mass Balance in the Tibetan Plateau and Surrounding Regions

The fundamental cause of glacial behavior is mass balance, which is directly related to climatic change. Mass balance is the algebraic sum of glacial mass gain (precipitation, avalanches, etc.) minus mass losses (melting, evaporation, sublimation, calving) over a year. Glacier mass balance is determined using contour maps of accumulation and ablation data. Ablation is measured with stakes and accumulation is measured with snow pits on the glacier surface. A positive algebraic sum means more mass input and a negative algebraic sum means more mass output.

Glacial mass-balance observations are not many in the past because of its difficulty of measurement on the Tibetan Plateau and surrounding regions. A few observed sites include the Glacier No. 1 in the Urumqi River basin (1956–2001), Small Dongkemadi Glacier in the Tanggula Mountains (1990–2001), and Meikuang

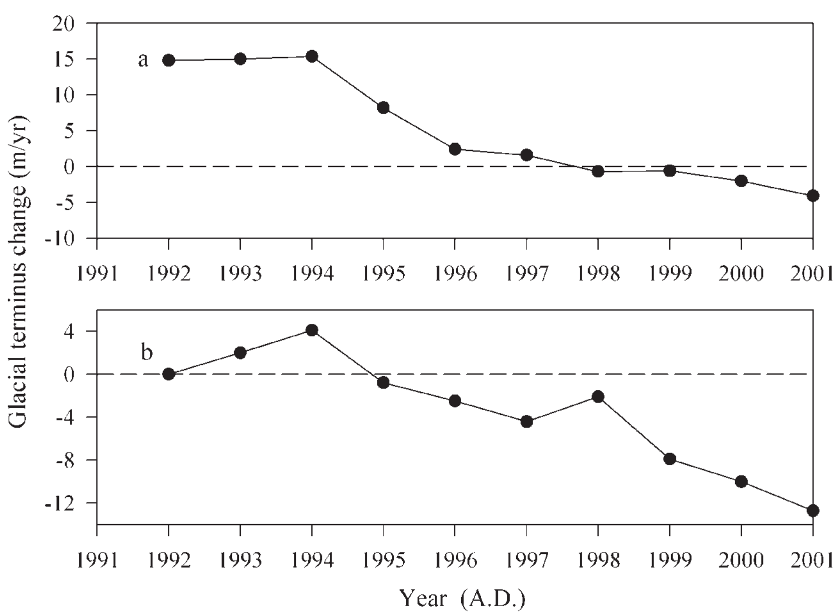

FIGURE 3. Fluctuations of the Larger Dongkemadi Glacier (a) and the Small Dongkemadi Glacier (b) in the Tanggula Mountains. Positive value shows glacial advance and negative value shows glacial retreat.

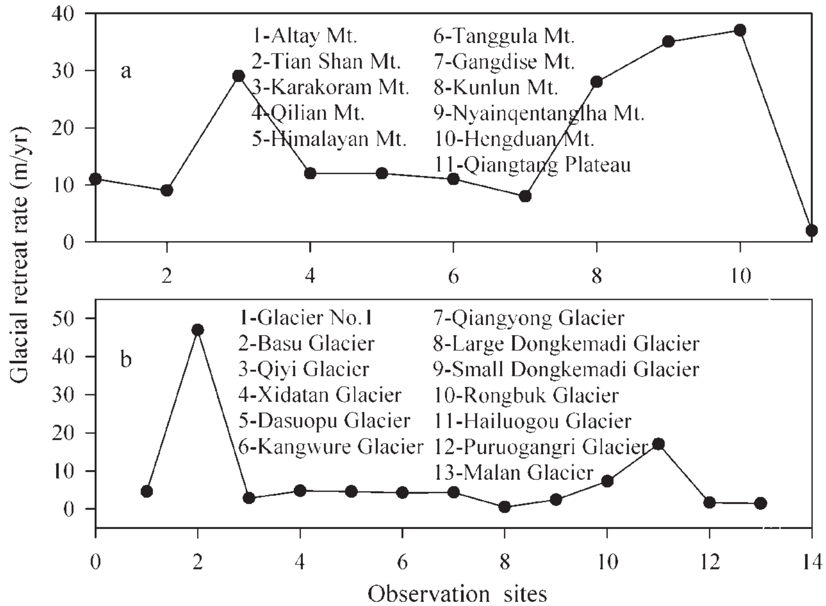

FIGURE 4. Regional features of glacial retreat since 1960s in the Tibetan Plateau and surrounding regions. (a) Annual retreat rate generalized for all the glaciers in the region. The Qiangtang Plateau is the nonmountainous parts of the Tibetan Plateau. (b) Annual retreat rate for specific glaciers in different regions.

Glacier (1990–2001) in the Kunlun Mountains (Pu et al., 1998, 1999; Jiao et al., 2004; Wang et al., 2004). The data from Glacier No. 1 and Small Dongkemadi Glacier have been included in the Glacier Mass Balance Bulletin of the World Glacier Monitoring Service. Obviously, the limited monitoring sites of mass balance can not represent the pattern of the whole Tibetan Plateau and surrounding regions, but help us to understand the regional behavior of glaciers. To further understand the nature of glacial retreat on the Tibetan Plateau in terms of mass balance, more sites have been monitored in the past 1 to 2 yr. The new sites include the Gurenhekou Glacier and the Zhangdang Glacier (Fig. 1).

From Figure 5a, it is clear that the net mass balance of Glacier No. 1 in the Tian Shan Mountains was strongly negative during most of the observation period, that the mass balances of the glaciers in the central and northern Tibetan Plateau shifted recently from positive to negative with different magnitudes. For example, the mass balances of the Small Dongkemadi Glacier and Meikuang Glacier became negative in the mid-1990s, characterizing the general retreat of glaciers in the central and northern Tibetan Plateau. However, the mass balance of the Meikuang Glacier in the Kunlun Mountains was less negative than that of the Small Dongkemadi Glacier in the Tanggula Mountains, and their glacial mass balances were mostly positive before the 1990s (Fig. 5a). If enough new sites added, we can further study the spatial pattern of glacial mass balance in the Tibetan Plateau, which is not possible so far. However, with existing mass balance sites in the Tibetan Plateau, we can see that the most negative mass

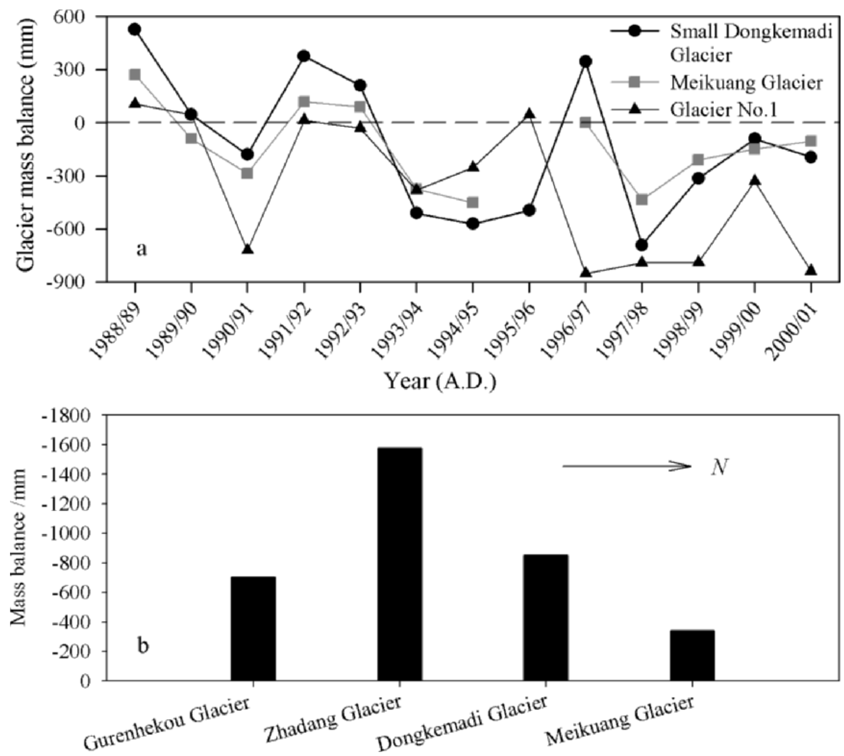

FIGURE 5. Mass balances of glaciers in the Tibetan Plateau with 10 yr of records (a) and additional glaciers in 2006 (b).

TABLE 3

Glacial retreats around the Xingxinghai Lake in 1970, 1990, and 2000.

Year	Glacial area (km^2)	Retreated area (km^2)	Percentage of retreated area to original total
1970	125.5		
1990	116.4	−9.1	−7.3
2000	103.8	−21.7	−17.3

balance is found in the southern Tibetan Plateau as shown in Figure 5b.

Precipitation in most parts of the Tibetan Plateau and surrounding regions is increasing, probably adding more snow to the accumulation zone of glaciers. However, the additional mass gains have not been reflected as positive mass balances. The reason is that along with precipitation increasing, temperatures are rising (Shrestha et al., 1999; Liu and Chen, 2000; Yao et al., 2000). Increased melt due to rising temperatures outweighs any increased snowfall on glaciers. Therefore, the key cause of more and more negative glacial mass balance and general glacial retreat on the Tibetan Plateau and surrounding regions is climatic warming.

The Impact of Glacial Retreat on Hydrological Process on the Tibetan Plateau

The glacial retreating on the Tibetan Plateau is impacting hydrological process in many ways including increased discharge, lake level rising, more frequent glacial lake outburst flood (GLOF), glacial debris flow, and so on.

The annual glacial meltwater runoff in China is about 56 km^3 (Yang and Hu, 1992; Yang, 1995), and is equal to the total annual runoff of the Yellow River. It is therefore important for the Tibetan Plateau and surrounding regions, particularly, northwest China because glacial melting water supplies the desert oases. In northwest China, which includes Gansu, Qianghai, and Xinjiang provinces, there are 24,752 glaciers, with a total area of 31,351 km^2, and a glacial volume of 3108 km^3 (Wang and Yang, 1991; Yang et al., 1996). Glacial meltwater accounts for more than 20% of the water resource in Xijiang, Gansu, and Qinghai. The rivers in these provinces are mostly inland rivers disappearing in the arid or desert area. The large outflow rivers such as the Yangtze River, the Yellow River, and the Brahmaputra River are also impacted in their headwaters.

Yang (1995) estimated that the total annual glacial meltwater runoff in Northwest China is about 22 km^3. Yao et al. (2004) recently pointed out that the supply of glacial meltwater runoff to the rivers in Northwest China has increased 5.5% in the past 27 yr. Obvious climate warming appeared in the 1980s and became more intensive in the 1990s (Yao et al., 1996). It would therefore be reasonable to speculate that glacial meltwater runoff contributed even more than 5.5% in the 1990s. Ren et al. (2004) predict that glacial retreat will speed up in the central Himalayas if climatic warming and drying continues. Shi and Liu (2000) forecasted that small glaciers would be retreating more intensively responding to global warming in the future. All these studies mean that, in the future, global warming will result in more contribution of glacial meltwater to the river discharge in Northwest China.

A runoff increase of 13% in the 1990s was estimated in the Tarim River basin and glacial melting caused by climatic warming is the major cause (Shi et al., 2002). Shen and Liu (2003) suggested that the Tailan Glacier, which is at the upper reaches of the Tarim River basin had thinned 1.26 m with an average thinning of 0.29 m yr^{-1} between 1957 and 2000, is a major source. The supply of glacial melting water from the Tailan Glacier had increased by 13% between 1957 and 1986 and by 23% between 1987 and 2000.

Lake level rising caused by more input of glacial melting water is now a particularly serious problem in the Tibetan Plateau because grassland and villages near these rising lakes are devastated (Yang et al., 2003). To investigate quantitatively the impact of the glacial melting water on lake level rising, several specific areas occupied by large lakes including Xingxinghai Lake, Nam Co Lake, and Selin Co Lake on the Tibetan Plateau (Fig. 1) have studied based on aerial photos in 1970 and TM satellite remote-sensing data in 1990 and 2000.

In the Xingxinghai region, glaciers are small in both numbers and areas, with a total of 57 glaciers and an area of 103.8 km^2 in 2000 (Table 3). Our study shows that, except three advancing glaciers and two stable glaciers, the remainder of the 57 glaciers had retreated in 1970–2000. The total glacial area in the region had decreased 17.3% between 1970 and 2000 (Table 3). The largest retreat glacier was the Yehelong Glacier. The glacier retreated 1950 m in length, about 76.8% in about 30 yr.

The lake area change in the Xingxinghai region is shown in Table 4. Five lakes are located in this region with a total area of 1262 km^2 in 1970, of 1245 km^2 in 1990, and 1215 km^2 in 2000 (also see Fig. 6). It means that the water supply from the lost of glacial mass balance did not help the water evaporation because of global warming. The reason is that glacial area is small and scattered in different places and some of them do not supply the lakes.

Glacial retreat in the Nam Co region was studied by Lu et al. (2005) and by Wu et al. (2007). Unlike the Xingxinghai region, the glaciers in the Nam Co region have greater area, are rather concentrated in distribution, and supply Nam Co Lake (Table 5). The glacial area decrease in the Nam Co region is dramatic, with a retreat rate of 15.4% in glacial area in about 30 yr.

TABLE 4

Lake area changes in the Xingxinghai region in 1970, 1990 and 2000.

	Area (km^2)			1970–1990		1990–2000		1970–2000	
Lake	1970	1990	2000	Area variation (km^2)	Percent (%)	Area variation (km^2)	Percent (%)	Area variation (km^2)	Percent (%)
Zhalin	528	520	519	−8.4	−1.6	−0.6	−0.1	−9.0	−1.7
Cuorang	12.6	11.9	11.4	−0.7	−5.6	−0.5	4.2	−1.2	−9.5
E'ling	613	609	613	−4.9	−0.8	4.0	0.7	−0.9	−0.2
Long'A Co	19	16	0	−2.9	−15.3	−16.0	−100	−18.9	−100
Xingxinghai	89	88	72	−0.8	−0.9	−16.8	−19.0	−17.6	−19.7
Total	1262	1245	1215	−17	−1.4	−30	−2.4	−47	−3.8

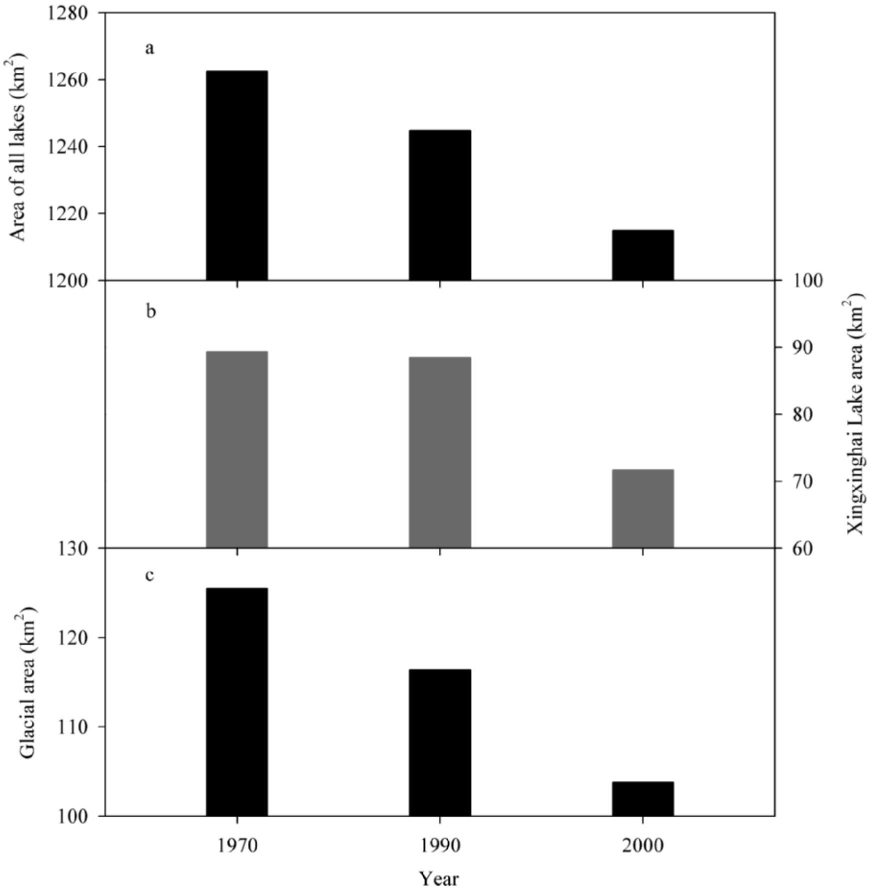

FIGURE 6. Lake area changes including total area of all the lakes and of Xingxinghai lake itself, and glacial area changes in the Xingxinghai region. a and b are lake areas standing, respectively, for all the lakes (a) and for the Xingxinghai (b), c is for glacial area.

Based on the remote-sensing data, the areas of all the lakes in the Nam Co region had expanded between 1970 and 1990 (Table 6). The areas of the Nam Co Lake, Baimalangmu Co Lake, Tong Co Lake, and Shen Co Lake are expanding continuously between 1990 and 2000. However, Cuojiana Lake shrank during this period.

TABLE 5

Glacial area changes in the Nam Co region in 1970, 1990 and 2000.

Year	Glacial area (km^2)	Retreated area (km^2)	Percentage of retreated area to original total (%)
1970	167.6		
1990	151.5	−16.0	−9.6
2000	141.8	−25.7	−15.4

From Tables 5 and 6, the lake area in the Nam Co region is obviously increasing with the decline in glacial area between 1970 and 2000 (also see Fig. 7)

The remote-sensing analyses of glaciers around the Selin Co region indicated that there were 6 advancing glaciers, 26 stable glaciers, and the remainder were generally retreating between 1970 and 2000. The total glacial area decreased 1.7% between 1970 and 2000 (Table 7), and the largest retreat in glacier length is the Qianggudiru Glacier with a 1288 m retreat. However, the largest retreat glacier in area is Glacier No. 5K451F3 with a decrease of 19.4%.

Area changes of eight lakes in the Selin Co region were analyzed based on the aerial photos in 1970, and the TM satellite remote-sensing data in 1990 and 2000 (Table 8). It showed that the area of the eight lakes had expanded at a rate of 10.9% from 1970 to 2000. The exception is two small lakes, Xiaqiong Co and Gejialing Co, with area only about 4 km^2 which once disappeared in 1990.

TABLE 6

Lake area changes in the Nam Co region in 1970, 1990 and 2000.

Lake	Area (km^2)			1970–1990		1990–2000		1970–2000	
	1970	1990	2000	Area variation (km^2)	Percent (%)	Area variation (km^2)	Percent (%)	Area variation (km^2)	Percent (%)
Nam Co	1941	1970	1982	28.7	1.5	12.1	0.6	40.8	2.1
Cuojiana	0.6	0.6	0.5	0.1	9.1	−0.1	−13.3	0	−5.5
Baimalangmu Co	0.8	1.1	1.2	0.3	32.5	0.1	11.3	0.4	47.5
Tong Co	2.4	2.5	2.5	0.1	5.5	0	0	0.1	5.5
Shen Co	43.7	44.2	44.8	0.5	1.1	0.6	1.4	1.1	2.5
Total	1988	2018	2031	30	1.5	13	0.6	43	2.2

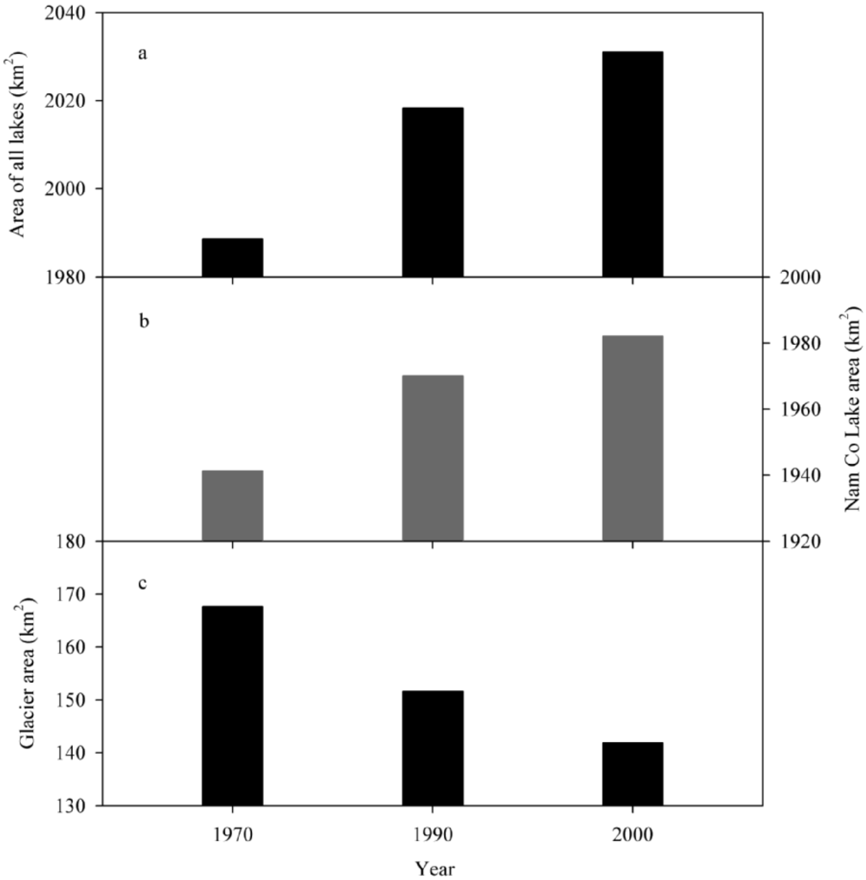

FIGURE 7. Lake area including total area of all the lakes and the Nam Co Lake itself and glacial area in the Nam Co region. a and b are lake areas standing, respectively, for all the lakes (a) and the Nam Co (b), c is for glacial area.

The Selin Co region has a large glacial melt water supply, and larger number and area of glaciers compared to the Xingxinghai region, or even the Nam Co region. The lake area increase in the Selin Co region is evident in the past 30 yr as shown in Figure 8.

TABLE 7

Glacial retreats in the Selin Co region in 1970, 1990, and 2000.

Year	Glacial area (km^2)	Retreated area(km^2)	Percentage of retreated area to original total (%)
1970	899		
1990	892	−6.7	−0.8
2000	884	−15.0	−1.7

Conclusions

Glaciers in the Tibetan Plateau and surrounding regions are retreating rapidly. The glacial retreat has resulted from negative glacial mass balance. Many glaciers that previously had positive glacial mass balance also shifted to negative balance. The glacial retreat in the 1990s was the most intensive of any period during the 20th century.

The general glacial retreat in the Tibetan Plateau and surrounding regions in the 1990s caused glacial runoff to increase significantly, more than 5.5% in Northwest China. In the Tarim River basin where glaciers are most concentrated, the net increase of water from glacial retreat reached 13%.

Glacial retreat also caused lake level rising in the areas with larger coverage of glaciers in the Tibetan Plateau, such as the Nam

TABLE 8

Lake area changes in the Selin Co region in 1970, 1990, and 2000.

Lake	Area (km^2)			1970–1990		1990–2000		1970–2000	
	1970	1990	2000	Area variation (km^2)	Percent (%)	Area variation (km^2)	Percent (%)	Area variation (km^2)	Percent (%)
Selin Co	1628	1716	1743	87	5	27	1.6	114	7
Coemu Co	263	263	270	0.2	0.1	7.3	2.8	7.5	2.8
Bange Co	55	76	106	20	37	30.7	0.6	51	92
Yagedong Co	35	38	42	3	8.6	3.9	10.2	7	20
Namka Co	16	18	22	1.2	7.6	4.4	24.8	6	34
Shibu Co	13	13	15	0.1	0.8	1.7	12.5	1.8	13
Xiaqiong Co	4.5	0	6.7	−4.5	−100	6.7	100	2.1	47
Gejialing Co	3.6	0	36	−3.6	−100	36	100	32	88.9
Total	2020	2124	2242	104	5.1	118	5.6	222	10.9

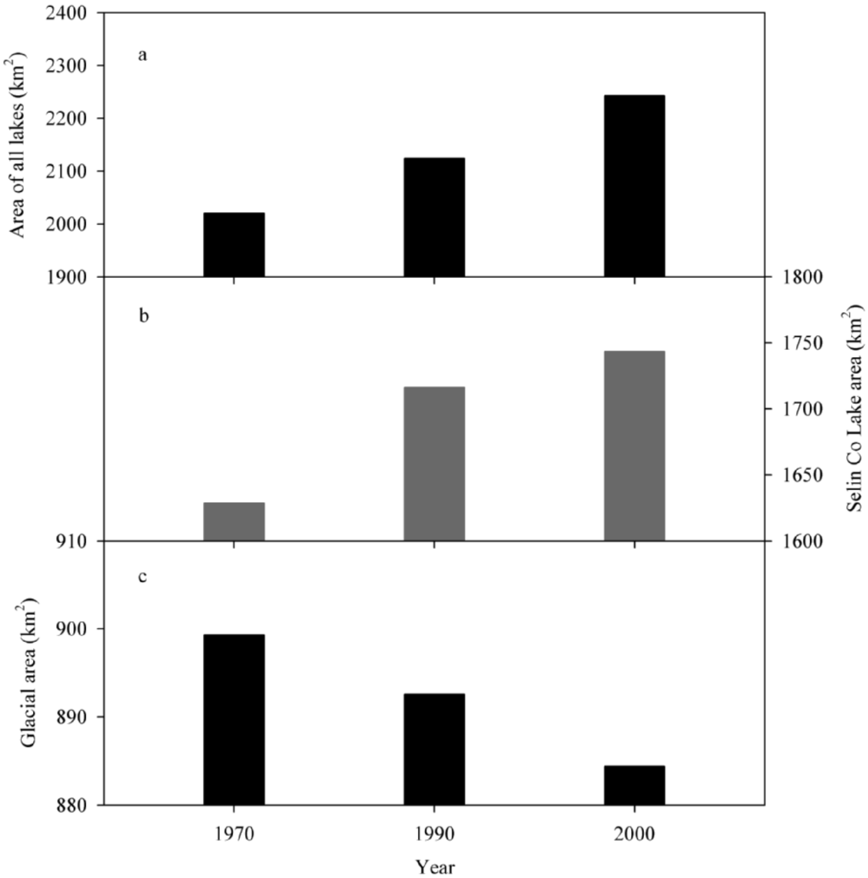

FIGURE 8. Lake area including total area of all the lakes and the Selin Co Lake itself and glacial area in the Selin Co region. a and b are lake areas standing, respectively, for all the lakes (a) and the Selin Co (b), c is for glacial area.

Co region and Selin Co region. In the region where glacial area is small and precipitation dominates, lake level is dropping.

With continued global warming in the future, stronger glacial retreat is anticipated (Shi and Liu, 2000) and its more intensive impact on hydrological processes is expected. More studies should be focused on the mechanism of the interaction between glaciers and lakes in the future study.

Acknowledgments

This study has been supported by the project from MOST (2005CB422004), the Innovation Group Fund of the National Natural Science Foundation of China (40121101), and the program BRAHMATWINN (FP6-036952).

References Cited

Chen, J. M., Liu, C. H., and Jin, M. X., 1996: Application of the repeated aerial photogrammetry to monitoring glacier variation in the drainage area of the Urumchi River (in Chinese with English Abstract). *Journal of Glaciology and Geocryology*, 18(4): 331–336.

Jiao, K. Q., Jing, Z. F., Han, T. D., Ye, B. S., Yang, H. A., and Li, Z. Q., 2004: Variation of the Glacier No. 1 at the headwaters of the Urumqi River in the Tian Shan Mountains during the past 42 years and its trend prediction. *Journal of Glaciology and Geocryology*, 26(3): 253–260. (In Chinese with English abstract).

Jing, Z. F., Ye, B. S., Jiao, K. Q., and Yang, H. A., 2002: Surface velocity on the Glacier No. 51 at Haxilegen of the Kuytun River, Tian Shan Mountains. *Journal of Glaciology and Geocryology*, 24(5): 563–566. (In Chinese with English Abstract).

Liu, C. H., Kang, E. S., Liu, S. Y., Chen, J. M., and Liu, Z. X., 1999: Study on glacier variation and its runoff responses in the arid region of Northwest China. *Science in China, Series D*, 42(supp): 64–71.

Liu, S. Y., Xie, Z. C., and Liu, C. H., 2000: Mass balance and fluctuations of glaciers. *In*: Shi, Y. F., Huang, M. H., and Yao, T. D. (eds.), *Glaciers and Their Environments in China—The Present, Past and Future*. Beijing: Science Press, 101–131. (In Chinese).

Liu, S. Y., Shen, Y. P., Sun, W. X., and Li, G., 2002: Glaciers variation since the Maximum of the Little Ice Age in the western Qilian Mountains, Northwest China. *Journal of Glaciology and Geocryology*, 24(3): 227–233. (In Chinese with English abstract).

Liu, X. D., and Chen, B. D., 2000: Climatic warming in the Tibetan Plateau during recent decades. *International Journal of Climatology*, 20(14): 1729–1742.

Lu, A. X., Yao, T. D., Liu, S. Y., Ding, L. F., and Li, G., 2002: Glacier change in the Geladandong area of the Tibet Plateau monitored by remote sensing. *Journal of Glaciology and Geocryology*, 24(5): 559–562. (In Chinese with English abstract).

Lu, A. X., Yao, T. D., Wang, L. H., Liu, S. Y., and Guo, Z. L., 2005: Glacier and lake changes in the Tibet Plateau monitored by remote sensing. *Journal of Glaciology and Geocryology*, 27(6): 783–791. (In Chinese with English abstract).

Pu, J. C., Su, Z., Yao, T. D., and Xie, Z. C., 1998: Mass balance on Xiao Dongkemadi Glacier and Hailuogou Glacier. *Journal of Glaciology and Geocryology*, 20(4): 408–412.

Pu, J. C., Yao, T. D., and Tian, L. D., 1999: Glacial mass balance in the middle of the Tibetan Plateau. *In*: *Proceedings of International Symposium on the Verification of Cryoshpere Models, Zurich, Switzerland*, 16–20.

Pu, J. C., Yao, T. D., Wang, N. L., and Zhang, Y. L., 2001: Recently variation of Malan glacier in Hoh Xil Region, Center of Tibetan Plateau. *Journal of Glaciology and Geocryology*, 23(2): 189–192. (In Chinese with English abstract).

Ren, B. H., 1988: Recent fluctuation of glaciers in China. *In*: *An Introduction to the Glaciers in China*. Beijing, Science Press, 171–186. (In Chinese).

Ren, J. W., Qin, D. H., and Jing, Z. F., 1998: Climatic warming causes the glacier retreat in Mt. Qomolangma. *Journal of Glaciology and Geocryology*, 20(2): 184–185. (In Chinese with English abstract).

Ren, J. W., Qin, D. H., Kang, S. C., Hou, S. G., Pu, J. C., and Jin, Z. F., 2004: Glacier variations and climate warming and drying in the Central Himalayas. *Chinese Science Bulletin*, 49: 165–169.

Shen, Y. P., 2003: Mechanism and future regime of glacial lake outburst flood from Lake Marzbacher in North Inylchek Glacier, Central Asia Tienshan. *Journal of Glaciology and Geocryology*, 25(6): 611–615. (In Chinese with English abstract).

Shen, Y. P., and Liu, S. Y., 2003: Glaciers mass balance change in Tailanhe River water sheds on the south slope of the Tian Shan Mountains and its impact on water resource. *Journal of Glaciology and Geocryology*, 25(2): 124–129. (In Chinese with English abstract).

Shi, Y. F., 2001: Estimation of the water resources affected by climatic warming and glacier shrinkage before 2050 in West China. *Journal of Glaciology and Geocryology*, 23(4): 333–341. (In Chinese with English abstract).

Shi, Y. F., 2005: *Glacial Inventory of China* (Synthesis volume). Shanghai: Science Popularization Press, 33–178. (In Chinese).

Shi, Y. F., and Liu, S. Y., 2000: Estimation on the response of glaciers in China to the global warming in the 21st century. *Chinese Science Bulletin*, 45: 668–672.

Shi, Y. F., Shen, Y. P., and Hu, R. J., 2002: Preliminary study on signal, impact and outlook of climatic shift from warm-dry to warm-humid in Northwest China. *Journal of Glaciology and Geocryology*, 24(3): 219–225. (In Chinese with English abstract).

Shi, Y. F., Liu, S. Y., Shangguan, D. H., Li, D. L., and Ye, B. S., 2006: Peculiar phenomena regarding climatic and glacial variations on the Tibetan Plateau. *Annals of Glaciology*, 43: 106–110.

Shrestha, A. B., Wake, C. P., Mayewski, P. A., and Dibb, J. E., 1999: Maximum temperature trends in the Himalaya and its vicinity: an analysis based on the temperature records from Nepal for the period 1971–94. *Journal of Climate*, 12(9): 2775–2786.

Su, Z., Song, G. P., and Cao, Z. T., 1996: Maritime characteristics of Hailougou Glacier in the Gongga Mountains. *Journal of Glaciology and Geocryology*, 18(supp.): 51–59. (In Chinese with English abstract).

Su, Z., Liu, Z. X., Wang, W. T., Yao, T. D., Shao, W. Z., Pu, J. C., and Liu, S. Y., 1999: Glacier fluctuations responding to climate change and forecast of its tendency over the Qinghai-Tibet Plateau (in Chinese with English Abstract). *Advance in Earth Sciences*, 14(6): 607–612.

Wang, N. L., Jiao, K. Q., Li, Z. Q., Jing, Z. F., and Han, T. D., 2004: Recent accelerated shrinkage of Urumqi Glacier No. 1, Tien Shan, China. *Journal of Glaciology*, 50(170): 464–465.

Wang, Z. T., and Yang, H. A., 1991: Characteristics of the distribution of glaciers in China. *Annals of Glaciology*, 6: 17–20.

Wang, Z. T., and Liu, C. H., 2001: Geographical characteristics of the distribution of glaciers in China. *Journal of Glaciology and Geocryology*, 23(3): 231–237. (In Chinese with English abstract).

Wu, Y. H., Zhu, L. P., Ye, Q. H., and Wang, L. B., 2007: Response of lake-glacier area change to climate variations in Namco Basin, Central Tibetan Plateau during the last three decades. *Journal of Geography*, 62(3): 301–311. (In Chinese with English abstract).

Yang, H. A., Mi, D. S., and Kang, X. C., 1996: The distribution and features of glacier resource in Northwest China. *In*: *Proceeding of the Fifth Chinese Conference on Glaciology and Geocryology* (Vol. 1) Gansu Culture Press, 175–181. (In Chinese).

Yang, R. H., Yu, X. Z., and Li, Y. L., 2003: Remote sensing analysis of lake area increase of Selin Co. *Land Resource Remote Sensing for Land and Resources*, 56(2): 64–67. (In Chinese with English abstract).

Yang, Z. N., 1991: *Glacier Water Resources in China*. Lanzhou: Gansu Science Press, 137–141. (In Chinese).

Yang, Z. N., and Hu, X. G., 1992: Study of glacier meltwater resources in China. *Annals of Glaciology*, 16: 141–145.

Yang, Z. N., 1995: Glacier meltwater runoff in China and its nourishment to river (in Chinese with English Abstract). *Chinese Geographical Science*, 5: 66–76.

Yao, T. D., 2002: *Dynamical Features of Cryosphere in Middle Tibetan Plateau*. Beijing: Geological Press, 207–233. (In Chinese).

Yao, T. D., and Shi, Y. F., 1990: Fluctuations and future trend of climate, glaciers and discharge of the Urimuqi River, Xinjiang. *Science in China, Series B*, 35: 504–512.

Yao, T. D., Ageta, Y., Ohata, T., Jiao, K. Q., Shao, W. Z., Ding, L. F., and Pu, J. C., 1991: Preliminary results from China-Japan Glaciological Expedition in Tibet Plateau in 1989. *Journal of Glaciology and Geocryology*, 13(1): 1–8. (In Chinese with English abstract).

Yao, T. D., Thompson, L. G., Qin, D. H., Tian, L. D., Jiao, K. Q., Yang, Z. H., and Xie, Z. C., 1996: Variations in temperature and precipitation in the past 2000 years on the Xizang (Tibet) Plateau—Guliya ice core record. *Science in China, Series D*, 39(4): 425–433.

Yao, T. D., Liu, X. D., and Wang, N. L., 2000: Amplitude of climatic change in Qinghai-Tibetan Plateau. *Chinese Science Bulletin*, 45(1): 98–106.

Yao, T. D., Wang, Y. Q., Liu, S. Y., Pu, J. C., Shen, Y. P., and Lu, A. X., 2004: Glacial retreat High Asia and its influence on water resource in northwest China. *Science in China, Series D*, 47(12): 1065–1075.

Ye, B. S., Ding, Y. J., and Kang, E. S., 1999: Response of the snowmelt and glacier runoff to the climate warming-up in the last 40 years in Xinjiang Autononmous Region, China. *Science in China, Series D*, 42: 44–51.

Zhang, X. S., Zheng, B. X., and Xie, Z. C., 1981: Recent variations of existing glaciers on the Qinghai-Xizang (Tibet) Plateau. *In*: *Geological and Ecological Studies of Qinghai-Xizang Plateau*. Beijing: Science Press, 1625–1629. (In Chinese).

Ms accepted July 2007