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Glacier changes from 1964 to 2004 in the Jinghe River basin, Tien Shan

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ABSTRACT

This study reports glacier changes in the Jinghe River basin during the period 1964–2004 based on ASTER image and topographic maps. The results show that the total area of the studied glaciers in the Jinghe River basin decreased by ~15% from 1964 to 2004. The loss in glacier length and ice volume is 229.5 m and 1.17 km^3, respectively, during the period 1964–2004. The rate of glacier retreat in the Jinghe River basin is similar to that of glaciers in the eastern and central Tien Shan, but slower than the retreat rate in the Northern Tien Shan. The retreat in glacier area during the two time periods is consistent with rising temperatures in the basin, which have been increasing by an average of 0.32 °C per decade. During this period there has been a general increase in glacial runoff. If glacier ice loss in the basin continues at the current rate down stream water resources will be negatively impacted.

1. Introduction

Glaciers store 70% of the global freshwater reserves and are estimated to comprise over 24 million km^3 (Gleick, 1996). Changes in glacier extent in mountainous regions are widely recognized as one of the best natural indicators of global climate change (Oerlemans, 2005), and the decline in glacier extent in mountains and other regions contributes to sea level rise (Arendt et al., 2002; Larsen et al., 2007). Correct evaluation of glacier area and volume change has large practical application in water resource, water supply and hydropower assessments. In arid and semi-arid regions, especially in northwest China, glacier runoff is the main contributor to water resources that are used to support the sustainable development of the environment, industry and agriculture. As in many other parts of the world, glaciers in the Tien Shan have been retreating since the end of the Little Ice Age (LIA) in the mid-19th century— a tendency that has accelerated since the 1970s. Intensified glacier melt causes the glaciers to have a mainly negative mass-balance, and strongly affects the quantity and seasonal distribution of runoff in Central Asia's glacier-fed watersheds (Aizen et al., 1997; Hagg et al., 2007; Sorg et al., 2012).

The Tien Shan covers a large fraction of Central Asia, spanning regions from Uzbekistan to Kyrgyzstan and from southeastern Kazakhstan to Xinjiang/China, and with its 15,953 glaciers having a total area of 15,416 km^2 (Liu, 1995; Shi, 2008), has attracted a large amount of attention for climate change research during the past decades (Aizen et al., 2006; Bolch, 2007; Kutuzov and Shahgedanova, 2009; Li et al., 2006; Narama et al., 2010). Glacier variation has been noticed since the early comprehensive field survey on glaciers in 1958 (Ren, 1988), but long-term observation on glacier variation, as well as the relationship between climate change and glacier variation, has been limited, except for those on Glacier No. 1 at the headwaters of Urumqi River (Li et al., 2003). With the development of Geographic Information System (GIS) and Remote Sensing (RS), abundant information about glacier fluctuation has been acquirable (Li et al., 2010a). Based on high-resolution remote sensing images taken at different times, many scientists have focused on regional glacier variation and climate change (Wang et al., 2009). However, most of the studies have been conducted in western and central Tien Shan, only a few studies have been conducted in the eastern region of the Tien Shan (Hagg et al., 2012; Narama et al., 2010). Meanwhile, there is a lack of long-term time series and field investigations, especially for glaciers at higher elevations. This paper reports on the current state of glaciers and on potential problems related to the observed glacier shrinkage during the period 1964–2004 in the Jinghe River basin, Tien Shan.

2. Study area

Jinghe River basin is located on the north slope of the Tien Shan and southwest of the Junggar basin (Fig. 1). It is surrounded by mountains to the north, west and south. There is a typical temperate arid continental climate, with the mountain-oasis- desert system having the typical characteristics of temperate arid ecology. The investigated region is also one of the places with greatest distance from oceans (~2000 km to the Pacific or Indian Ocean and ~3000 km to the Arctic Ocean) and the farthest distance of moisture sources from Atlantic Ocean (~7000 km) in the world.

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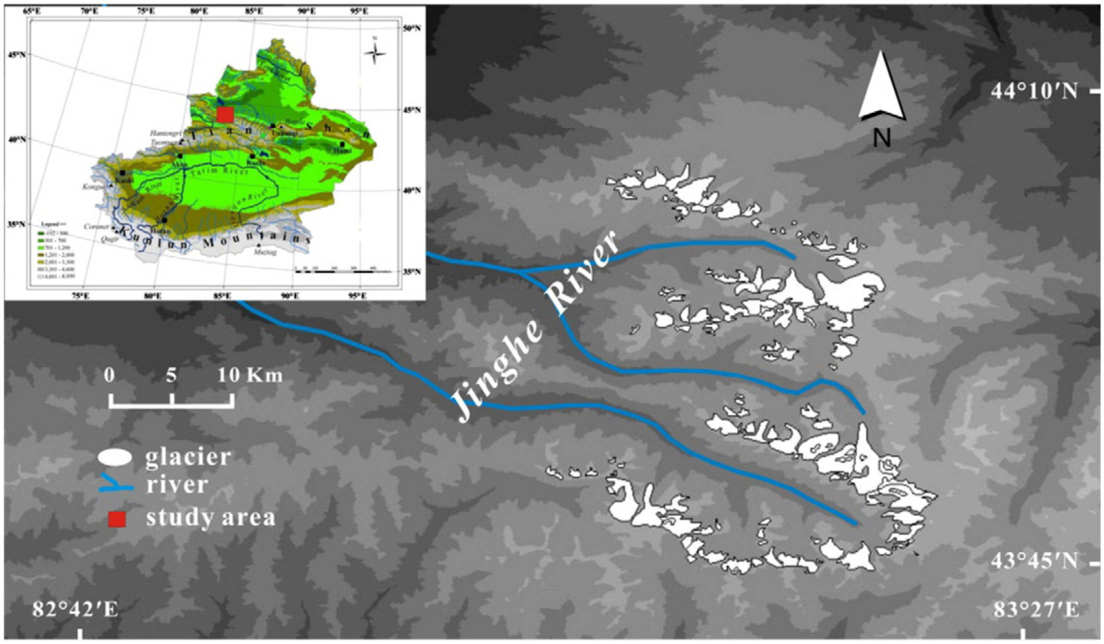

Fig. 1. Location of Jinghe River basin.

The Jinghe River basin has a total length of 114 km and a catchment area of about 2150 km^2 (Li et al., 2010b). It is one of the primary glacier regions in the source region of Ebinur lake basin, and the main fresh water provider for the city of Jinghe. According to the Chinese Glacier Inventory (CGI) there are 129 glaciers within the entire Jinghe River basin. These glaciers spread throughout an elevation that range from 3000 m to 4356 m a.s.l., and had a total estimated area of 96.20 km^2, an ice volume of 5.50 km^3 and a mean glacier area of 0.75 km^2 (Liu and Ding, 1986).

This region is dominated by the westerly circulation and the Siberian High. The precipitation is mainly from the moisture carried by the westerlies in summer, and winter temperature is controlled by the Siberian High (Aizen et al., 1995). The dominant weather patterns are orographic thunderstorms in summer and cold-dry in winter. Precipitation varies horizontally between 400 and 600 mm at elevations of 2500–3700 m a.s.l.(Liu and Ding, 1986). Meteorological parameters and stream flow are observed at Jinghe meteorological station in the lower basin of the Jinghe River. At this station, the mean annual precipitation and air temperature are 251.9 mm and 7.8 °C, respectively (Li et al., 2010b).

3. Data and methods

One ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) image was taken on June to September 2004 with a resolution of 15 m covering the most heavily glaciated part of the investigated area. The image obtained was for (nearly) cloud-free conditions during the ablation period, when the extent of snow cover was minimal, to reduce potential uncertainty in glacier boundary delineation due to snow cover. A total of 5 topographic maps (1:50 000), derived from aerial photographs acquired in 1964 by the Chinese Military Geodetic Service, were analyzed. A digital elevation model (DEM) of Jinghe river basin at the 1:50 000 scale (DEM5) was created by contour digitization and interpolation from the 1:50 000 topographic maps. The satellite images were orthorectified using methodologies described by Paul et al. (2004) and PCI Geomatica 9.1 Orthoengine software (Kutuzov and Shahgedanova, 2009; Svoboda and Paul, 2009). Geocorrection and co-registration were established using ERDAS Imagine 9.0 software. The clearly distinguishable terrain features were selected from topographic maps that could be identified on each image. On average, 30–50 ground control points were collected, with the root-mean-square error (RMSE) value limited to <0.5 pixel in both x and y directions. All images and maps were presented in a Universal Transverse Mercator (UTM) coordinate system referenced to the 1984 World Geodetic System (WGS84).

Data assessments conducted under the Global Land Ice Measurements from Space (GLIMS) framework confirmed that artificial interpretation remains the best tool for extracting higher-level information from satellite images for glaciers, especially debris-covered glaciers (Paul et al., 2004; Raup et al., 2007). The glacier outlines are mapped manually with the DEM by commercial GIS software (ARCVIEW), using the topographic maps and satellite images, which is a useful tool for extracting detailed information from satellite imagery of glaciers (Raup et al., 2007), particularly when mapping is conducted by the same person using a combination of different types of imagery (Paul et al., 2002). A DEM with 25 m grid spacing was used to derive the elevation and slope orientation data for glaciers.

4. Results

4.1. Characteristics of glacier distribution

A total of 91 glaciers with an area of 73.4 km^2 has been identified and mapped on the satellite imagery in 2004. Fig. 2 shows the distribution of glacier coverage in the Sikeshu River basin, according to the glacier size

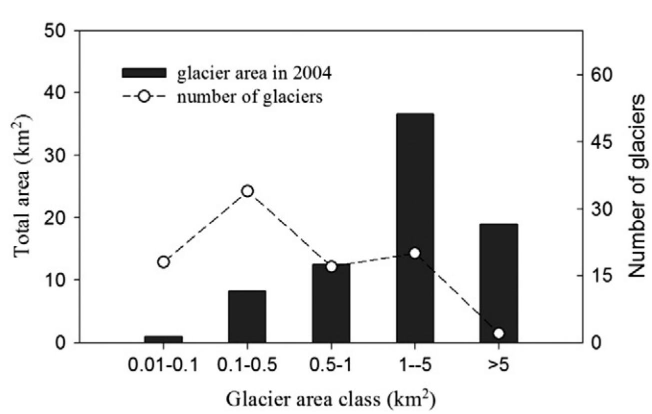

Fig. 2. Glacier number and area of the Jinghe River basin in 2004.

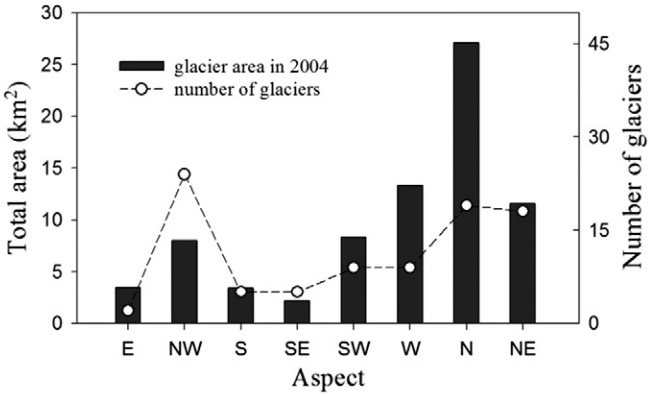

Fig. 3. Distribution of glaciers by aspect in 2004.

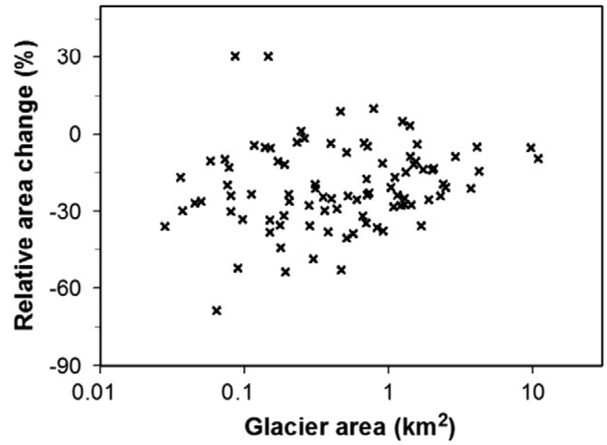

Fig. 4. The relationship between glacier area and relative area change (%) in the Jinghe River basin.

class (<0.1, 0.1–0.5, 0.5–1, 1–2, 2–5 and >5 km^2). The vast majority of glaciers (75.8%) are smaller than 1 km^2. These glaciers contain about a quarter of the total area, which is a common feature in the mountains of the mid-latitudes. About 22.0% of the glaciers have an area of 1–5 km^2, and account for 47.3% of the total area. Only two glacier areas are larger than 5 km^2, and account for 24.6% of the total area. Small glaciers are prevalent in this region. The lowest position of any glacier tongue in the Jinghe River basin is about 3000 m a.s.l. The median elevation, which is widely used to estimate the long-term mean equilibrium line altitude (Braithwaite and Raper, 2009), is approximately 3722 m a.s.l. The mean aspect of each glacier is calculated from the arc tangent of the respective sine and cosine grids following Paul (2007). The aspect of glaciers by number and area is shown in Fig. 3. In detail, the area of glaciers with a northern orientation makes up 35% of the area, and the number of glaciers with a north-western orientation accounts for about 26.4% of all glaciers, while their area represents 10.3% (8.0 km^2) of the total. The aspect distribution shows that the location of glaciers is dependent on local topographical constraints (Andreassen et al., 2008).

4.2. Glacier change

The comparative analysis shows that during the last 40 years, glaciers of the area studied have receded (Table 1). The glaciated area of the Jinghe River basin decreased from 91.3 km^2 in 1964 to 77.4 km^2 in 2004, resulting in a relative ice cover loss of 15.2% (average rate of −0.38% yr^{-1}). Among these glaciers, 84 (92.3%) glaciers shrank by approximately 14.3 km^2, 7 (7.7%) glaciers grew by about 0.4 km^2. The maximum area loss occurred in the 1.0–5.0 km^2 size class, which decreased in total area from 50.9 to 36.6 km^2, or 28.1%. The number of the smallest size class (<0.1 km^2) increased from 15 to 18, which is due to the larger glaciers melt down into several smaller glaciers, while the number of glaciers between 1 and 5 km^2 decreased from 27 to 20. At the same time, the mean length change of all analyzed glaciers between 1964 and 2004 was- 229.5 m (−5.7 m yr^{-1}). On average, the glaciers lost 16.8% of their length.

The relative changes in glacier areas also varied with glacier size as seen in Fig. 4. It can be seen that small glaciers (<1 km^2) had a large range of change from −68.8% to 30.2%. In contrast, the relative shrinkage of large glaciers (>1 km^2) for each glacier was small, although large glaciers lost comparatively large areas at lower elevations. The termini of small glaciers are particularly sensitive to climatic changes, and small glaciers are distributed over a wide elevation range, resulting both in larger overall area loss and larger variability of area changes compared to larger glaciers. Thus, small glaciers contribute disproportionately to the overall glacier shrinkage.

4.3. Comparison of glacier changes in Jinghe River basin with other regions

A portion glacier changes in Tien Shan were compared in this study (Table 2). Regional glacier shrinkage has varied as a function of the regional climate conditions, glacier area variation with elevation (hypsography), and the proportional of glacier-size distribution. In central Tien Shan, glacier area shrunk by 15.8% in the Ala Archa (1963–2003), 19% in the Pskem region (1970–2000), 12% in the Ili-Kungöy region (1970–2000), 12% in the At-Bashy region (1970–2000), and 9% in the SE-Fergana region (1970–2000). In northern Tien Shan, the average loss of glacier ice coverage in the valleys of Zailiyskiy and Kungey Alatau between 1955 and 1999 is more than 32%. In eastern Tien Shan, the glaciers located in the southern slope of Kalik Mountain reduced their area by 12.3% from 1972 to 2005. Those results indicate that the glaciers in Tien Shan are in a state of rapid retreat. Comparing with the above research, the rate of glacier retreat in the Jinghe River basin is similar to the glaciers in the eastern and central Tien Shan but slower than the glaciers in the Northern Tien Shan.

4.4. Changes in ice volume

The significant decreases in the areal extent of glaciers in Jinghe River basin discussed above must be accompanied by large volumetric ice losses. The relationship between ice volume and area can be defined as $V = c \cdot S^{\lambda}$, where the value of λ is 1.36 and 1.25 for glacier and ice

Table 1
Glacier area, number and mean length change during 1964–2004 in the Jinghe River basin.

Glacier area class (km^2)	Area (km^2)			Number			Mean length (m)		
	1964	2004	Change	1964	2004	Change	1964	2004	Change
0.01–0.1	1	1	0 (0%)	15	18	3 (20%)	378.4	313.3	−65.1 (−17.2%)
0.1–0.5	7.9	8.3	0.4 (5.1%)	31	34	3 (9.7%)	699.0	626.5	−72.5 (−10.4%)
0.5–1	11	12.5	1.5 (13.6%)	16	17	1 (6.3%)	1356.3	1374.2	17.9 (1.3%)
1–5	50.9	36.6	−14.3 (−28.1%)	27	20	−7 (−25.9%)	2377.1	2189.7	−187.4 (−7.9%)
>5	20.5	19	−1.5 (−7.3%)	2	2	0 (0%)	5428.0	4553.0	−875.0 (−16.1%)
Total	91.3	77.4	−13.9 (15.2%)	91	91	0 (0%)	1363.6	1134.1	−229.5 (−16.8%)

Table 2
The glacier changes in Tien Shan.

Area	Location	Periods	Glacier changes (%)	Rate of glacier changes (% a^{-1})	Document source
Zailiyskiy and Kungey Alatau	Northern Tien Shan	1955–1999	−32.6	−0.74	Bolch (2007)
Pskem region	Central Tien Shan	1970–2000	−19.0	−0.63	Narama et al. (2010)
Ili-Kungoy Region			−12.0	−0.40	
At-Bashy region			−12.0	−0.40	
SE-Fergana region			−9.0	−0.30	
Big Naryn basin		1950–2007	−23.4	−0.43	Hagg et al.(2012)
Ala Archa		1963–2003	−15.8	−0.40	Aizen et al. (2007)
Southern slope of Kalik Mountain	Eastern Tien Shan	1972–2005	−12.3	−0.37	Wang et al. (2011)
Jinghe River Basin	Eastern Tien Shan	1964–2004	−15.2	−0.38	This Study

cap, respectively (Bahr et al., 1997; Liu et al., 2003). However, this formula is limited by the determination of the empirical constant c. Bahr et al. (1997) improved this formula by eliminating c. Thus, the estimation of ice volume depends only on relative area change: $(1 + p_v) = (1 + p_s)^{\gamma}$, Where p_v is the estimated change in volume, and p_s is the change in area. Thus, based on the change in area of Jinghe River basin glaciers (15.2%), ice volume loss is estimated to be 21.2% over the 40 years from 1964 to 2004. The ice volume in the Jinghe River basin is 5.50 km^3. Therefore, the ice volume of the Jinghe River basin has decreased 1.17 km^3, which is approximately 10.7×10^8 m^3 water equivalent (assuming an ice density of 900 kg m^{-3}) during the period 1964–2004. In other words, water resources in the Jinghe River basin increased by approximately 10.7×10^8 m^3 as a result of the loss of ice volume during the period studied.

4.5. Recent glacier shrinkage related to local climate changes

A glacier system is influenced by many factors such as climatic, topographic and glacier supplying conditions (Rachlewicz et al., 2007; Racoviteanu et al., 2008). Among all the contributing factors to the glacier area variation, climatic may be the most important factor (Wang et al., 2009; Wu and Zhu, 2008). In this study, five meteorological stations were chosen near the Jinghe basin: Jinghe, Alashankou, Bole, Wenquan, and Wusu (Table 3).

During the last decades a significant increase in the air temperature has been detected in the Jinghe River basin (Fig. 5). The annual air temperatures, according to the records of 5 meteorological stations, show a positive trend of increase during 1951 to 2004, particularly after 1995 (Fig. 5). The rate of the temperature increase was 0.32 °C per decade, which means the temperature increased by 1.28 °C during the past 40 years. The trend is similar with that found in the Xinjiang Uygur Autonomous Region (0.33 °C per decade), and significantly higher than that throughout China (0.22 °C per decade) (Liu et al., 2009). In a larger spatial scope, the air temperature in this area is generally in phase with other locations throughout Tien Shan. According to the IPCC Fourth Assessment Report AR4 (IPCC, 2001), observed temperature changes in Central Asia reveal decadal trend coefficients between +0.1 and +0.2 °C. Air temperatures in the melting season (June to August) have increased only slightly, but a significant temperature increase has been detected for the month of September throughout Central Asia (Bolch and Marchenko, 2009), thus resulting in a prolonged melting season for Tien Shan glaciers (Aizen et al., 1997).

Table 3
Meteorological stations used in this study.

District station number	Meteorological station	Longitude (E)	Latitude (N)	Elevation /m
51334	Jinghe	82°54′	44°37′	320.1
51232	Alashankou	82°35′	45°11′	284.8
51238	Bole	82°04′	44°54′	531.9
51330	Wenquan	81°01′	44°58′	1354.6
51346	Wusu	84°40′	44°26′	478.8

The variation of the annual average precipitation can be divided into two periods: 1959–1980, and 1981–2004. For 1959–1980, the precipitation decreased at a rate of 13.6 mm per decade, and for 1981–2004 the precipitation increased at a rate of 11.1 mm per decade. Thus, annual precipitation has continually increased since 1980. The precipitation increase has provided good conditions for glacier accumulation. However, the temperature increase caused an increase in liquid precipitation instead of solid precipitation in the high-altitude glacierized area for the glaciers with accumulation, especially with summer accumulation, leading to reduced accumulation and accelerated ablation. Also, previous studies have indicated that precipitation only has an obvious effect on glaciers on short time scales (less than 10 years) and small spatial scales in the Tien Shan (Gao and Tang, 2000). The increasing amount of precipitation could not compensate for the glacier mass loss due to the temperature increase in the Jinghe River basin. This suggests that

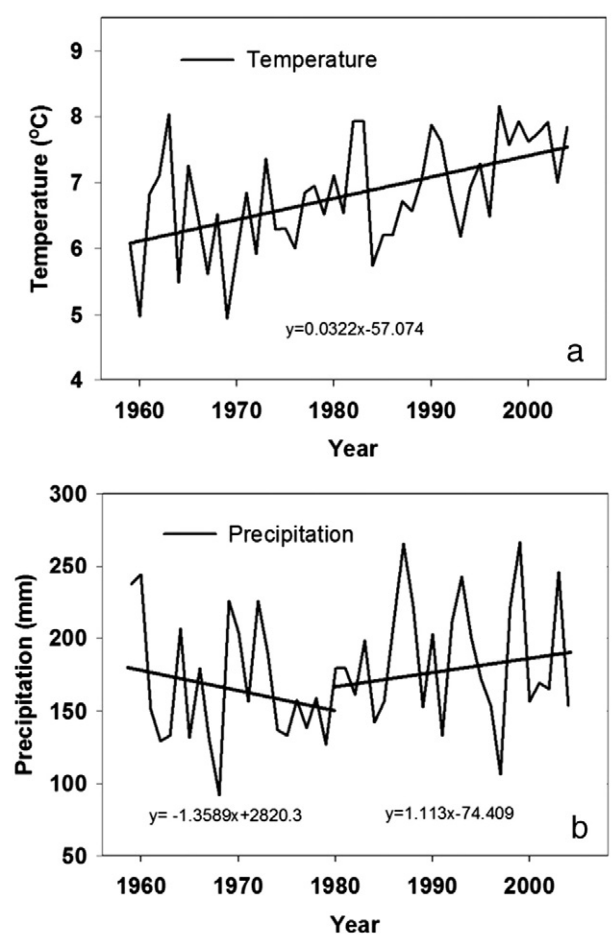

Fig. 5. Variation of annual average temperature (a) and annual average precipitation (b) in the five meteorological stations during 1959–2004.

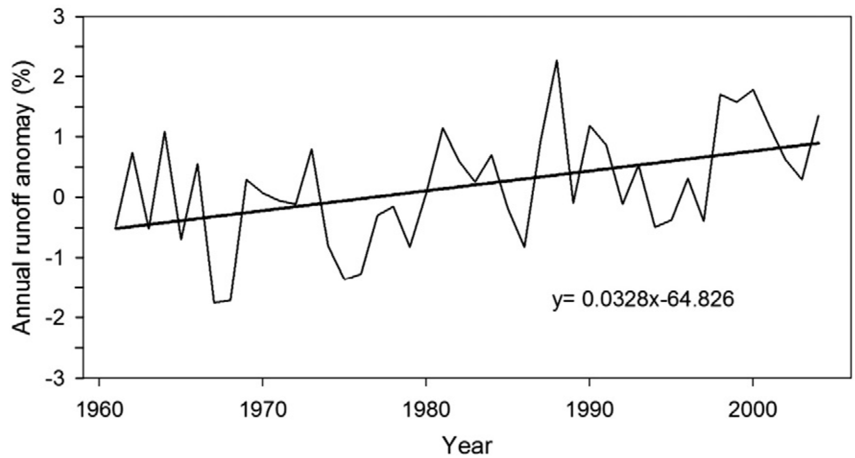

Fig. 6. Annual runoff records at Jinghe hydrologic station during 1964–2003.

the temperature warming is the main reason for the glacier melting on Jinghe River basin during the past four decades.

According to the IPCC scenarios for the lower and higher bounds of greenhouse-gas emission trajectories, future winter precipitation in Central Asia is likely to increase by 4 to 8% by 2050 (Cruz et al., 2007). Both summer and winter air temperatures are expected to increase further through to the 2050s (+3.1 to +4.4 °C and +2.6 to +3.9 °C, respectively) and beyond. So, glacier shrinkage is likely to continue with the temperature increase expected in coming decades (Cruz et al., 2007).

4.6. Effect on regional water resources

Glaciers play a crucial role in Central Asia's hydrological cycle. It has been demonstrated that even a basin whose glacier fraction is less than 5% can provide a significant contribution from ice melt to summer runoff, when water is most needed for irrigation. The continued glacier shrinkage that can be expected in a warming climate has therefore raised concerns about the future role of Tien Shan glaciers as a source of freshwater. An estimated 20.6% of runoff in Jinghe River basin originates from glaciers (Liu and Ding, 1986), but this glacial contribution can even be 1.5 to 3 times larger during the melting season. The mean runoff at the Jinghe hydro-meteorological station was 4.75×10^8 m^3 a^{-1} during 1961–2004. Fig. 6 presents annual runoff at the stations from 1961 to 2004. It can be seen that there has been a general increase in glacier runoff in the river basin. Accurate estimation of changes in future runoff is difficult and needs more detailed observation parameters and use of hydrological models. Undoubtedly, continuous warming perturbations have resulted in glacier wastage. Currently, glaciers less than 1.0 km^2 in area are rapidly melting, adding to the flow of downstream rivers. On the other hand, meltwater from individual small glaciers has lessened as their areal extent has decreased, and as a result becomes more sensitive to future climate warming. Climate modeling by Hagg et al. (2007) investigated the impact of a doubling of CO_2 on Tien Shan glaciers. The study suggests a 50% decrease in glaciation in Tien Shan, increasing the risks of flood in summer and turning into a runoff deficiency after a higher degree of deglaciation is reached. Glaciers larger than 1 km^2 are the main supplier of glacier runoff, but the regulation effect of such glaciers to river runoff is weakening. If climate warming causes ice loss to continue at rates like those reported in the present study, downstream water sources will also deplete. This could endanger local economic development and people's safety.

5. Conclusion

Glaciers are among the most distinctive natural objects for studying changes from space related to climate. By using ASTER image and topographic maps of 1:50 000. We have determined that glacial recession has occurred in the Jinghe River basin over the past 40 years. Compared to 1964 the 2004, the glacier area in the basin has shrunk by approximately 15%.The rate of glacier retreat in the Jinghe River basin is similar to the glaciers in the eastern and central Tien Shan but slower than the glaciers in the Northern Tien Shan. The maximum area loss occurred in the 1.0–5.0 km^2 size class, which decreased in total area from 50.9 to 36.6 km^2, or 28.1%. The mean length change of all analyzed glaciers between 1964 and 2004 was −229.5 m (−5.7 m yr^{-1}). The ice volume of the Jinghe River basin has decreased 1.17 km^3, which is approximately 10.7×10^8 m^3 water equivalent during the period 1964–2004. The mean annual temperatures in the Jinghe River basin have been increasing by 0.32 °C per decade; climate time series show that increasing temperatures in the basin were responsible for the reduction in glacier area between 1964 and 2004. The glacier shrinkage is likely to continue with the temperature increase expected in coming decades. During this period the basin has experienced a general increase in glacier runoff. If the current rate of ice loss continues downstream water resources will be impacted.

Acknowledgments

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