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Glacier changes in the Sikeshu River basin, Tienshan Mountains

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ABSTRACT

Glaciers are widely recognized as sensitive indicators for regional climate change. This study reports changes of glaciers in the Sikeshu River basin, Tienshan Mountains, northwest China, between 1964 and 2004. Analysis of satellite images showed that the glaciated area decreased by about 15.4% (0.38% y^{-1}) from 114.6 to 96.9 km^2. The average glacier front retreat amounts to 195.3 m (4.9 m y^{-1}) during the last four decades. Data from the Jilede hydro-meteorological station in the Sikeshu River basin showed increases in both the annual mean air temperature and annual precipitation during 1964–2004. This indicates that the glacier shrinkage in the Sikeshu River basin over the last 40 years was largely due to regional climate warming that enhanced glacier ablation and overcompensated for the effects of increased precipitation on the glacier mass balance. Glaciers smaller than 0.5 km^2 in area experienced the strongest retreat, whereas glaciers larger than 2 km^2 in area experienced gentle recession but may be the main contributors in the future to river runoff. Glacial shrinkage in the Sikeshu River basin is likely to continue with the temperature increase expected in coming decades.

1. Introduction

Changes in mountain glaciers are a natural indicator of climate change (Oerlemans, 1994, 2005). Moreover, glacier runoff is the major contributor to water resources that are used to support the sustainable development of the environment, industry and agriculture in arid regions of northwest China (Yao et al., 2004). Glacier change also leads to glacial hazards such as glacial lake outburst flooding in some regions (Narama et al., 2010a,b; Bolch et al., 2011). However, owing to the remote location and dispersed distribution of glaciers, there has been little glacier monitoring in northwest China. Thus, there is a very limited dataset derived from continual glacier observation, and application of other techniques is desirable. Satellite data is used for regional detection and analysis of glaciers and glacier changes (Paul et al., 2002; Khalsa et al., 2004).

Mean annual air temperatures rose dramatically in the 20th century (IPCC, 2001). This has caused increasing glacier retreat in many parts of the world (Haeberli and Beniston, 1998). Glacier area is estimated to have decreased by 25–35% in the Tienshan Mountains (Narama et al., 2006; Bolch, 2007; Kutuzov and Shahgedanova, 2009), and by 30–35% in the Pamirs (Yablokov, 2006) during the 20th century. In Altai, the glacier area has decreased by 9–27% since 1952 (Narozhniy and Zemtsov, 2011).

Atmospheric warming in northwest China has been found to be stronger than in other areas, with summer warming particularly severe since the mid 1980s (Shi et al., 2007). In China, the glacier area loss since the 1960s is estimated to about 14.3%, and is more pronounced in the Chinese Himalaya, Qilian Mountains and Tienshan Mountains, but with small recessions in the hinterland of the Tibetan Plateau (Li et al., 2006; Yao et al., 2012). Glacier shrinkage in the Tienshan Mountains is likely to continue with the temperature increase expected in the coming decades (Sorg et al., 2012). Initial results provided valuable information on glacier change in the Tienshan Mountains. However, most of the studies have been conducted in the western and central Tienshan Mountains, with few in the eastern region (Narama et al., 2010a,b; Hagg et al., 2012a). This paper reports on the current state of glaciers and on potential problems related to the observed glacier shrinkage during 1964–2004 in the Sikeshu River basin. In addition, we analyze hydrometeorological time series and try to connect glacier behavior with regional climate variations.

2. Study area

The Sikeshu River basin (43°53′–44°58′ N, 83°37′–84°30′ E) is located on the north slope of the Tienshan Mountains, southwest of the Junggar basin (Fig. 1). The Sikeshu River has a total length of 137 km and a catchment area of about 6669 km^2, with about 5% glacierization (Shang, 2011). It is one of the primary glacier regions

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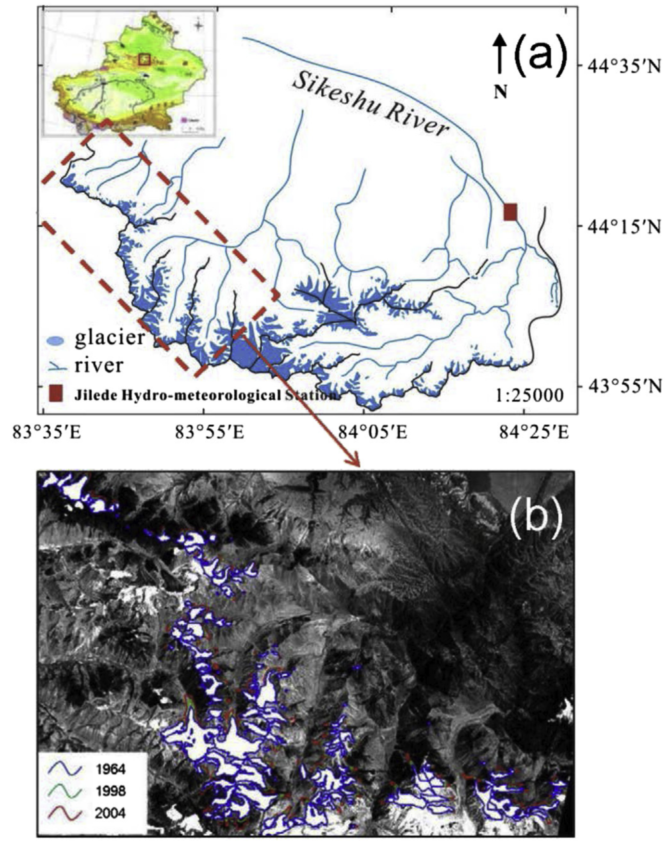

Fig. 1. Location of Shikeshu River basin. (a) the location of the study region,(b) An example of glacier delineation on the ASTER image.

in the source region of Ebinur Lake Basin, and is the main fresh water source for the cities of Usu and Kuytun, population of 0.22, and 0.31 million, respectively (NPCC, 2010). According to the Chinese Glacier Inventory (CGI), which was accomplished in 2002 (Shi, 2008), there were 364 glaciers within the entire Sikeshu River basin. These glaciers had a total estimated area of 336.25 km^2, with a mean glacier area of 0.92 km^2 in 1964 (Liu and Ding, 1986).

Climatically, the Tienshan Mountains are characterized by interactions between the Westerlies and the Siberian High over complex mountain topography (Aizen et al., 1995). The precipitation is mainly from the moisture carried by the westerlies in summer, and the winter temperature is controlled by the Siberian High (Aizen et al., 1995). The dominant weather patterns are orographic thunderstorms in summer and cold-dry anticyclones in winter. Precipitation varies horizontally (west-east gradient) between 400 and 600 mm at altitudes of 1500–2700 m a.s.l. The glaciers in this region are the summer accumulation type. Typically, 70% of the precipitation occurs between May and September (Shang, 2011).

Glacier runoff discharge and meteorological data were measured at the Jilede hydro-meteorological station (44°22′N, 84°25′E, 1050 m a.s.l., catchment area 921 km^2). This station was established in 1954 at the lower basin of the Sikeshu River (Fig. 1). The observations were carried out from May to September each year, where the observed water level records are converted to discharges based on rating curves. Over 95% of the annual runoff at the stations occurs during the observation period, whereas for the rest of the year, the streams are mostly frozen. At this station, the mean annual, summer (June to August), and winter (December to February) of precipitation and air temperature are 262.2, 120.0, and 19.7 mm, and 8, 22.5, −11.3 °C, respectively, during 1954–2006 (Tang, 2009; Ge and Zhu, 2010; Shang, 2011). The summer zero degree isothermal line is situated between 3700 and 4100 m a.s.l.(Liu and Ding, 1986). The equilibrium line altitude is situated around 3710 m a.s.l. (Liu and Ding, 1986).

3. Data and methods

To compare recent changes in glacier area, Landsat 5, ASTER images and historical topographic maps were used in this study (Table 1). One Landsat 5 image (1998) with a ground resolution of 30 m was downloaded from the USGS (United States Geological Survey) web server (Table 1). Two ASTER images with a ground resolution of 15 m were taken on August 25th 2004. These images cover the most heavily glaciated part of the investigated area. Seasonal snow, shadow, and clouds may be identified as glacier pixels, resulting in overestimation (Nakano et al., 2013). The debris cover may be identified as rocks, resulting in underestimation in these regions. Excellent images ensure clear glacier boundaries, minimizing uncertainty. For this study, image selection for glacier mapping was guided by acquisition at the end of the ablation period, cloud-free conditions, and lack of snow fields adjacent to glaciers. 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). A total of 8 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 the Sikeshu 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 by combine the advantages of multispectral remote sensing (mapping of clean ice and vegetation free regions) with a DEM, which was derived from shuttle radar topographic mission (SRTM) (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. Clearly distinguishable terrain features that could be identified on each image were selected from the topographic maps. On average, 30–50 ground control points were collected for each pair of images to obtain satisfactory root-mean-square error (RMSE) values (10 m). All images and maps were presented in a Universal Transverse Mercator (UTM) coordinate system referenced to the 1984 World Geodetic System (WGS84).

Table 1
Data sources used in this study.

Source	Satellite ID	Date	Resolution or scale	Cloud cover
Topographic map	–	1964	1:50000	–
Landsat 5	LT51450291998245BIK00	02/09/1998	30 m	0%
ASTER	AST-L1A.04082505251004090500 81	25/08/2004	15 m	0%
ASTER	AST-L1A 0.040825052519040905008 2	25/08/2004	15 m	0%

The glacier outlines for 1964, 1998 and 2004, from the topographic maps and satellite images were used in this study, respectively. The outlines were mapped manually with the DEM using commercial GIS software (ArcView), as well as using the topographic maps and satellite images. ArcView is a useful tool for extracting detailed information from satellite imagery of glaciers