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Glacier shrinkage in the Chinese Tien Shan Mountains from 1959/1972 to 2010/2012

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A B S T R A C T

This paper employs remote sensing methods to address a large number of glaciers and their change in the Chinese Tien Shan Mountains for the period from 1959/1972 to 2010/2012. Our results show that the total area of the 1428 glaciers studied decreased from $1299 \pm 4 \text{ km}^2$ in 1959/1972 to $1013 \pm 4 \text{ km}^2$ in 2010/2012. This 22% reduction in glacier surface area represents a total loss of 287 km^2 . The rate of glacier shrinkage throughout the nine regions varied from $0.3\% \text{ a}^{-1}$ to $0.8\% \text{ a}^{-1}$, and approximate individual glacier area loss varied from $0.002 \text{ km}^2 \text{ a}^{-1}$ to $0.008 \text{ km}^2 \text{ a}^{-1}$. The greatest decrease in glacier extent occurred in the Ili River valley, followed by the Toutun River valley and Urumqi River valley. In contrast, relatively minor decreases occurred in the Miaoergou Gully and Aksu River valley regions.

INTRODUCTION

Global warming has triggered a large-scale retreat of glaciers throughout the world (Haeberli, 2005; Sorg et al., 2012; IPCC, 2013; Nuimura et al., 2015; Guo et al., 2015). This has resulted in most glaciers in mountainous regions receding substantially during the past century, and it has affected stream runoff (Hall et al., 2001; Bolch, 2007). Previous studies have shown that the indicative role of glacier change in global climate change in this century has been more obvious (Shi and Liu, 2000; IPCC, 2013). Qin et al (2006) reported that modern glacier change has an important effect on water resources in the Tien Shan Mountains. In China, glaciers are predicted to lose 27.20% of their total area during the first half of the 21st century (Qin et al., 2006). This is important because alpine glaciers constitute vast solid reservoirs, serving to regulate annual runoff and providing water for sustaining ecology, industry, and agriculture in the Chinese Tien Shan (Yao et al., 2004; Shangguan et al., 2009). Moreover, because the headwaters of numerous rivers in Xinjiang lie within the Chinese Tien Shan, alpine glaciers play a fundamental role in regional development. Thus, advancing

our understanding of modern glacier change in the Chinese Tien Shan is a matter of growing importance.

Interest in monitoring glacier change in the Tien Shan has grown as evidence of rapid glacier recession in many regions of the world has been reported (Aizen et al., 2006; Niederer et al., 2007; Narama et al., 2009). However, although glacier variability was reported by the first comprehensive field survey in 1958 (Ren, 1988), long-term observations have been limited. Remote sensing (RS) provides an effective means to address this shortcoming by assessing the spatial distribution of glaciers, particularly in remote areas (Frezzotti et al., 1998; Raup et al., 2001; Bishop, 2004). Glacier monitoring involves primarily the detection of spatial variations and mass or thickness changes (Josberger et al., 1993; Bayer et al., 1994). Moreover, multitemporal and multispectral satellite data enable simultaneous monitoring of large areas of remote mountainous terrain via automated glacier mapping (Paul et al., 2002; Kargel, 2005; Pieczonka and Bolch, 2015; Earl and Gardner, 2016). Thus, with the development of Geographic Information System (GIS) and RS technology, long-term observation of glacier variability has become practicable.

Previous work on glacial change in the Chinese Tien Shan has focused on the Tarim and Junggar drainages, and has revealed significant regional variability in glacier sensitivity to climate warming (Wang et al., 2008; Shangguan et al., 2009). To our knowledge, however, there has been no systematic assessment of glacier variability using GIS and RS. In the present study, we present more than 50 years of glacier-change data from the Chinese Tien Shan derived from topographic maps and RS. The aims of this study are to (1) analyze glacier variability between the periods 1959/1972 and 2010/2012; (2) examine spatial variability and regional differences in glacier evolution; and (3) discuss potential climatic drivers of glacial change in the Chinese Tien Shan.

STUDY AREA

The Tien Shan Mountains of Central Asia run through China, Kirghizstan, and Kazakhstan and contain 15,953 glaciers with a combined area of 15,416 km². Of these, 9081 glaciers are located in China, with a total area of 9235.96 km² and a volume of 1011.748 km³, according to the first Glacier Inventory of China (GIC 1st; Shi et al., 2009). The main factors determining the climatic regimes of the Tien Shan Mountains are three dynamical elements: the Siberian anticyclonic circulation, the westerly jet stream in the upper troposphere, and the cyclonic disturbances of the west wind circulation (Aizen et al., 2001; Bothe et al., 2012).

The computation of glacier variability for the entire Chinese Tien Shan presents considerable difficulty owing to the large number of glaciers and the poor repre-

sentation of certain glaciers because of snow and cloud cover or errors in the original topographic maps. In this study, we investigated 1428 glaciers with a combined area of 1299.32 km² (Table 1). Our selection was based on existing studies and is broadly representative of the Chinese Tien Shan, comprising both small and large glacier systems, debris-covered and debris-free glaciers, and high- and low-elevation regions (Narama et al., 2009). Selected glaciers were subdivided into nine groups: Ili River, Aksu River, Kuytun River, Manas River, Kaidu River, Toutun River, Urumqi River, Bogeda Range, and Miaoergou Gully. We discuss each group below (Fig. 1).

DATA AND METHODS

Data Acquisition

RS data used in this study are shown in Table 2. The main sources were Landsat TM/ETM+ scenes, which were available from the U.S. Geological Survey (USGS; <http://glovis.usgs.gov/>) and were orthorectified automatically by the USGS using the Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEMs).

The topographic maps used were acquired from 1959 to 1972 at the scale of 1:50,000 or 1:100,000 in different regions. The errors assessments of the topographic maps were reported as 3–5 m over flat and hilly areas and vary regionally by 8–14 m (State Bureau of Surveying and Mapping, 2007). Glacier elevation data are provided by a 90-m-resolution SRTM DEM (fourth version), which is jointly measured by the U.S. National Aeronautics and Space Administration (NASA) and the

TABLE 1
Summary of glaciers in the nine regions of the Chinese Tien Shan.

| Study area | Period | Selected glaciers* | |
|-----------------|------------------------|--------------------|--------------------------|
| | | Number | Areas (km ²) |
| Ili River | 1959/1964 to 2011 | 113 | 54.80 |
| Aksu River | 1972–2011 | 113 | 435.44 |
| Kuytun River | 1964–2011 | 144 | 94.27 |
| Manas River | 1964–2011 | 131 | 76.20 |
| Kaidu River | 1963/1964 to 2011 | 293 | 265.81 |
| Toutun River | 1964–2012 | 167 | 50.67 |
| Urumqi River | 1964–2012 | 121 | 39.84 |
| Bogeda Range | 1962–2010 | 205 | 151.73 |
| Miaoergou Gully | 1972–2010 | 141 | 130.56 |
| Total | 1959/1972 to 2010/2012 | 1428 | 1299.32 |

*The number and areas of the selected glaciers are according to the first Glacier Inventory of China (GIC 1st) (Shi et al., 2009).

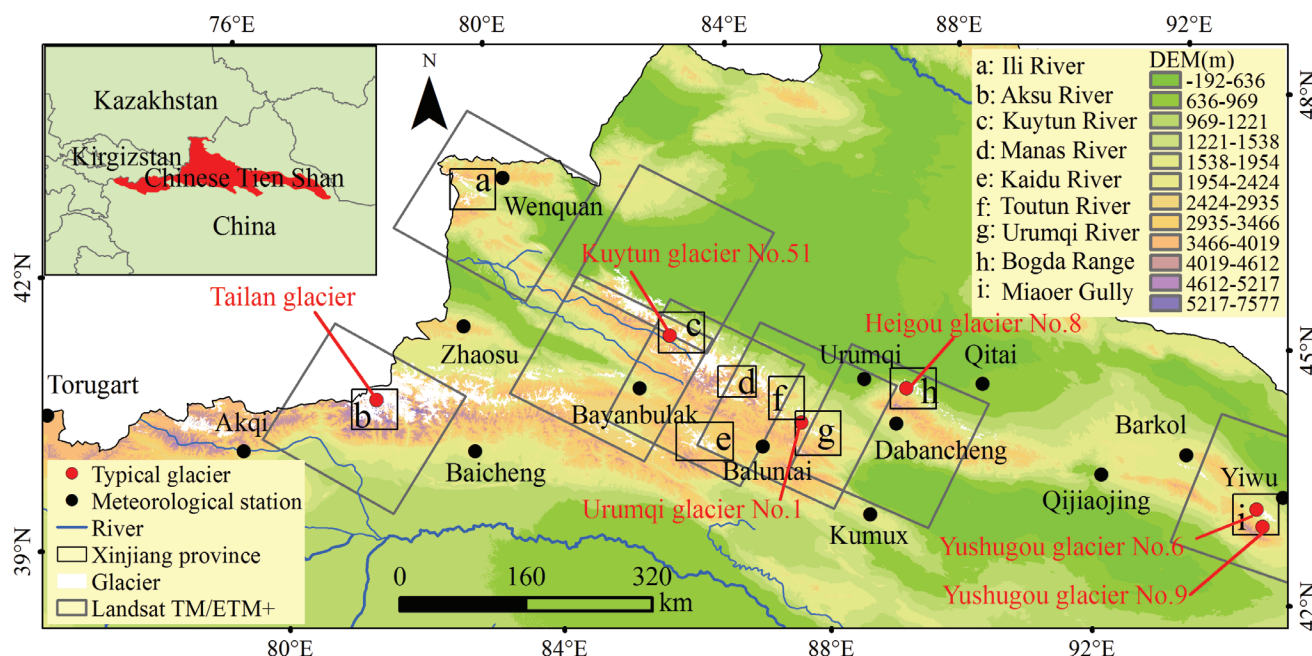


FIGURE 1. Sketch map showing the study area and the distribution of glaciers.

U.S. Department of Defense National Mapping Agency (NIMA). The SRTM in the region was also used for visual examination of glacier boundaries. The nominal vertical accuracy of SRTM is 6 m relatively and 16 m absolutely, whereas the nominal horizontal accuracy is 15 m relatively and 20 m absolutely (Rabus et al., 2003).

We used the GIC 1st as a reference to assist identification of glacier boundaries in the Chinese Tien Shan. These data were provided by the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences (CAS).

Temperature and precipitation data are provided by China Meteorological Data Sharing Service System, which is administered by National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA). According to the geophysical boundary of Chinese Tien Shan Mountains (Hu, 2004), 14 meteorological stations were chosen in this study: Wenquan, Qitai, Zhaosu, Urumqi, Baluntai, Dabancheng, Qijiaoqing, Kumux, Bayanbulak, Baicheng, Torugart, Akqi, Barkol, and Yiwu (Fig. 1). Annual temperature and precipitation data recorded by each station

TABLE 2
Remote sensing data used in this study.

| Date* | Landsat TM/ETM+ | Resolution (m) | Path/Row | Utilization |
|------------|-----------------|----------------|---------------------|-----------------|
| 2011-09-11 | TM | 30 | 148-029 | Ili River |
| 2011-09-10 | ETM+ | 30 | 147-031 | Aksu River |
| 2011-09-06 | TM | 30 | 145-029, 145-030 | Kuytun River |
| 2011-07-13 | TM | 30 | 144-030 | Manas River |
| 2011-07-13 | TM | 30 | 144-030 | Kaidu River |
| 2012-08-17 | ETM+ | 30 | 143-030 | Toutun river |
| 2012-08-17 | ETM+ | 30 | 143-030 | Urumqi river |
| 2010-08-13 | ETM+ | 30 | 142-030 | Bogeda Range |
| 2010-08-13 | ETM+ | 30 | 138-030 | Miaoergou Gully |

*Dates recorded as yyyy-mm-dd.

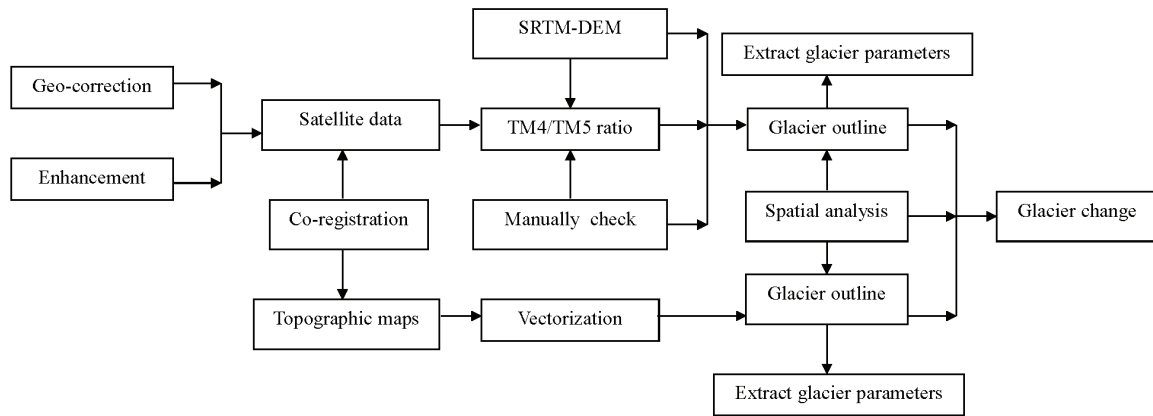


FIGURE 2. Technical flowchart of glacier outline extraction.

were incorporated for the period 1960–2012. Additionally, several typical glaciers were chosen for a detailed discussion of change in glacier area and length (Fig. 1).

Methods

Geocorrection and coregistration were established in ENVI 5.0 for all images. Topographic maps were scanned into digitized products at a resolution of 600 dpi and georegistered using the Beijing 1954 geodetic coordinate system. Fifteen ground control points that could be identified on each image were selected from topographic maps. All images, topographic maps, and RTK-GPS data were reprojected in a Universal Transverse Mercator (UTM) coordinate system referenced to the World Geodetic System of 1984 (WGS84), based on a seven-parameter transformation model.

The glacier outlines of the period 1959/1972 were interpreted by ArcGIS 10 from topographic maps. For the period 2010/2012, we generated preliminary glacier boundaries automatically using the band ratio method, which is most appropriate for glacier mapping in larger study areas (Paul and Svoboda, 2010). Specifically, we applied the band ratio approach using the TM4/TM5 combined manual interpretation to produce glacier outlines (Bayer et al., 1994; Jacobs et al., 1997; Bolch, 2007). For non-debris-covered glaciers, identification of snow, ice, and rock on satellite images is possible because of substantial differences in spectral reflectance. We checked glacier polygons derived from the ratio method visually for gross errors, and manually improved them where necessary. The technical method overview is shown in Figure 2. Some glaciers are covered to varying degrees by supraglacial debris, which has the same spectral characteristics as the surrounding terrain and thus cannot be discerned from it spectrally. Consequently, mapping of debris-covered

glaciers required a combination of manual delineation and the band ratio method. Debris outlines were then verified by real-time kinematic GPS (RTK-GPS; Unis-trong E650) surveys conducted in July 2013. To estimate changes in glacier extent over time, we incorporated the topographic-map-derived and Landsat-derived glacier boundaries in ArcGIS for overlay analysis.

Uncertainty in the interpretation of remote sensed images arises from the image resolution and coregistration errors. We evaluated this error in two ways. First, we assessed image resolution and coregistration errors. Accuracy of measurements is affected by the spatial resolution of the RS image and the Root Mean Square Error (RMSE) of coregistration. The uncertainty (un) of each position can be calculated as follows (Hall et al., 2003; Silverio and Jaquet, 2005; Shangguan et al., 2009):

$$un = \sqrt{\sum_{i=1}^n \lambda^2} + \sqrt{\sum_{i=1}^n \epsilon^2}, \quad (1)$$

where λ is the image resolution (30 m for TM or ETM+) and ϵ is the registration error of each image to the topographic map. The mean uncertainty of glacier terminus derived from 10 images can then be calculated by:

$$un' = \sum_{i=1}^{10} un_i / 9. \quad (2)$$

Therefore, the mean uncertainty for all glacier terminuses is 44.2 m. Uncertainty in the measurement of individual glacier area is calculated as follows (Hall et al., 2003):

$$a = A * (2 * un'' / \lambda), \quad (3)$$

where a is the uncertainty of glacier area and $A = \lambda^2$. Thus, uncertainty of glacier-change area measurements are calculated with an accuracy of $\pm 0.003 \text{ km}^2$ using TM or ETM+ imagery. Second, the greatest difficulty in using automatic classification for map glacier outlines is the presence of supraglacial debris. In order to delineate debris-covered glaciers, corrections must be based on visual interpretation and field data. As the Qingbingtan glacier No. 72 and Tomur glacier were surveyed as representative glaciers for debris-covered glaciers in Aksu River (Wang, et al., 2013), the field surveying data were referenced for delineating debris-covered glaciers.

For the glacier area error, it is mostly inversely proportional to the length of the glacier margin (Pfeffer et al., 2014). We estimated the uncertainty by the buffer method suggested by Guo et al. (2015). The average uncertainty of the mapped glacier area was 6% for 1959/1972 (topographical maps) and 4% for 2010/2012 (satellite images).

RESULTS

Glacier Area Changes

According to vector data statistics, the total number of selected glaciers in the Chinese Tien Shan has decreased from 1428 in 1959/1972 to 1344 in 2010/2012. However, in the Aksu River and Kaidu River regions, some larger glaciers have divided into several smaller glaciers, thereby increasing the total number of glaciers counted (Fig. 3, parts b and e). Consequently, the change in glacier number does not reflect accurately the overall glacier shrinkage situation. In the Urumqi River and Toutun River regions (Fig. 3, parts f and g), where mean glacier area was relatively small in the period 1959/1972, many small glaciers have since disappeared. Over the same period, the total area of the 1428 glaciers decreased from $1299.3 \pm 4.3 \text{ km}^2$ to $1012.5 \pm 4 \text{ km}^2$, which means an area reduction of 286.8 km^2 , or 22.1% (Fig. 3). Among the nine regions, total area loss ranged from $15.7 \pm 0.4 \text{ km}^2$ (Urumqi River) to $64.1 \pm 0.9 \text{ km}^2$ (Kaidu River), with values of $22.8 \pm 0.3 \text{ km}^2$ for the Ili River, $50.1 \pm 0.3 \text{ km}^2$ for the Aksu River, $26.7 \pm 0.4 \text{ km}^2$ for the Kuytun River, $23.1 \pm 0.4 \text{ km}^2$ for the Manas River, $20.4 \pm 0.5 \text{ km}^2$ for the Toutun River, $43.5 \pm 0.6 \text{ km}^2$ for the Bogeda Range, and $20.5 \pm 0.4 \text{ km}^2$ for the Miaoergou Gully region. Rates of area reduction varied among the nine regions from $0.3\% \text{ a}^{-1}$ to $0.8\% \text{ a}^{-1}$.

Figure 4 shows that the greatest decreases in glacier area occurred in the Ili River (42%), followed by the Toutun River (40%), and Urumqi River (39%). Smaller decreases occurred in the Miaoergou Gully (16%) and Aksu River (12%). Mean glacier area shrank from 0.91

km^2 in the period 1959/1972 to 0.75 km^2 in 2010/2012. Among the nine study regions, the Toutun River and Urumqi River regions exhibit similar values (0.30 km^2 and 0.33 km^2 , respectively) for mean glacier size in 1964.

We selected six representative glaciers (Fig. 1) of the Chinese Tien Shan to perform a detailed analysis of glacier change (Table 3). Examples of the recession of three of these glaciers are given in Figure 5. Between 1962 and 2011, the glacier terminus of Heigou glacier No. 8 and Kuytun glacier No. 51 retreated 409 m and 159 m , respectively. Moreover, imagery from 2010 shows that terminus retreat of Heigou glacier No. 8 has resulted in the formation of a proglacial lake that was not present in 1962 (Fig. 5).

Although all six glaciers show negative trends in both area and length throughout the period of investigation (Table 3), rates of change are variable. For example, the rate of area shrinkage is significantly higher for Urumqi Glacier No. 1 than for the remaining five glaciers, whereas the Tailan Glacier underwent relatively low rates of shrinkage. Changes in glacier length show a similar pattern. Total area loss for the six glaciers ranged from 0.8% (Tailan Glacier) to 15.7% (Urumqi Glacier No. 1), whereas length changes ranged from -0.2% to -11.1% .

Glacier Variation in Different Altitude Ranges

We investigated the characteristics of glacier distribution in the study regions by analyzing statistically the elevation of glaciers from the two periods (Fig. 6). For the Aksu River region, the majority of glacier terminuses (70.8%) was located at elevations of $<3200 \text{ m}$ in 1972, and at elevations of $3200\text{--}3400 \text{ m}$ in 2011 (52.1%). This pattern suggests that the higher rate of glacier recession at lower elevations resulted in the increasing dominance of terminuses at higher elevations within each region. Moreover, in all nine regions the glaciers at lower elevations underwent more obvious change than those at higher elevations.

The equilibrium line altitude (ELA) separates the ablation area of a glacier from the accumulation area. The mean elevation of a glacier is probably the most glaciologically relevant elevation variable since it can be considered as a proxy of the ELA (Braithwaite and Raper, 2010). Figure 7 shows that the mean ELA of all these nine region glaciers displayed an ascended trend within a normal fluctuation range from 5 m (Toutun River) to 151 m (Kaidu River) between 1959/1972 and 2010/2012, indicating that the elevations of glacier ELAs rose in concert with changes in terminus elevations.

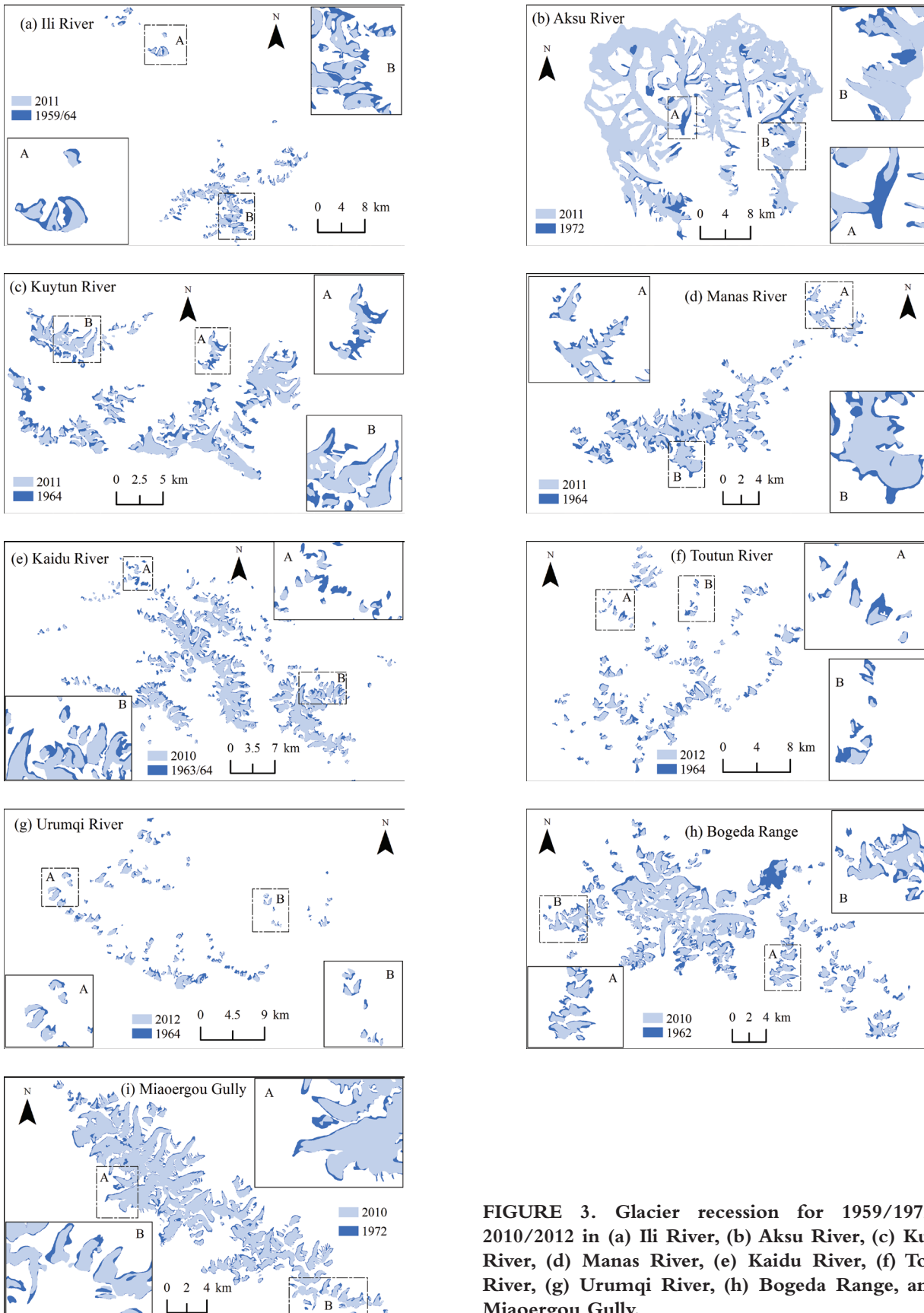


FIGURE 3. Glacier recession for 1959/1972 to 2010/2012 in (a) Ili River, (b) Aksu River, (c) Kuytun River, (d) Manas River, (e) Kaidu River, (f) Toutun River, (g) Urumqi River, (h) Bogeda Range, and (i) Miaoergou Gully.

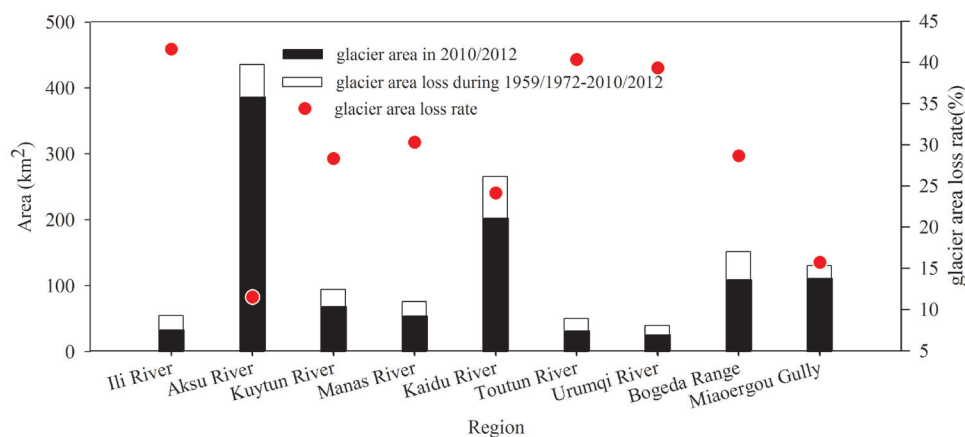


FIGURE 4. Glacier area change of each region for 1959/1972–2010/2012.

TABLE 3
Typical glacier areas and length changes.

| Glacier name | GIC number | 1959/1972 | | 2010/2012 | | Change rate | |
|------------------------|------------|-------------|-------------------------|-------------|-------------------------|-----------------------------|---------------------------|
| | | Length (km) | Area (km ²) | Length (km) | Area (km ²) | Length (% a ⁻¹) | Area (% a ⁻¹) |
| Urumqi glacier No. 1 | 5Y730C0029 | 2.2 | 2 | 2 | 1.7 | −0.2 | −0.3 |
| Tailan glacier | 5Y674B0028 | 21 | 257.5 | 20 | 255.5 | −0.1 | −0.02 |
| Kuytun glacier No. 51 | 5Y741C0051 | 1.4 | 1.5 | 1.3 | 1.3 | −0.2 | −0.3 |
| Yushugou glacier No. 6 | 5Y822B0006 | 4.3 | 4.3 | 3.9 | 3.8 | −0.2 | −0.3 |
| Yushugou glacier No. 9 | 5Y822B0009 | 4.2 | 3.5 | 3.9 | 3.1 | −0.2 | −0.3 |
| Heigou glacier No. 8 | 5Y813B0008 | 5.3 | 5.8 | 4.9 | 5.5 | −0.2 | −0.1 |

Glacier Changes and Size

As for the relative change of different glacier sizes (Jóhannesson et al., 1989), percentages of area reduction of small glaciers were usually higher than those of large glaciers. Taking into account the influence of the glacier size distribution, we observed a nonlinear relationship between initial glacier size and percentage area loss in the Urumqi River region. As shown in Figure 8, part a, the relative change of glaciers in Urumqi River increased with decreasing glacier size. For the 121 glaciers selected, variability in the percent area lost is higher for small glaciers, ranging from 0 to 100%, and lower for large glaciers (20–40%). For glaciers with areas of 0.1–0.5 km² and 1–2 km² (which account for 39.43% and 22.87% of the total glacier area, respectively), total glacier loss was relatively high, contributing ~38.13% and 51.72% of the total loss of glacier area, respectively. In contrast, the total area of smaller (<0.1 km²) glaciers increased by as much as 68.7% between 1964 and 2012 due to the fragmentation of larger ice bodies. These statistical results confirm the importance of initial glacier size in dictating

patterns of subsequent ice retreat. In this case, small glaciers with narrow altitudinal ranges lose a relatively higher percentage of their areas, suggesting that smaller glaciers are inherently more sensitive to climate forcing than larger glaciers.

To further examine relationships of glacier size and shrinkage rate, we focused on glaciers in the Urumqi River, Toutun River, Kuytun River, and Bogeda Range regions (Fig. 8, part b). For the Toutun River region, glaciers with areas of <0.1, 0.1–0.5, 0.5–1, 1–2, 2–5, and >5 km² underwent area changes of −38.7%, 30.8%, 64.3%, 47.9%, 0%, and 0%, respectively. In the Kuytun River region, respective area losses for each size class were −8.5%, 14.7%, 37.7%, 7.1%, 51.3%, and 25.9%. Meanwhile, both the Urumqi River and Bogeda Range regions experienced a significant increase in the total area of small (<0.1 km²) glaciers. Apparently, the increase in the total area of glaciers <0.1 km² is because of the fragmentation of larger glaciers over time. Specifically, although such glaciers comprise 4.1% of the total area of the Urumqi River region, 4.9% of the Toutun River region, 2.4% of the Kuytun River region, and 1.33% of Bogeda Range region, their total areas increased by

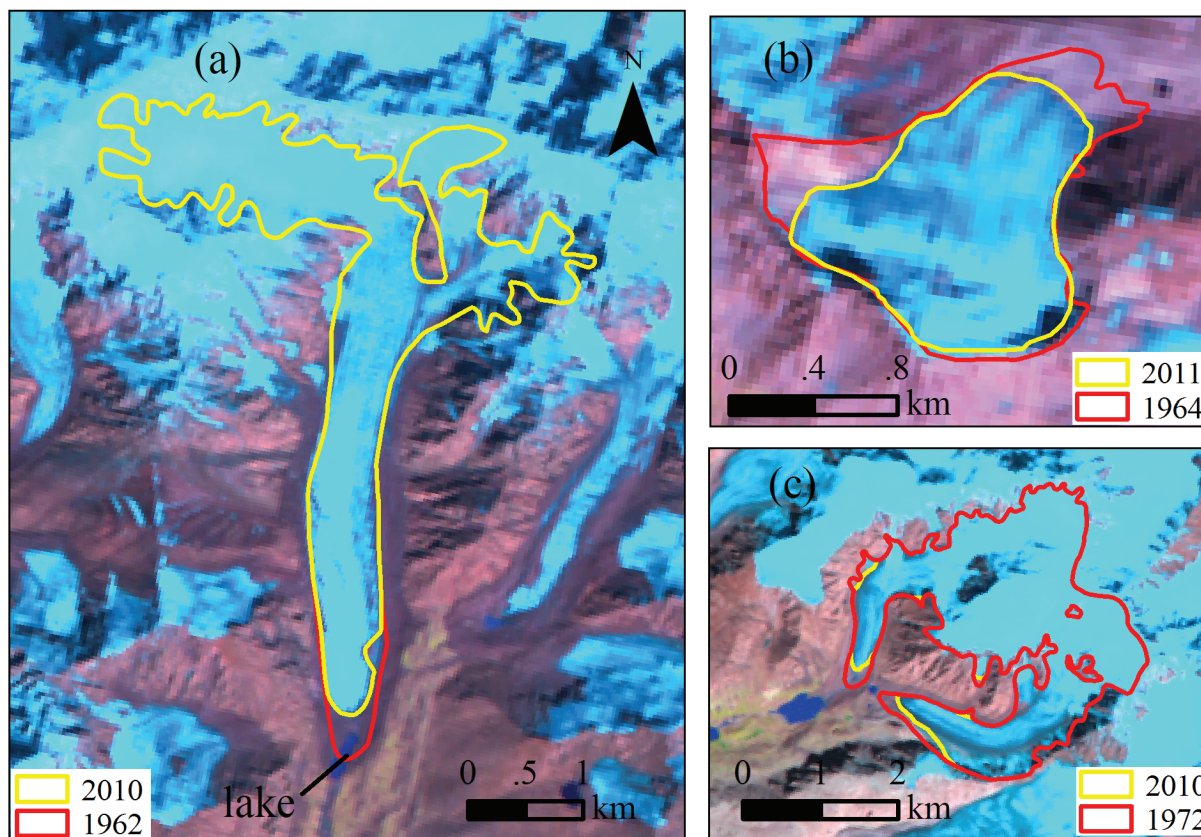


FIGURE 5. Change of (a) Heigou glacier No. 8 for 1962–2010; (b) Kuytun glacier No. 51 for 1964–2011; and (c) Yushugou glaciers No. 6 and No. 9 for 1972–2010.

68.7%, 38.7%, 8.5%, and 85.5% for each region, respectively. Thus, the relative abundance of glaciers in the different size classes strongly affects the percentage of total glacier area loss. In all classes of glacier size, recession was greatest (40.3%) in the Toutun River region, with its many small ($<1 \text{ km}^2$) glaciers, followed by the Urumqi River (39.3%). Indeed, all four regions show similar trends of glacier shrinkage within size classes of <0.1 , $0.1\text{--}0.5$, $2\text{--}5$, and $>5 \text{ km}^2$. Within the size classes $0.5\text{--}1$ and $1\text{--}2 \text{ km}^2$, there are obvious nonsynchronous changes between the Urumqi River region and the other three regions.

Glacier Fragmentation

The fragmentation of the glaciers is also an important index that reflects the shrinkage state. As shown in Table 4, considering all the fragments still should be as an initial single unit, and then we calculated the glacier number change. Actually, 82 glaciers had fragmented, the total number of selected glaciers changed from 1428 to 1246, and 182 glaciers have disappeared. It shows that the number change varied among the nine regions from 10 (Aksu River and Miaoergou Gully) to 32 (Kaidu River).

DISCUSSION

Regional Differences in Glacier Variation

Our analysis shows that rates of area loss among the nine study regions varied from $0.3\% \text{ a}^{-1}$ to $0.8\% \text{ a}^{-1}$ between the periods 1959/1972 and 2010/2012, and that each glacier lost between $\sim 0.002 \text{ km}^2 \text{ a}^{-1}$ and $\sim 0.008 \text{ km}^2 \text{ a}^{-1}$ in surface area. Furthermore, the mean area of individual glaciers among the 1428 glaciers declined from 0.91 km^2 to 0.75 km^2 , highlighting the general trend of glacier recession between 1959/1972 and 2007/2012.

Nonetheless, significant variability in glacier change exists among the different regions (Fig. 9). For example, whereas retreat rates have been relatively high in the Ili River ($0.83\% \text{ a}^{-1}$), Touyun River ($0.82\% \text{ a}^{-1}$), and Urumqi River ($0.8\% \text{ a}^{-1}$) regions, recession in the Aksu River, Miaoergou Gully, and Kaidu River regions has been comparatively minor, with glacier areas decreasing at rates of 0.29% , 0.4% , and $0.5\% \text{ a}^{-1}$, respectively. Similarly, the mean glacier area is 3.85 km^2 in the Aksu River region, but only $0.3\text{--}0.9 \text{ km}^2$ in the Toutun River and Urumqi River regions.

Much work has been done to investigate glacier variability in Tien Shan Mountains. Sorg et al. (2012) re-

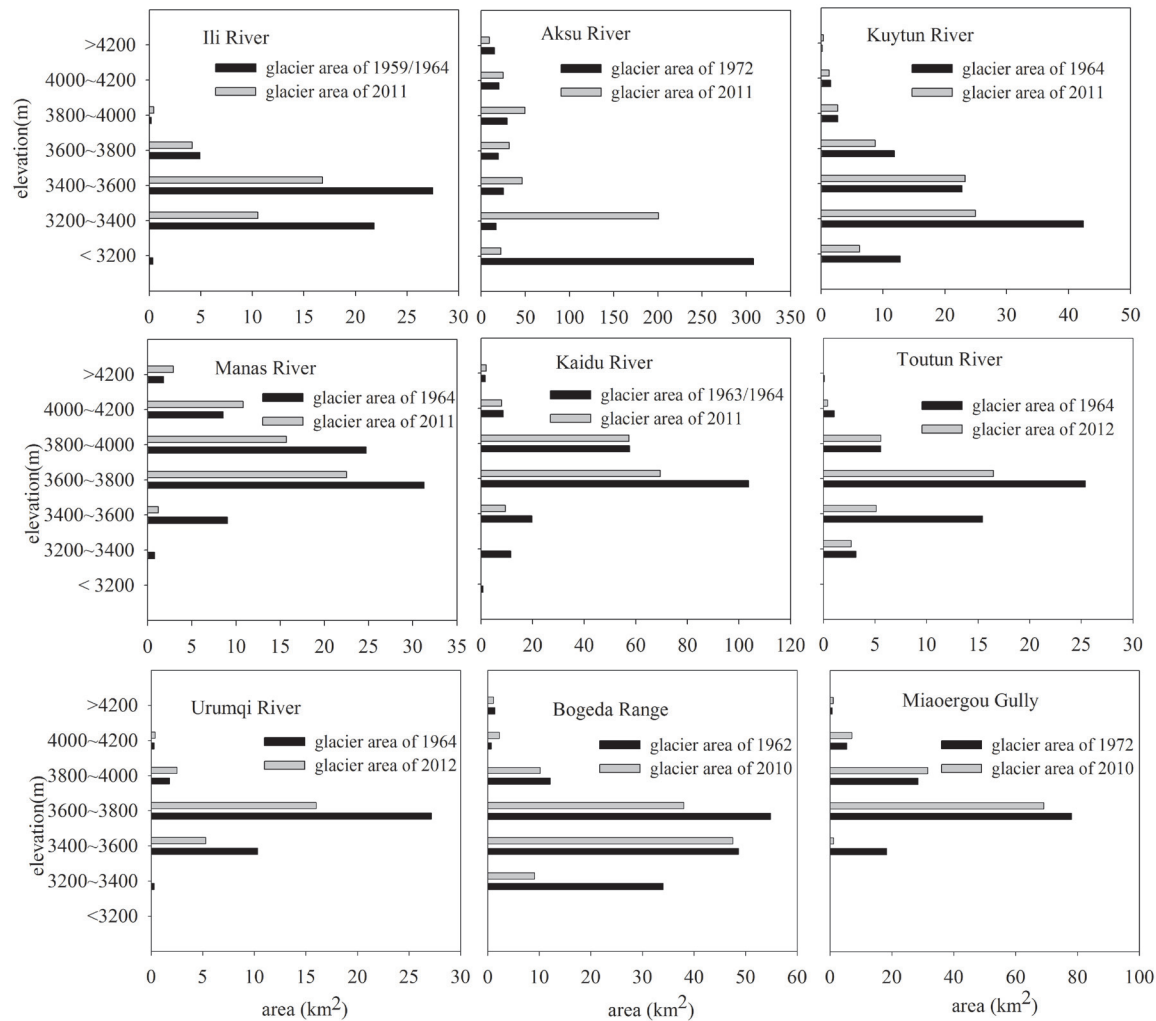


FIGURE 6. Glacier area change in different altitude range of the nine regions in 1959/1972 to 2010/2012.

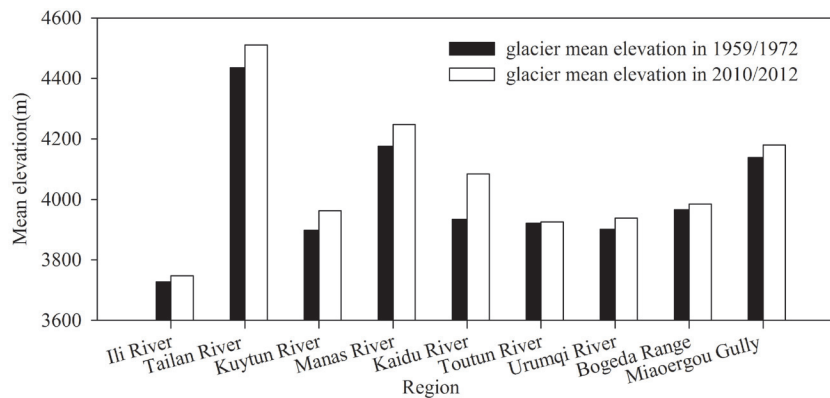


FIGURE 7. Glacier area change with different altitude ranges in the nine regions in 1959/1972 to 2010/2012.

ported average glacier ice loss of $0.3\% \text{ a}^{-1}$ in Tien Shan over the past half century. The strongest annual area shrinkage rates were found in the outer ranges (0.4% to $0.8\% \text{ a}^{-1}$), whereas smaller rates were reported for glaciers in the inner (0.2% to $0.4\% \text{ a}^{-1}$). Our investigation of the studied 1428 glaciers in the nine regions during

the period from 1959/1972 to 2010/2012 also showed a high retreat speed ($0.3\% \text{ a}^{-1}$ to $0.8\% \text{ a}^{-1}$), and the overall range of annual area changes in Tien Shan Mountains was similar to that for the Himalaya-Karakorum region, which represents the southern margin of the Asian high mountains complex (Bolch et al., 2012).

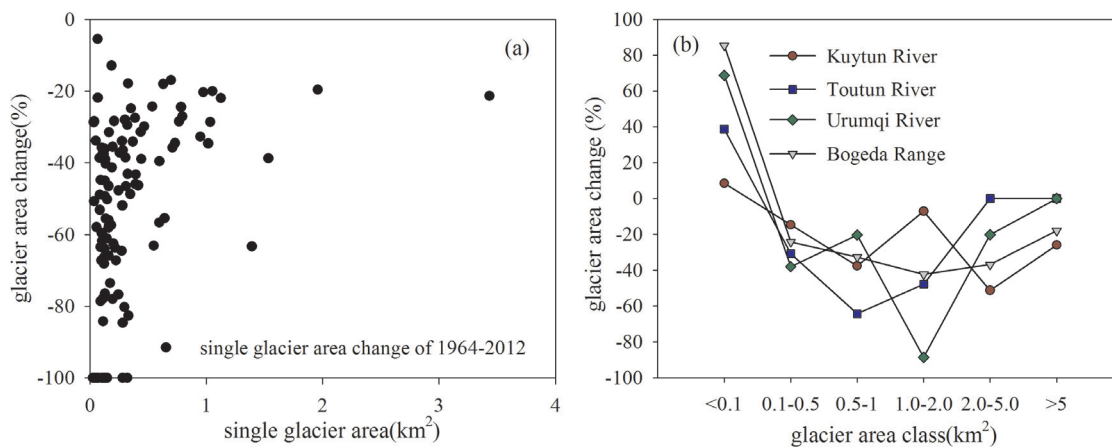


FIGURE 8. Glacier-size changes. (a) Single glacier area loss for 1964–2012 of different size in Urumqi River. (b) Total glacier area loss for 1962/1964 to 2010/2012 by different glacier area size class.

TABLE 4
Glacier fragmentation in the nine regions of Chinese Tien Shan.

| Study area | Glacier units | | Fragmented glaciers | | Fragmented areas (km²) | |
|-----------------|---------------|-----------|---------------------|-----------|------------------------|-----------|
| | 1959/1972 | 2010/2012 | 1959/1972 | 2010/2012 | 1959/1972 | 2010/2012 |
| Ili River | 113 | 93 | 6 | 14 | 11.7 | 7.6 |
| Aksu River | 113 | 103 | 3 | 9 | 299.5 | 270.5 |
| Kuytun River | 144 | 119 | 11 | 25 | 17.1 | 12.4 |
| Manas River | 131 | 112 | 13 | 28 | 14.1 | 9.6 |
| Kaidu River | 293 | 261 | 14 | 29 | 30 | 22.3 |
| Toutun River | 167 | 142 | 6 | 13 | 4 | 2.3 |
| Urumqi River | 121 | 100 | 6 | 12 | 5.2 | 2.8 |
| Bogeda Range | 205 | 185 | 8 | 16 | 25.5 | 22.3 |
| Miaoergou Gully | 141 | 131 | 15 | 34 | 38.6 | 30.9 |
| Total | 1428 | 1246 | 82 | 180 | 445.4 | 380.6 |

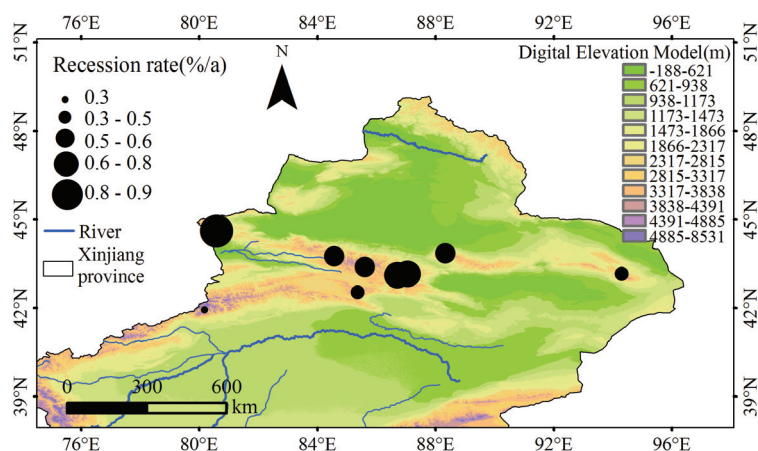


FIGURE 9. Glacier recession rate distribution. DEM = Digital Elevation Model.

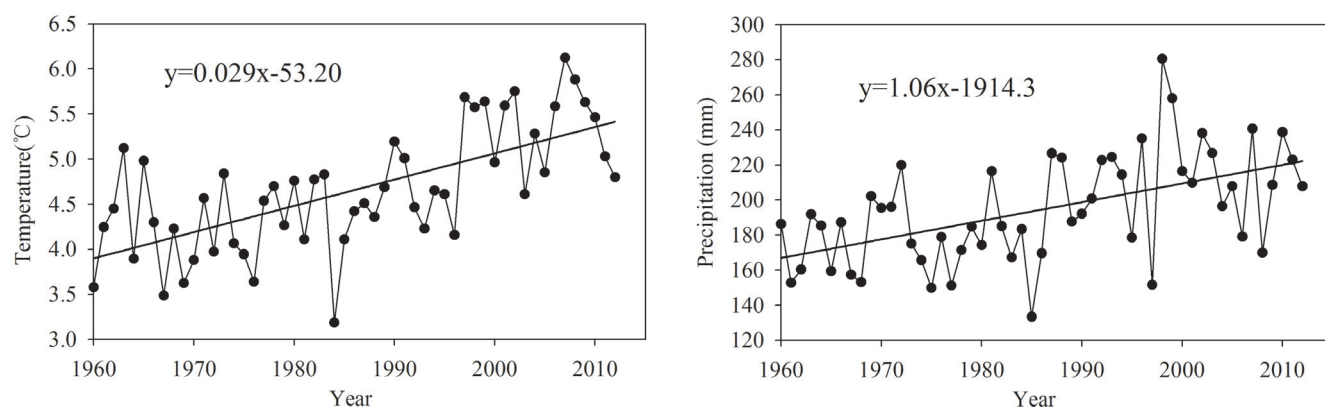


FIGURE 10. Annual mean temperature and total precipitation trends during 1960–2012 at 14 meteorological stations.

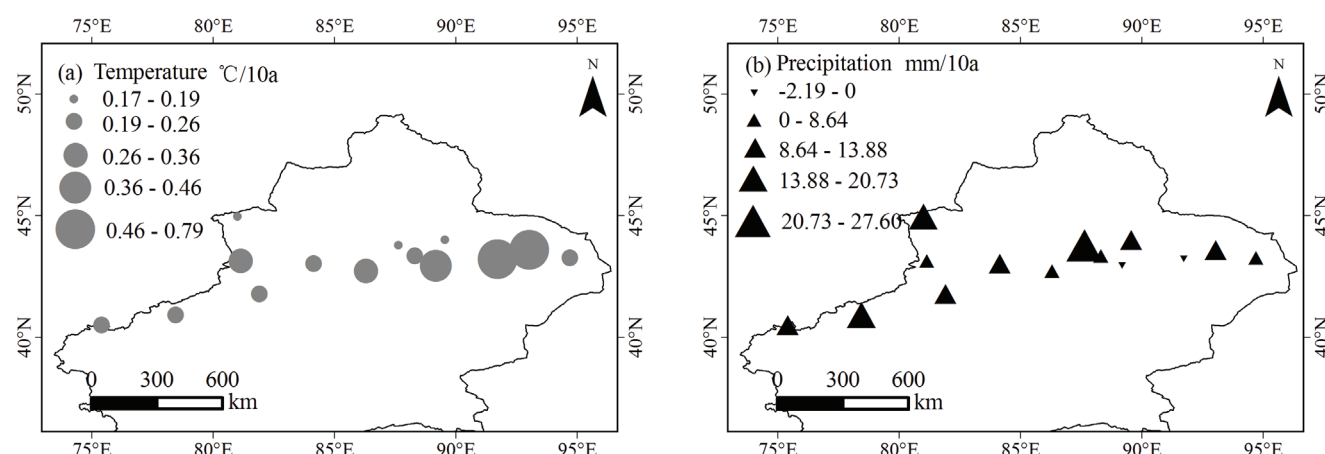


FIGURE 11. Trends for temperature and precipitation at 14 meteorological stations: (a) trends for annual mean temperature ($^{\circ}\text{C}$ [10 a] $^{-1}$); (b) annual precipitation (mm [10 a] $^{-1}$).

Recent Glacier Variation Related to Local Climate Changes

The glacier system is influenced by several factors, including climate, topography, and glacier-supply conditions (Hoffmann et al., 2007; Racoviteanu et al., 2008). In the Chinese Tien Shan, glaciers are primarily of the summer-accumulation type, whereby maximum accumulation and ablation both occur in the summer (Ageta and Fujita, 1996). Thus, precipitation and temperature may be the most important factors controlling mass balance. The linear trend analysis of annual temperature shown in Figure 10 indicates that the average rate of temperature increase was $0.29\text{ }^{\circ}\text{C}$ per decade over the study period (statistically significant at the 0.001 level), which exceeds the global average of $0.148\text{ }^{\circ}\text{C}$ per decade (IPCC, 2007). Over the same period, annual precipitation increased gradually at an average rate of 10.6 mm per decade, serving to increase glacier sensitivity to temperature. There-

fore, modern climatic conditions in the Chinese Tien Shan are conducive to the areal shrinkage and rise of the ELA observed throughout the study area.

The amplitudes of changes in temperature and precipitation varied among the regions, indicating that glacier recession is closely related to regional climate conditions observed at meteorological stations (Fig. 11). The linear trend in annual mean temperature for the period 1960–2012 varied between $0.17\text{ }^{\circ}\text{C}$ and $0.79\text{ }^{\circ}\text{C}$ per decade, whereas trends in annual precipitation varied between -2.19 mm and 27.6 mm per decade. We note that temperature increased at all stations, whereas precipitation increased at all but two (the Torugart and Qijiaojing stations recorded little change in annual precipitation). Climate warming was strongest in the Urumqi River and Toutun River regions and is correlated with the high rates of glacier recession in these regions. However, glaciers in the Ili River region lost 42% of their total area due to a low trend of the annual mean

temperature and an obvious positive trend of the annual precipitation. We suggest that this pattern is due to the low elevation (3200–3600 m) and small mean glacier size (0.28 km²) of this region (DeBeer and Sharp, 2009).

CONCLUSIONS

We assessed changes in the areal extent of 1428 glaciers in the Chinese Tien Shan between 1959/1972 and 2010/2012. Over this period, total glacier area decreased from 1299 ± 4 km² to 1013 ± 4 km², representing a total loss of 287 km². This value translates to a change in glacier surface area of –22%. Rates of glacier shrinkage across the nine regions range from 0.3% a^{–1} to 0.8% a^{–1}. We identified a correlation between patterns of recent climate change and glacier retreat in the Chinese Tien Shan.

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