Glacier retreat of the Tian Shan and its impact on the urban growth and environment evaluated from satellite remote sensing data

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Abstract. The retreat of mountain glaciers, notably in high Asia, provides evidence for the rise of global temperature. The mass balance is vital for the health of a glacier. If the amount of frozen precipitation in the accumulation zone exceeds the quantity of glacial ice loss due to melting or lies in the ablation zone, the glacier will advance. Conversely, if the accumulation is less than the ablation, the glacier will retreat. Glaciers in retreat will have negative mass balances, and if they do not reach an equilibrium between accumulation and ablation, will eventually disappear. Long-term changes of the mountain glaciers in the Tian Shan, Central Asia, are not well constrained. Analyses of satellite remote sensing data combined with the ground observations reveal a 37.5% decline of glaciered area from 1989 to 2014 in No.1 Glacier, the headwaters of the Urumqi River basin, Chinese Tian Shan, which could be linked to increased summer melting. The results show that the area of glaciers was reduced from 31.55 km² in 18 August 1989 to 28.66 km² in 24 August 1994 and 19.74 km² in 31 August 2014. The glacier area was reduced by 0.47 km²/per year in recent 25 years since 1989, and the annual reduction was 1.5%. Meanwhile, the urban area of Urumqi, the biggest city of Xinjiang Uygur Autonomous Region, increased from 156 km² in 1989 to 555 km² in 2014. Correspondingly, the population of permanent residents increased from 1.06 million in 1989 to 3.53 million in 2014. We suggest that the decline of glacier area is driven primarily by summer melting and, possibly, linked to the combined effects of the global rise in temperatures and black carbon/CO₂ emission from coal-fired power plants, cement plants and petroleum chemical plants from the nearby Urumqi and surrounding regions. The continuing retreat of glaciers will have a number of different quantitative impacts. Populations in the arid Central Asia regions are heavily dependent on snow and glacier melt for their irrigation and drinking supplies. A continuation of the current retreat will eventually deplete the glacial ice and substantially reduce or eliminate runoff. It will also affect the availability of fresh water for mountain recreation, animals and plants that depend on glacier-melting.

1. Introduction
Central Asia is one of the world’s most vulnerable regions to climate change. The arid climate, combined with a history of environmental mismanagement and limited climate-related risk mitigation strategies,
have created a region that is increasingly vulnerable to the effects of rising temperatures, changing rainfall patterns, and increasing of aridity and frequency of extreme events. Since glaciers are highly sensitive to temperature increases, their changes are also considered as key indicators of some consequences of global warming.

Glaciers play an important role in the water cycle of Central Asia. Snow and glacier melting from the Tian Shan is essential for the water supply in the arid areas [1], such as Kazakhstan, Kyrgyzstan, Uzbekistan, and the Xinjiang Uyghur Autonomous Region, northwest China. Despite this importance, only little was known about how glaciers in this region changed in the past decades. In the last 50 years, the glaciers of Central Asia are estimated to have shrunk by between 20 to 30%. Glaciers of Central Asia are disappearing at rather high rates [2].

Most of the direct monitoring projects on the glaciers were shut down with the collapse of the Soviet Union except for the limited ground observations in China, though these modern observations often cover a limited region [2,3].

In the context of remote sensing, change detection refers to the process of identifying differences in the state of surface features by observing them at different times. The goal of change detection is generally an image that highlights areas that have changed between two (or more) time periods and the direction and magnitude of change.

Retreat of glaciers is likely to aggravate existing problems and pose additional risks to sustainable development, energy and food security in the arid area like Central Asia. In this study, we document the change of glaciers in upper reach of Urumqi River basin, Tian Shan and urban sprawl of Urumqi City, capital city of Xinjiang Uygur Autonomous Region over the past decades using the multi-temporal remote sensing. Emphasis is placed on results from the optical remote sensing interpretations and ground observations.

Figure 1. Landsat image shows the location of study region

2. Study area and methods
The No.1 glacier, one of the largest ice bodies in the Chinese Tian Shan, is located in the headwaters of the Urumqi River, Tian Shan, China (Figure 1). Being the main source of the Urumqi River, it attracts thousands of visitors every year. The No.1 glacier is a vital source of freshwater storage and water supply, especially during the summer season for a large human population living downstream. There are around 15 glaciers exist in the headwater of the Urumqi River covering approximately 38 km² [4]. The 214 km-long Urumqi River system with its tributaries covers an area of 4684 km² [5].

2.1. Detecting glacier changes and urban sprawl from Landsat time-series data during 1989 to 2014
In this study, cloud-free full scenes of path 143, row 30, and path 143, row 29 acquired by Landsat series were used (see Table 1).

Table 1. List of Landsat time-series data used in this study

| Satellite Data | Path/Row | Date of acquisition | Spatial resolution (m) |
|----------------|----------|---------------------|-----------------------|
| Landsat TM     | 143/30   | 18 August 1989      | 30                    |
| Landsat ETM+   | 143/30   | 24 August 1994      | 30                    |
| Landsat 8 OLI  | 143/30   | 31 August 2014      | 30                    |
| Landsat TM     | 143/29   | 18 September 1989   | 30                    |
| Landsat 8 OLI  | 143/29   | 31 August 2014      | 30                    |

As shown in Figure 2, retreat of glaciers in the source region of Urumqi River is notably identifiable in the Landsat time-series images with around 30m resolution. We can calculate the area of glaciers in the upstream region of Urumqi River basin with an area of 1243 km² using GIS software. The results show that the areas of glaciers are 31.55 km² in 18 August 1989, 28.66 km² in 24 August 1994 and 19.74 km² in 31 August 2014 (Figure 3), respectively. The analysis of early air-photos indicated that the area of glaciers is about 38 km² in the 1950s [4].

Figure 2. Landsat images show the glacier changes in the source region of Urumqi River from 1989 to 2014

Figure 3. The changes of glaciared area in upstream region of Urumqi River basin based on GIS during 1989 to 2014
Meanwhile, we also investigate the urban sprawl of Urumqi city during 1989 to 2014. As we see from Figure 4, the urban land use grows rapidly in the same time span. The urban area expands from 156 km² in 1989 to 555 km² in 2014. At the same time, the population of permanent residents increased from 1.06 million in 1989 to 3.53 million in 2014 according to the Urumqi city yearbook.

2.2. Ground observations
In early October 2014, we conducted a field investigation and measurements along the Tian Shan No.1 Glacier and Urumqi River, based on the area of interests detected with optical remote sensing as described above.

We found that the Tian Shan No.1 Glacier was experiencing a rapid retreating caused by summer climate warming in recent years. Our measurements showed that the retreating distance is about 5-6 meters during May 18 to October 6, 2014 (see Figure 5a). We are surprised that the glaciers are still melting in early October (see Figure 5b.)

In the past 30 years, the small glaciers of the Tian Shan have been disappeared due to continued glacier shrinkage (see Figure 6a).

Figure 4. Landsat images of the Urumqi city show the urban sprawl from 1989 to 2014
Figure 5. Field photographs show the rapid retreating (a) and melting (b) of glaciers observed at western branch of Tian Shan No.1 Glacier.

Figure 6. Field photographs show the bare rocks caused by the rapid retreating of glaciers (a) in the source region of Urumqi River and (b) CO$_2$, black carbon and thermal emissions from coal-fired power plant of glaciers observed at 30 km north to Tian Shan No.1 Glacier.

3. Discussion
Climate-driven changes in glacier-fed streamflow regimes have direct implications on freshwater supply, irrigation and hydropower potential. Reliable information about current and future glaciation and runoff is crucial for water allocation, a complex task in Central Asia, where the collapse of the Soviet Union has transformed previously interdependent republics into autonomous upstream and downstream countries. Although the impacts of climate change on glaciation and runoff have been addressed in previous work undertaken in the Tian Shan [3,5,6], a coherent, regional perspective of these findings has not been presented until now. Here we show that glacier shrinkage is most pronounced in peripheral, lower-elevation ranges near the densely populated forelands, where summers are dry and where snow and glacial meltwater is essential for water availability. Shifts of seasonal runoff maxima have already been observed in the Urumqi River. Based on the observations of runoff and precipitation in the Urumqi River basin, the variation features in climatic shift from warm dry to warm humid are analysed [5]. It is reveals that there is an obvious increasing trend of runoff at the Glacier No.1 and Yingxunqiao Hydrologic Stations of the Urumqi River after 1987. Especially, the runoff at the Glacier No.1 Hydrologic Stations has a very clear shift in 1997. Moreover, analyses of long-term climate and glacier records over the past 45 years (1959 to 2003) in Urumqi River source region, Tian Shan show that summer temperature and annual precipitation near the glacier increased by 0.8°C and 87 mm (19%), respectively. The glacier continuously retreated during the same period, with the cumulated mass balance being 10,032 mm, or 20% of the glacier volume. Annual basin runoff has significantly increased by 413 mm or 62% during 1980–2003 due to precipitation increase and enhanced glacier melt caused by summer climate warming. Both summer precipitation and temperate are negatively correlated with
mass balance and positively associated with runoff. Relative to precipitation mass balance relation, the regression between temperature and mass balance is much stronger, indicating that summer temperature controls glacier mass balance and runoff changes [3].

The main reason of the increasing runoff in the hydrologic stations of upstream region is due to the two factors: strong melting of glacier and durative increase in precipitation in the source area of the Urumqi River [3,5]. Moreover, many recent studies also revealed that industrial black carbon has caused the melting of glaciers [7,8] as well as observed in the field (Figure 5b and 6b).

The increasing water consumption of a growing population is likely to put additional pressure on both food and energy supplies, and could aggravate tensions within the region and between Central Asia and neighbouring countries. Currently observed changes in glaciers threaten the region in the short term with floods and with reduced water resources availability in the long term. However, it is suggested that summer runoff will further decrease in these rivers if precipitation and discharge from thawing permafrost bodies do not compensate sufficiently for water shortfalls.

Effective or accurate monitoring of the glaciers rate of degradation and their current status are essential to minimizing the negative effects of this degradation through better planning and management of water resources.

4. Conclusions
The situation is of particular concern in light of both the local population growth and the continued glacier shrinkage anticipated in response to climatic changes. Our study demonstrated that multi-temporal Landsat series optical remote sensing data were particularly useful for capturing surface change at sufficient frequency to study glacier dynamics and changes for the urban region.

We combined geospatial analysis techniques with remote-sensing and field data to document spatial patterns of glacier changes in the headwaters of Urumqi River basin in the past 25 years (from 1989 to 2014).

We summarize as follows:

1. Glaciers of the source region of Urumqi River lost 37.5 % (11.81 km²) of their area from 1989 to 2014. Glaciered area was reduced from 31.55 km² in 18 August 1989 to 28.66 km² in 24 August 1994 and 19.74 km² in 31 August 2014. The glacier area was reduced by 0.47 km²/year, and the annual reduction was 1.5%.

2. The urban area of Urumqi, the capital city of Xinjiang Uygur Autonomous Region, increased from 156 km² in 1989 to 555 km² in 2014. Correspondingly, the population of permanent residents increased from 1.06 million in 1989 to 3.53 million in 2014.

3. We suggest that the decline was driven primarily by summer melting and, possibly, linked to the combined effects of the global rise in temperatures and carbon/CO₂ emission from coal-fired power plants, cement plants and petroleum chemical plants from the nearby Urumqi and surrounding regions.

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