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Early 21st century glacier thickness changes in the Central Tien Shan

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ABSTRACT

Although studies based on satellite gravimetry (2003 − 2010) and laser altimetry (2003–2009) measurements have achieved region-wide glacier mass change for the Tien Shan, the dynamic process of glacier yet to be closely monitored and understood so that its impact can be assessed accurately. In this study, we investigated region-wide glacier thickness change in the Central Tien Shan (CTS) during 2000–2012 by differencing the Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM) with a newly constructed DEM from 27 TanDEM-X images. For a total glacier area of 7239.8 ± 527.2 km^2, an average glacier thickness change rate of −0.24 ± 0.22 m/a was derived. This result agrees well with the result based on satellite laser altimetry measurements reported earlier (−0.31 ± 0.41 m/a). With temporal synchronization, a fine spatial resolution and wide coverage, our measurements are able to reveal abundant glacier change features and dependencies in the CTS. Firstly, the lower mountains have seen a more severe glacier decline, and the glaciers facing the prevailing wind (westerlies) have experienced a greater decline because of the stronger evaporation. Furthermore, those glaciers lying along the extremely high Meridian mountain range have obviously gained mass in their upper reaches, because the air current from the west is blocked and lifted by the Meridian mountain range. Secondly, for the entire glacier body, the theoretical hyperbolic dependence between debris thickness and ice decline was very difficult to establish. Some huge glaciers covered by heavy debris have still experienced a severe decline. However, even though the heavy debris did not prevent the ablation, its attenuating effects were considerable. Thirdly, for the glaciers that surged before 2000, the mass gain in the restoring zones has not been enough to cover the mass loss in ablation zones. Some large glaciers surged again during 2000–2012; however, with much lower magnitudes than in previous surges. In general, the surge glaciers have experienced a greater decline than the non-surge glaciers. Fourthly, due to the ice front calving and subglacial thermal erosion, glaciers connected to proglacial lakes have receded and thinned much more rapidly than the land-terminated glaciers. Overall, the glaciers in the CTS are more stable than those in other parts of the Tien Shan. However, the glacier state there is still alarming. A moderate average thinning rate was derived because the drastic thinning in the ablation zones was balanced by the slight thinning in the broad accumulation zones.

1. Introduction

Mountain glaciers are sensitive to climate change. In remote inland areas where glacial meltwater serves as a vital fresh water resource, constant deglaciation since the 1980s has placed both the local societies and ecosystems under pressure (Li et al., 2008; Yao et al., 2012). Meanwhile, glacial hazards become increasingly frequent after glaciers lose substantial mass, such as floods and mudslides. Major social issues involving mountain glaciers are how much influence the glacier change will make and how long the glaciers will remain on the mountains. Technically, these issues can be answered by the region-wide glacier mass balance; more precisely, the representative thickness change magnitude and the high-resolution thickness change maps. Therefore, since the beginning of systematic glacier study, thickness change measurement has always been the major undertaking of glaciologists.

The Tien Shan is known as the 'Water Tower of Central Asia'. According to the latest version of the Randolph Glacier Inventory (RGI5.0) (Arendt et al., 2015), the glaciated area in the Tien Shan covers ~11,856.4 km^2 in total (not including the 520.9 km^2 of the Dzhungar Alatoo). The Tien Shan can be divided into five parts, i.e. Northern, Western, Eastern, Inner and Central (see Fig. 1). The glaciated area within the CTS amounts to 56.6% of the glaciated area of the Tien Shan. Clearly, among the five sub-regions, the CTS plays a dominant role in terms of glaciation. The CTS peripheral forelands are basically arid. Taking Aksu (a prefecture-level city located between the CTS and the Takla Makan Desert) as a typical example, it receives precipitation of only 60–80 mm per year. Nevertheless, Aksu serves as a significant commodity grain and cotton base of China, and is regarded as an area of high-quality fruits. It is the glacial meltwater flowing from the CTS that provides

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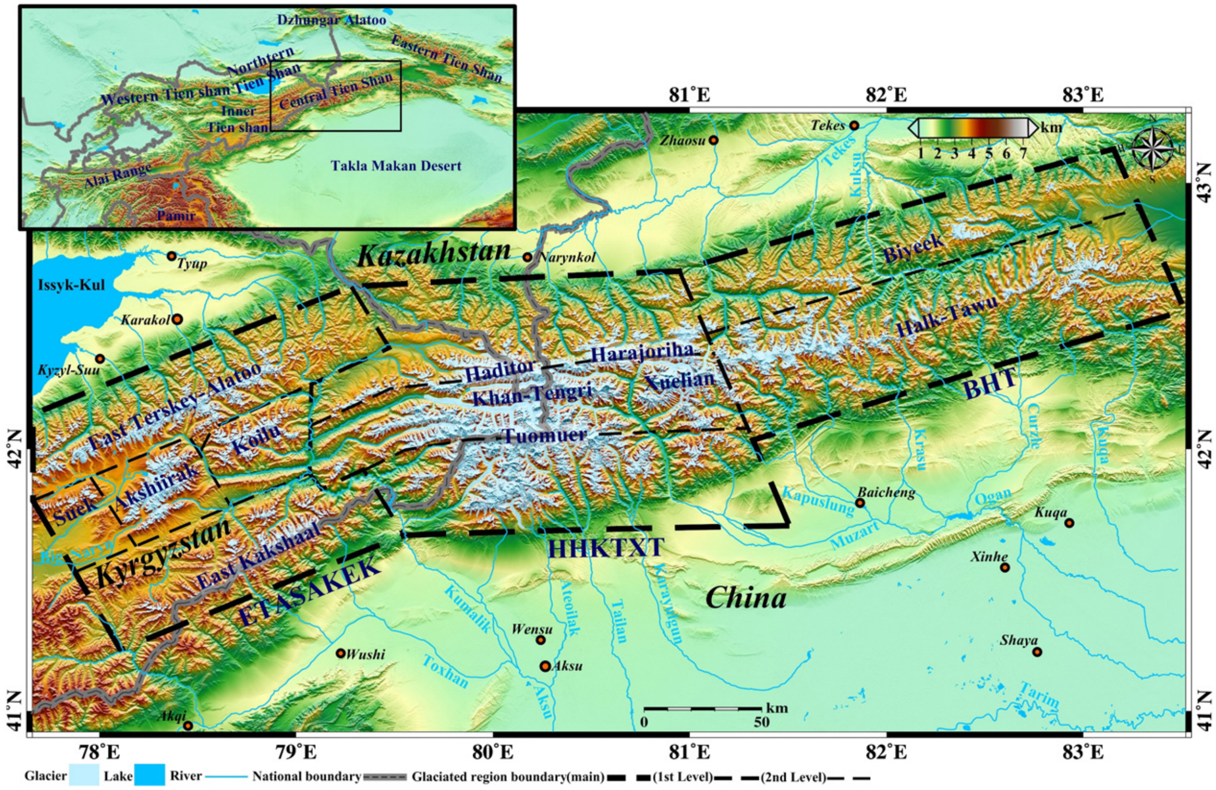

Fig. 1. Hydrology and topography in the Central Tien Shan. Names of the mountain ranges are shown in deep blue. The thickest dashed line polygon represents the measured glaciated region. Glaciers within it are separated into 31st level (ETASAKEK, HHKTXT and BHT) and 10 2nd level sub-regions. Note that the separation of sub-regions in HHKTXT is based on mountain orientations rather than mountain ranges. The insert panel shows the approximate location of the Central Tien Shan.

most of the fresh water supply of the peripheral forelands, especially in dry summers (Sorg et al., 2012). Owing to the abundant glacial meltwater, the CTS peripheral forelands played a pivotal role in the ancient 'Silk Road', and have become a densely populated area with prosperous multi-cultural exchange. However, there is some evidence that the glaciers in the CTS are undergoing significant changes (Pieczonka et al., 2013; Pieczonka and Bolch, 2015; Shangguan et al., 2015). Hence, region-wide glacier thickness change measurement in the CTS is of great importance for both local hydrological policy making and an input to glaciological modelling.

Conventional thickness change measurements, such as Global Position System (GPS) surveys, stake records and ground radio echo sounding, are directly conducted on the ice fields. Undoubtedly, such field measurements can acquire accurate information. However, due to the vast extent of the glaciers, the great altitude variation and the difficult logistics, conventional thickness change data are still scarce. To the best of our knowledge, in the CTS, only seven glaciers have been measured via conventional methods (see Table 1). Mathematical extrapolation or glaciological modelling based on inadequate and uneven observations can result in great uncertainty, since glacier changes are subject to many local factors, e.g., altitude, location, orientation, surge activity, debris cover and glacial lakes. In terms of large-scale thickness/mass measurements in polar ice sheets, satellite laser altimetry and gravimetry are efficient and suitable approaches (Sørensen et al., 2011; Gardner et al., 2013). However, in terms of small-scale mountain glacier monitoring, the rough spatial resolution of satellite gravimetry and the sparse spatial coverage as well as large footprint size of satellite laser altimetry limit the reveal of thickness change features and dependencies. To date, to the best of our knowledge, three teams have measured the Tien Shan glacier thickness/mass changes via satellite laser altimetry or gravimetry, i.e., Jacob et al. (2012), Gardner et al. (2013) and Farinotti et al. (2015). These teams focused on deriving representative glacier thickness changes, and only Farinotti et al. (2015) presented sub-regional thickness changes by dividing the Tien Shan into seven sub-regions.

Through the use of optical or synthetic aperture radar (SAR) images, we can derive the region-wide glacier thickness changes via geodetic measurement, i.e., generating a new DEM via photogrammetry or

Table 1
Field glacier measurements in the CTS.

Glacier	Time	Method	Mass balance (m/a w.e.)	Data source
Sary-Tor	1985–1989	Stake record	−0.14	WGMS, 1991
Kara-Batkak	1957–1998	Stake record	−0.44	WGMS, 1999
Suek Zapadniy	2010–2013	Stake record	−0.37	WGMS, 2015
Akshiirak No. 354	2010–2013	Stake record	−0.38	WGMS, 2015
Gregoriev	2006–2007	GPS survey	−0.25	Fujita et al., 2011
Qingbingtan No. 72[a]	1964–2008	Photogrammetry in 1964 and GPS survey in 2008	−0.20	Wang et al., 2011
Koxkar[b]	1981–2004	Ground radio echo sounding	–	Xie et al., 2007

[a] The mass balance is limited to glacier tongue.

[b] The measurements were available at only two cross profiles of glacier tongue.