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Detailed comparison of glaciological and geodetic mass balances for Urumqi Glacier No.1, eastern Tien Shan, China, from 1981 to 2015

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ABSTRACT

The mass balance of Urumqi Glacier No.1, eastern Tien Shan, has been monitored since 1959, using the direct glaciological method. This study presents a detailed comparison of the glaciological mass balance with a high-quality product of geodetic surveys in the overlapping period from 1981 to 2015. We analyzed the generic differences between glaciological and geodetic mass-balance measurements, including in-depth uncertainties assessments. The statistical comparison shows that the reduced discrepancy ($\delta = 0.53$) between the geodetic mass balance (-0.53 ± 0.14 m w.e. a^{-1}) and corrected annul glaciological mass balances (-0.46 ± 0.14 m w.e. a^{-1}) falls within the 95% confidence interval and reveals that no statistical significant bias between the two datasets is detectable over the period. Thanks to the good agreement, calibration of the glaciological to the geodetic data series is currently not required. The more negative geodetic mass balance is probably relevant to the glacier surface characteristics. The uncertainty of our results measured with geodetic method was close to the majority of similar studies, but bigger than those derived from multi-temporal high-quality DEMs. Further studies should continue using a long-range terrestrial laser scanning (TLS) system to derive high-resolution and -precision digital elevation models (DEMs) of the glacier surface at the monthly time-scale, which will provide a powerful complement to the glaciological measurements.

1. Introduction

Populations in Central Asia depend largely on glacier melt for their water supplies and this situation is well reflected in the Tien Shan (Farinotti et al., 2015). Glacier mass balance provides direct information on the gain or loss in glacier ice, which are crucial for studying the impact of mass changes to water resources, sea level rise and climate-glacier interactions (Kaser et al., 2006; Zemp et al., 2015). Mass balance is commonly obtained by the direct glaciological method, which provides in situ measurements of annual and sometimes seasonal mass balance using stakes and snow pits at the end of the hydrological year (Østrem and Brugman, 1991; Xie and Liu, 1991; Zemp et al., 2013). Mass balance can also be assessed indirectly using the geodetic method, in which two digital elevation models (DEMs) of the glacier surface are subtracted to calculate the volume changes, which is then converted to mass using a density conversion (Cogley et al., 2011). The glaciological method measures the surface mass balance, which can provide better understanding of glacier melt, and the geodetic measurements include surface, internal and basal mass balances. Comparison of glaciological and geodetic measurements has been widely studied (Cogley, 2009; Thibert and Vincent, 2009; Fischer, 2011). Some studies have shown good agreement, such as Storglaciären, Sweden (Zemp et al., 2010) and White Glacier, Canada (Thomson et al., 2017). Some studies showed significant discrepancy: for example Hagg et al. (2004) compared the two methods calculating mass balance of the Tuyuksu Glacier (Kazakhstan) and the difference was −4.2 m w.e. over 40 years. This discrepancy can be explained mainly by deficiencies in the glaciological measurements. For Abramov glacier (Kyrgyzstan), the disagreement was -0.48 m w.e. a^{-1} from 2000 to 2011, which can be explained by an underestimation of the SRTM C-band penetration depth into snow (Barandun et al., 2015). In some cases, the glaciological method implies systematic errors in one direction which increase linearly with the

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number of seasonal and annual measurements (Cox and March 2004; Thibert et al., 2008; Huss et al., 2009). Zemp et al. (2013) proposed a framework for assessment of random and systematic errors, as well as for validation and calibration of the glaciological series with the geodetic balance results.

Within the international glacier monitoring strategy, the strength of the geodetic method is that it provides decadal to sub-decadal values that take into account the entire glacier, including inaccessible areas. Its results are essential for validating and calibrating the glaciological data series (Zemp et al., 2015). The validation and calibration is predicated on the geodetic balance being accurate, which primarily depends on the quality of DEMs used to derived glacier volume changes. The available DEMs are usually of limited spatiotemporal resolution, which is the main constraint for the computation of reliable geodetic mass balance. Airborne and terrestrial Light Detection and Ranging (LiDAR) techniques have offered dense point clouds and high-resolution and -precision DEMs of glacier surface terrain (Joerg et al., 2012; Helfricht et al., 2014; Piermattei et al., 2015; Fischer et al., 2016). Terrestrial laser scanning (TLS) often has error margins in the range of a few centimeters (Hartzell et al., 2015). Fischer (2011) concluded that the accuracy of geodetic mass balance in Apline regions resulting from the accuracy of the DEMs ranges from 1 m w.e. a^{-1} for photogrammetric data to 0.001 m w.e. a^{-1} for LiDAR data. Gabbud et al. (2015) applied a new generation of TLS which can be used to investigate a glacier surface ablation at the seasonal and hourly scales. Fischer et al. (2016) showed that repeated TLS surveys yielded accurate results for annual geodetic mass balances of very small glaciers in the Swiss Alps. Compared to airborne laser scanning (ALS), the terrestrial laser scanning technique is an easier and more cost-effective way of monitoring the individual glacier mass balance (Gabbud et al., 2015; Fischer et al., 2016; Xu et al., 2017).

To date, direct glaciological measurements are available for a few hundred glaciers and there are currently 41 reference glaciers with > 30 years of data in the World Glacier Monitoring Service (WGMS) time series (WGMS, 2017); geodetic surveys are currently available for 450 glaciers (Zemp et al., 2015). Urumqi Glacier No.1 located in the eastern Tien Shan, with the longest and most detailed surface mass balance measurement time series in China. The long-term mass balances were observed beginning in 1959 (Li et al., 2011). Its surface topography has been surveyed nine times at intervals of several years from 1962 to 2012 (Chen et al., 1996; Wang and Shen, 2011; Wang et al., 2016). A long-range Riegl VZ®-6000 terrestrial laser scanner was utilized to survey the glacier surface in 2015 and subsequently a high-resolution and accurate DEM was generated. Urumqi Glacier No.1 can be considered as a well-suited test site to compare the glaciological and geodetic measurements.

Urumqi Glacier No.1 was taken here as a case study to compare the obtained results between the glaciological and the geodetic methods over the period of record (PoR, 1981–2015). The following research questions for this study were defined: What is the source of the observed uncertainties in both methods? To what extent the obtained results influenced by the different DEMs used, the existing snow cover, the reference area and processes of internal accumulation and ablation?

2. Study site

Urumqi Glacier No.1 (43°06′N, 86°49′E) is a northeast-orientated small valley glacier at the headwaters of the Urumqi River with an area of 1.59 km^2 and a length of 1.99 km in 2012 (Wang et al., 2016), situated on the northern slope of Tianger Summit II (4848 m a.s.l.) in the eastern Tien Shan (Fig. 1). The area of Urumqi Glacier No.1 decreased strongly over the PoR. The glacier area was 1.56 km^2 on 2 September 2015 based on TLS-derived high-resolution DEM. Compared with the glacier extent derived from the map in 1981, the overall area loss was 0.30 km^2 (−16.4%), the shrinkage rate is higher than the investigated glaciers in the Chinese Tien Shan (−11.5%) (Wang et al., 2011).

Note that Urumqi Glacier No.1 is a summer-accumulation-type glacier in a continental climate setting. Both accumulation and ablation occur simultaneously during summer (Li et al., 2011). The two branches (east and west branches) of the glacier separated completely in 1993 due to continued glacier retreat (Li et al., 2010). The glacier was for the first time monitored in 1959, and mass-balance data have been recorded in Annual Reports of the Tien Shan Glaciological Station from 1980 to present and published in the Glacier Mass Balance Bulletin (every two years) compiled by the WGMS (http://wgms.ch/). Urumqi Glacier No.1 is also one of the reference glaciers in the WGMS glacier monitoring network and a representative glacier in Central Asia (Zemp et al., 2009; Li et al., 2011).

3. Data and methods

3.1. Riegl VZ®-6000 TLS

Common TLS systems use class 1 laser beams with wavelengths around 1500 nm, with low reflectance over snow and ice cover, and the possible scanning distance is restricted to a few hundred meters, limiting the application of TLS surveys for glacier studies (Rabatel et al., 2008; Deems et al., 2013; Fischer et al., 2016). A new generation of Riegl VZ®-6000 TLS typically uses class 3B laser beams (wavelengths around 1064 nm); the instrument is, due to its laser wavelength, exceptionally well suited for measuring snowy and icy terrain in glacier mapping (Fischer et al., 2016). Faster surveys (up to 222,000 measurements s^{-1}) are possible, even at long range (better than 6000 m), with unprecedentedly high accuracy and precision (RIEGL Laser Measurement Systems, 2014a).

Based on time-of-flight measurement with echo digitization and online waveform processing, the Riegl VZ®-6000 TLS can capture repeated dense point clouds of the glacier surface terrain with emitting near-infrared laser signals (RIEGL Laser Measurement Systems, 2013). The laser pulse transmitter emits a laser pulse, which is reflected by the target object back to the laser receiver, and used to calculate the distance between object and sensor (RIEGL Laser Measurement Systems, 2014a).

3.2. TLS field surveying

On 2 September 2015 (at the end of the mass balance year), Riegl VZ®-6000 surveys of Urumqi Glacier No.1 were performed for four scan positions (Fig. 2), on the same day as the glaciological measurements. Each scan position was fixed on the stable bedrock using a reinforced concrete structure with a GPS-leveling point at the terminus of the glacier, and the instrument was mounted on a tripod for each scan position to prevent ground motion and guarantee data quality. Three-dimensional (3-D) coordinates of the four scan positions were obtained using the real-time kinematic (RTK) global positioning system. The accuracy of this type of RTK surveys has been reported to be within ± 1 cm horizontally and ± 2 cm vertically, according to previous studies on Urumqi Glacier No.1 (Wang et al., 2016; Xu et al., 2017). The coordinate system of RTK surveys is the World Geodetic System 1984 (WGS84).

The surveying parameters were configured as a compromise between ensuring high-level data quality and minimizing acquisition time. In order to avoid range ambiguity and to obtain the maximum scanning range of the glacier surface, coarse scanning was first implemented with vertical and horizontal angles range of 60–120° from zenith and 0–360°, respectively, and the laser pulse repetition rate was set to 50 kHz. On the basis of coarse scanning, we selected glacier surface terrain regions, and laser pulse repetition rate was then set to 30 kHz to carry out fine scanning for the regions of interest. The overlap percentage of each scan was not < 30% to meet the requirements of multi-station adjustment (MSA) (Mukupa et al., 2016). Surveying parameters of Urumqi Glacier No.1 are given in Table 1.