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Comparison of glaciological and geodetic mass balance at Urumqi Glacier No. 1, Tian Shan, Central Asia

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ABSTRACT

Glaciological and geodetic measurements are two methods to determine glacier mass balances. The mass balance of Urumqi Glacier No. 1 has been measured since 1959 by the glaciological method using ablation stakes and snow pits, except during the period 1967–1979 when the observations were interrupted. Moreover, topographic surveys have been carried out at various time intervals since the beginning of the glacier observations. Therefore, glacier volume changes are calculated by comparing topographic maps of different periods during nearly 50 years. Between 1962 and 2009, Urumqi Glacier No. 1 lost an ice volume of 29.51×10^6 m^3, which corresponds to a cumulative ice thickness loss of 8.9 m and a mean annual loss of 0.2 m. The results are compared with glaciological mass balances over the same time intervals. The differences are 2.3%, 2.8%, 4.6%, 4.7% and 5.9% for the period 1981–1986, 1986–1994, 1994–2001, 2001–2006 and 2006–2009, respectively. For the mass balance measured with the glaciological method, the systematic errors accumulate linearly with time, whereas the errors are random for the geodetic mass balance. The geodetic balance is within the estimated error of the glaciological balance. In conclusion, the geodetic and glaciological mass balances are of high quality, and therefore, there is no need to calibrate the mass balance series of Urumqi Glacier No. 1.

1. Introduction

Knowledge of the glacier mass balance is crucial both for climatic sensitivity studies and for understanding the hydrological behavior (Oerlemans and Fortuin, 1992; Fountain et al., 1999; Aizen et al., 2007; Bolch, 2007; Haeberli et al., 2008; Z.Q. Li et al., 2010; Z.X. Li et al., 2010; Z.Q. Li et al., 2011; Z.X. Li et al., 2011; Wang et al., 2012, 2013). However, there are only twelve mass balance programs with continuous observations dating back to 1960 (Zemp et al., 2009), and merely 33 glaciers worldwide have annual mass balance series longer than 40 years (Dyurgerov and Meier, 1999). The mass balance can be determined by various methods, including the glaciological, the geodetic and the hydrological-meteorological method. The glaciological and geodetic measurements are two commonly used methods (Hoinkes, 1970). Over the past decades, it has become a standard procedure to compare the glaciological with the geodetic mass balance method, utilizing techniques such as comparing digital elevation models (DEM) generated from topographic maps (e.g. Andreassen, 1999; Conway et al., 1999; Kuhn et al., 1999; Hagg et al., 2004; Andreassen et al., 2012), photogrammetry (e.g. Krimmel, 1999; Cox and March, 2004; Thibert et al., 2008; Haug et al., 2009; Huss et al., 2009; Fischer, 2010; Zemp et al., 2010), global positioning systems (GPS) (e.g. Hagen et al., 1999; Miller and Pelto, 1999) or laser altimetry (e.g. Echelmeyer et al., 1996; Sapiano et al., 1998; Conway et al., 1999; Geist and Stötter, 2007; Fischer, 2011). However, some studies (Østrem and Haakensen, 1999) show disagreeing results of the two methods, indicating that there were errors in the glaciological measurements. To decide whether a mass balance series needs calibration, Zemp et al. (2013) presented a conceptual framework for reanalyzing glacier mass balance series using statistical tools to assess the accuracy and errors of the glaciological and geodetic mass balance series.

With the glaciological method, the yearly point mass balances are obtained from ablation stakes and snow pits. These are then extrapolated over the glacier, based on the area-altitude distribution (AAD) (Østrem and Brugman, 1991). Systematic errors in field measurements increase linearly with the number of years and result in cumulative errors that are potentially problematic.

For the geodetic method, volume changes are used to estimate the mass balance over several years. The method is not suitable for annual change detection. As outlined by many studies, the intrinsic errors are mostly random (Finsterwalder, 1954; Echelmeyer et al., 1996; Andreassen et al., 2002; Cox and March, 2004; Cogley, 2009; Thibert and Vincent, 2009). Geodetic programs provide an independent check of the traditional mass balance measurements, by comparing the cumulative glaciological balances with the geodetic balances over ten or more years. Several studies have been undertaken to calculate the glaciological and geodetic mass balance and estimate the errors in the geodetic

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method, which are consistently about ±1 to 2 m w.e., depending on the map quality and photographs' condition (Andreassen, 1999; Krimmel, 1999; Cox and March, 2004). However, Krimmel (1999) reported a significant discrepancy between the two types of measurements and suggested the water-equivalent conversion and the area integration as possible sources of bias.

Urumqi Glacier No. 1, located in the eastern Tian Shan, in the middle of Central Asia, is considered as the best-monitored glacier in China. The continuous record of mass balance measurements begins in 1959/1960 and, thus, is among the longest worldwide. Since the 1950s, the glacier surface elevation has been surveyed eight times at intervals of several years and the glacier terminus twice every year. Because of the extensive glacier data sets available, Urumqi Glacier No. 1 can be considered as one of the test glaciers to study the glaciological and geodetic methods to determine the mass balance. The aims of this study are therefore to quantify the ice volume changes of Urumqi Glacier No. 1 during the period 1962–2009, to determine the geodetic balance over five time intervals, to compare the mass balances measured with the geodetic and glaciological method and to evaluate if the glaciological record needs to be calibrated.

2. Geographical setting

Urumqi Glacier No. 1 (43°06′N, 86°49′E) is located on the northern slope of Tianger Peak II (4484 m a.s.l.), eastern Tian Shan and at the headwaters of the Urumqi River. It is a northeast facing valley glacier with two branches covering 1.646 km^2 in 2009 (Fig. 1). The elevations of the East Branch and the West Branch range from 4267 m to 3743 m a.s.l. and 4484 m to 3845 m a.s.l., respectively. As described by Ageta and Fujita (1996), Urumqi Glacier No. 1 is classified as a summer-accumulation-type glacier because both accumulation and ablation occur in the summer. For the past several decades, Urumqi Glacier No. 1 has experienced a rapid and accelerated shrinkage (e.g. Han et al., 2006; Jing et al., 2006; Z.Q. Li et al., 2010). Because of glacier retreat, the glacier separated into two independent branches in 1993. Observed surface velocities on Urumqi Glacier No. 1 indicate that it is predominantly cold-based, with basal sliding occurring only close to the snouts and in summer (Zhou et al., 2009).

The region is dominated by the westerly circulation and the Siberian High. The precipitation originates mainly from the moisture carried by the westerlies in summer, while the winter temperature is controlled by the Siberian High (Aizen et al., 1995; Xu et al., 2009). During the past 50 years, the annual equilibrium line altitude (ELA) of the glacier was in average at approximately 4050 m a.s.l. (Wu et al., 2011).

At the Daxigou Meteorological Station (3539 m a.s.l.), 3 km southeast of Urumqi Glacier No. 1, the annual mean air temperature measured is about −5.0 °C, and the annual mean precipitation is 456 mm during 1959–2010. For the study period (1981–2010), the standard deviation values for the annual mean temperature and precipitation are 0.7 °C ($p < 0.01$) and 80.8 mm ($p < 0.05$), respectively. The linear trend analysis in Fig. 2 indicates that the annual mean temperature increased by approximately 0.603 °C $(10\ a)^{-1}$, and the annual precipitation had been increasing gradually with an average rate of 37.87 mm $(10\ a)^{-1}$.

Observations of Urumqi Glacier No. 1 were initiated in 1959, implemented by the Tianshan Glaciological Station, Chinese Academy of Sciences (CAS) (Li et al., 2003). It is one of the reference glaciers reported to the World Glacier Monitoring Service (WGMS), representing the glaciers in the Tian Shan due to its important location, ease of access and significance to local water supply. It provides the longest glaciological and climatological record of a glacier monitored in China and has been a major focus for glaciological, hydrological and climatological research in Central Asia.

3. Data and methods

3.1. Glaciological method

The glaciological method, or the so-called direct or traditional method, is used to measure the mass balance based on in situ determination of accumulation and ablation for the mass balance year (Hoinkes, 1970; Braithwaite, 2002). The glacier mass balance at Urumqi Glacier No. 1 is measured following the glaciological method as described by Østrem and Brugman (1991). The mass balance has been measured on a monthly basis from 1 May to 30 August since 1959 by the stake/snow pit method (Xie and Huang, 1965; Yang et al., 1992; Braithwaite, 2002), representing the longest time series in China. With the stakes, accumulation is

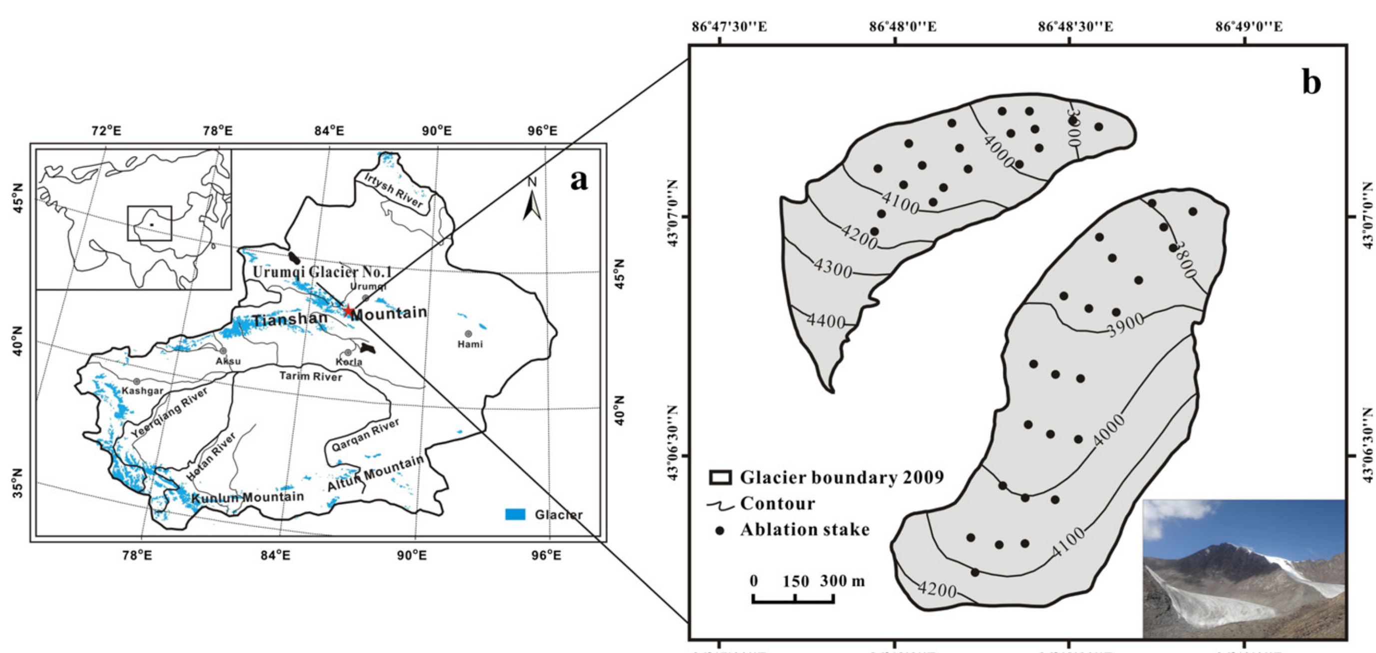

Fig. 1. (a) Location of Urumqi Glacier No. 1 within the eastern Tian Shan, Central Asia, and (b) an overview of Urumqi Glacier No. 1 with the ablation stake network in 2008. The photo in the bottom-right corner was taken by Zhongqin Li in 2009.