

Thinning and retreat of Xiao Dongkemadi glacier, Tibetan Plateau, since 1993

It is important to monitor glaciers and ice caps for their contribution to sea-level change and as sensitive indicators of local climate (Hoelzle and others, 2003; Oerlemans, 2005; Kaser and others, 2006; Meier and others, 2007). However, glacier mass-balance estimates determined by the direct glaciological method once or twice per year contribute very little to sea-level information (Braithwaite, 2002), and more data from measured glaciers are necessary to better extrapolate to particular glacier regions to examine their contribution (Hoelzle and others, 2003; Arendt and others, 2006; Haerberli and others, 2007a). Ice-elevation changes derived from multi-period digital elevation models (DEMs) offer one method of evaluating glacier mass balance through time. However, this method does not produce detailed interannual records like the traditional mass-balance technique (Pope and others, 2007; Berthier and others, 2008).

Xiao Dongkemadi glacier (XDG) is located near Tanggula Pass (the highest point on the Lanzhou–Lhasa road 5206 m a.s.l.), central Tibetan Plateau (33°04' N, 92°04' E). Here, glacier mass balance directly reflects the glacier's response to local climate change, and glacier changes on the Tibetan Plateau strongly influence human welfare since water supplies in this arid/semi-arid region are predominantly from glacier melt. Due to its remote location, the mass balance of XDG has been monitored discontinuously since 1988 by the direct glaciological method (Pu and others, 1998; Yao and others, 2007). Measured annual mass balances were 525, 49.4, –190.9, 375.8, 211.4, –517.9, –597, –506.4, 370 and –670 mm, respectively, for the years 1989–98. Mass balance has been negative most of the time since 1993. Here, we present results from a topographic map in 1969, observations between 1989 and 1998, and real-time kinematic (RTK) global positioning system (GPS) surveys in October 2007.

We have GPS measurements covering almost the entire glacier on 13 October 2007. We have surveyed 722 points on XDG within the glacier area, 1.20 km² (Fig. 1), at a sampling spacing of 25–50 m. All GPS data, measured with respect to the Universal Transverse Mercator (UTM) World Geodetic System 1984 ellipsoidal elevation (WGS84), were re-projected and transformed to the 1954 Beijing Geodetic Coordinate system (BJ54) GEOID (datum level is Yellow Sea mean sea level at Qingdao Tidal Observatory in 1956) using LandTop software version 2.0.5.1. The method of measuring a surface point in RTK differential mode results in a survey error of ~0.10–0.30 m for geodetic-quality GPS receivers (Rivera and others, 2005). The error using a seven-parameter space transform model is <0.002 m (Wang and others, 2003). We interpolated our GPS data to contours at 5 m intervals to generate a 2007 DEM (DEM2007) with a pixel resolution of 10 m, supported by Geographic Information System (GIS)-based methodology.

Another DEM for 1969 (DEM1969), with respect to BJ54, was produced by digitizing the 20 m interval contours and spot heights from a topographic map, interpolated and filtered with 10 m cell size, using Arcmap software. The map was derived from aerial photographs acquired in 1969 by the Chinese military geodetic service. The systematic errors of DEM1969 were $\leq \pm 11$ m over slopes $< 15^\circ$ and $\leq \pm 19$ m over slopes $> 25^\circ$ (State Bureau of Surveying and Mapping,

2007). However, the differences between DEM1969 and DEM2007 are within ± 5.2 m (with standard deviation, 2.4 m), ascertained by comparison at nine random independent points selected in surrounding non-glacial areas under 5600 m a.s.l.

Comparing the two DEMs (2007 with 1969), the mean ice elevation over XDG decreased by ~ 7.92 m, or 0.21 m a^{-1} . The largest decrease in ice elevation of 63.51 m was at the tongue, corresponding to a retreat of the glacier terminus of ~ 77 m. In addition, there was considerable variability of the elevation change with height (Fig. 1). The elevation change over the full study period was large (about –15 to –63.51 m) below ~ 5500 m a.s.l. It was negative between 5500 and 5600 m a.s.l., but slightly positive near 5650 m a.s.l. As a consequence the equilibrium line altitude (ELA) position, estimated to be 5650 m a.s.l. in 2007 for zero balance, is ~ 105 m higher than in 1993 (5545 m a.s.l.) (Pu and others, 1998). The ice-elevation changes are complex above 5650 m a.s.l., which is in the accumulation region. However, the error increases along with increased slope in parts of the accumulation region.

Summarizing, XDG has experienced two main change phases during the period 1969–2007. The elevation of XDG increased by an average of ~ 4.60 m, or 0.19 m a^{-1} , corresponding to a tongue advance of 16.9 m from 1969 to 1993 (Pu and others, 1998; Yao and others, 2002). After 1993, the ice surface elevation decreased ~ 1.62 m (0.54 m a^{-1}) from 1993 to 1996 and decreased by ~ 11.0 m (1.1 m a^{-1}) from 1996 to 2007, corresponding to a tongue retreat of 93.9 m between 1993 and 2007. These results support the finding that the observed acceleration trend corresponds to similar developments elsewhere and even at a global scale (Haerberli and others, 2007b). The first phase may be explained by a drop in summer temperature. Between 1969 and 1993 the mean temperature at TuoTuo weather station (34°13' N, 92°26' E; 4533.1 m a.s.l.) was 0.12°C lower than the 1957–2002 mean temperature. Associated with the temperature reduction, there was a reduction in the ablation on XDG, resulting in the advance of the glacier tongue. The second phase was triggered by summer warming by $\sim 0.65^\circ\text{C}$ after 1993, accompanied by increased annual precipitation, causing negative surface mass balance, which led to glacier retreat.

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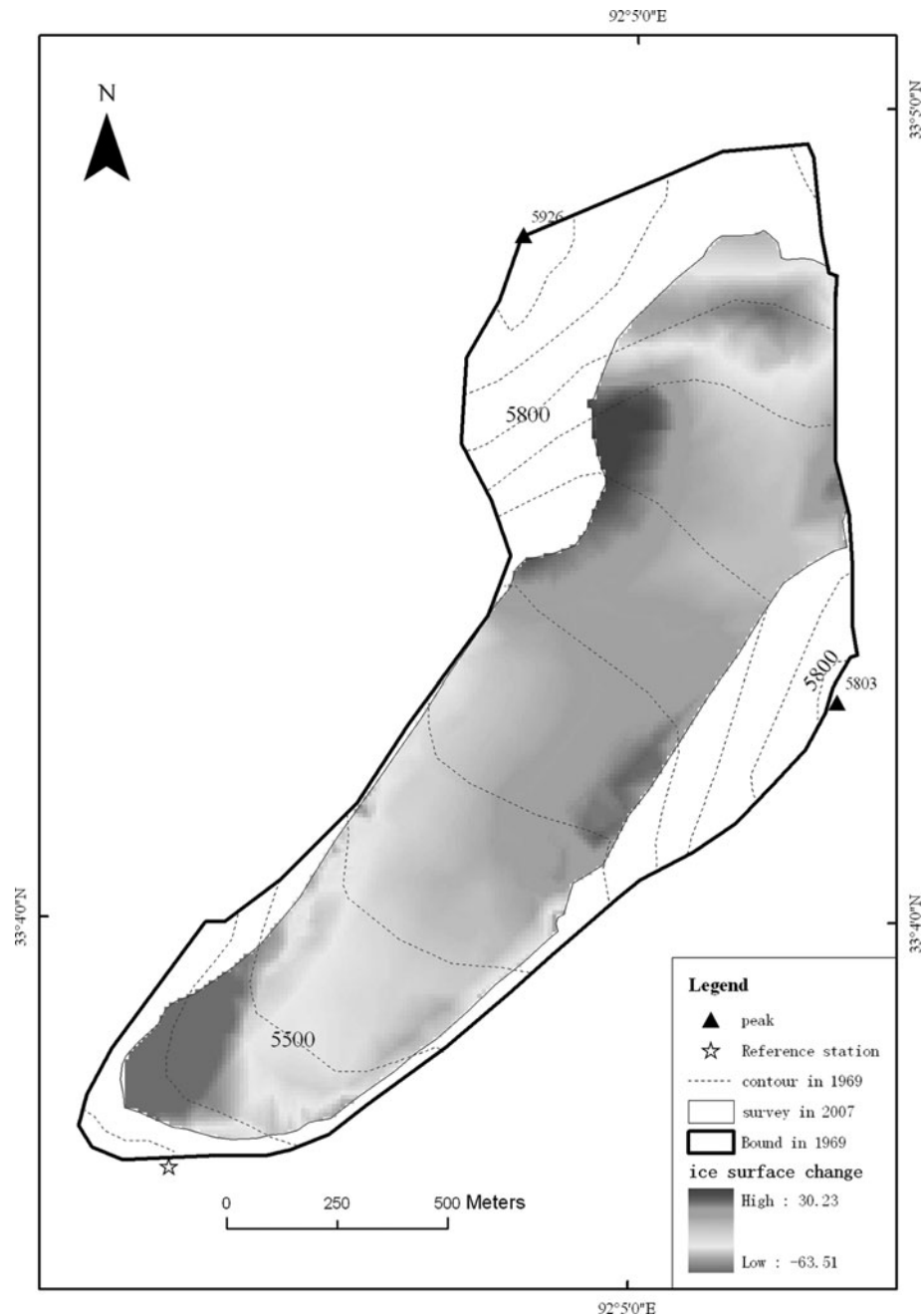


Fig 1. XDG ice-elevation changes based on DEMs developed from a topographic map (1969) and kinematic global positioning system (GPS) data (2007).

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