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Recent slowdown and thinning of debris-covered glaciers in south-eastern Tibet

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ABSTRACT

Recent large-scale remote sensing studies have shown that glacier mass loss in south-eastern Tibet, specifically in the eastern Nyainqêntanglha Range exceeds the average in High Asia. However, detailed studies at individual glaciers are scarce and the drivers behind the observed changes are poorly constrained to date. Employing feature tracking techniques on TerraSAR-X data for the periods 2008/2009, 2012/2013 and 2013/2014 we found measurable surface velocities through to the glacier terminus positions of five debris-covered glacier tongues. This is contrary to debris-covered glaciers in other parts of High Asia, where stagnant glacier tongues are common. Our feature tracking results for the 2013/2014 period suggest an average deceleration of 51% when compared with published Landsat velocities for the period 1999/2003. Further, we estimated surface elevation changes for the five glaciers from recently released one arc second resolution elevation data obtained during the Shuttle Radar Topography Mission in 2000 and an interferometrical derived TanDEM-X elevation model for the year 2014. With an average rate of -0.83 ± 0.57 m a^{-1} we confirm strong surface lowering in the region, despite the widely discussed insulation effect of debris cover. Beside the influence of thermokarst processes and delayed response times of debris-covered glaciers, we highlight that abundant monsoonal summer rainfall might contribute significantly to the pronounced negative mass balances in the study region.

1. Introduction

Recent large-scale remote sensing studies based on satellite laser altimetry data and differencing of digital elevation models (DEMs) have shown a heterogeneous pattern of glacier mass changes in High Asia (Gardelle et al., 2013; Neckel et al., 2014; Kääb et al., 2015). While balanced or slightly positive mass balances are evident for parts of the Pamirs and the Karakorum in recent years, pronounced negative glacier mass balances were found in south-eastern Tibet, specifically in the eastern Nyainqêntanglha Range. Details about these glaciers' specific response to climate change are, however, scarce, because few local glaciological mass balance measurements exist and multi-annual records are lacking. Furthermore, meteorological station records are rare and can not directly be transferred to the glacierized high mountain regions, as most stations are located in inhabited river valleys. Even if glaciers are located in the same climatic environment, local parameters such as catchment aspect, topography and debris cover can have a significant impact on how a specific glacier responses to climate change (Kääb, 2005; Scherler et al., 2011).

The combination of high mountain topography and abundant moisture facilitates ~8000 km^2 of glaciated area in the eastern Nyainqêntanglha Range, including some of the largest glaciers in High Asia (Shi et al., 2010; Hochreuther et al., 2015; Loibl et al., 2015). This study focuses on five debris-covered valley glaciers in the central-northern part of the mountain range, specifically in the upper reaches of Lequ Valley and Bodui Valley (Fig. 1). Glaciers in the study area are reported to be of temperate type and are influenced by the South Asian monsoon circulation (Shih et al., 1980; Huang, 1990). These glaciers receive most precipitation in summer and/or spring, which falls as snow in their high altitude accumulation areas, resulting in the coincidence of maximum accumulation and ablation phases (Maussion et al., 2014; Loibl et al., 2014). The lower portions of many temperate glaciers in this region are covered by supraglacial debris (Wei et al., 2010). Debris-covered glaciers are known to react differently to warming when compared to clean-ice glaciers, as the debris cover insulates

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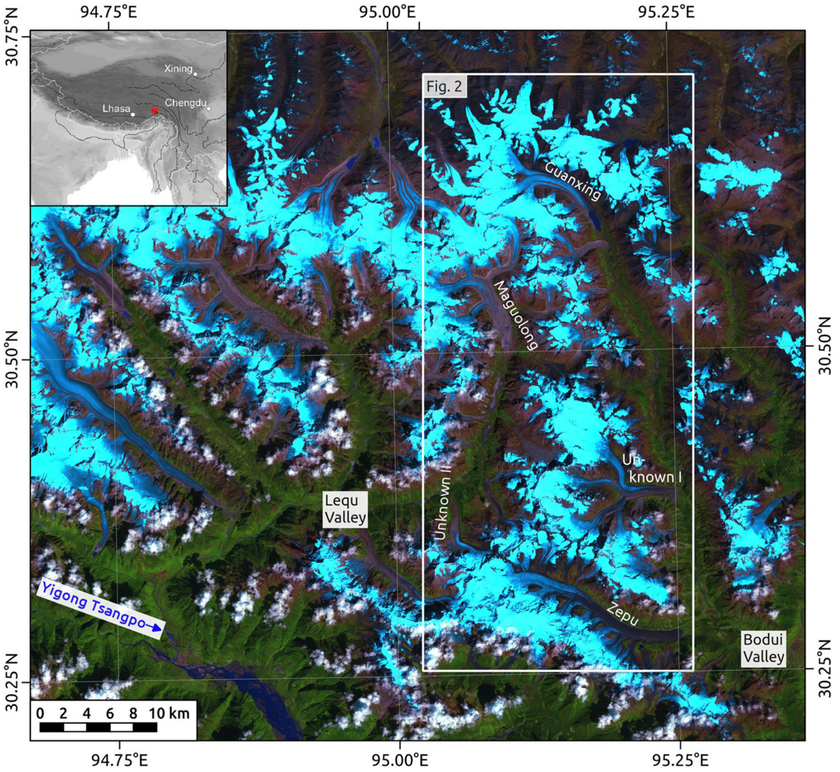

Fig. 1. Regional overview of the study area in the eastern Nyainqêntanglha Range, south-eastern Tibet. Location of Fig. 2 and the five investigated glaciers are indicated. Background: Landsat-7 ETM+, bands 5-4-3-pan, acquired on 23 September 1999.

the glacier surface provided a sufficient thickness of a few centimeters is reached (Östrem, 1959; Reznichenko et al., 2010). Due to this insulating effect debris-covered glaciers can extend to lower elevations than clean-ice glaciers would in a similar geographic environment (Rowan et al., 2015). However, this insulating effect is well known on local scales, but it remains unclear whether it can be applied to entire glacier tongues (Kääb et al., 2012).

Observations of glacier velocities and surface elevation changes are important parameters to better understand the current state of glaciers and their interaction with changes in regional climate conditions (Cuffey and Paterson, 2010; Paul et al., 2015; Thakuri et al., 2016). In this study, we applied a feature tracking approach based on TerraSAR-X data to derive glacier surface velocities for the periods 2008/2009, 2012/2013 and 2013/2014. The resulting velocity fields were compared to optical remote sensing-based estimates for the period 1999/2003 as published by Dehecq et al. (2015). The velocity fields and their interannual variability were analyzed to investigate glacier dynamics in this key region where no *in-situ* measurements are available. Further we discuss the differences to other debris-covered glaciers in the Himalayas and on the Tibetan Plateau. Additionally, we employed data from the TerraSAR-X add-on for Digital Elevation Measurement (TanDEM-X) mission to calculate recent glacier surface elevations. In order to estimate glacier surface elevation changes between 2014 and 2000 the TanDEM-X elevations were compared to digital elevation data from the Shuttle Radar Topography Mission (SRTM). Here, preference was given to the recently released one arc second version of the dataset. By conducting an integrated analysis of measured glacier velocities and surface elevation changes we investigated spatial and temporal properties of glacier dynamics against the background of the monsoonal climate setting in the study area.

2. Data and methods

2.1. Glacier surface velocities

Surface velocities between the periods 2008/2009, 2012/2013 and 2013/2014 were derived from intensity/feature tracking on repeat-pass TerraSAR-X satellite imagery (see Rankl et al., 2014, and references therein, for details). Based on the image intensity, this technique tracks surface features and, if coherence is retained, the speckle pattern on a pair of co-registered, single-look complex (SLC) images from two different acquisition dates. The tracking algorithm uses the maximum of cross correlation in a pre-defined moving search window. For this, a window size and a step size between patches need to be defined. After testing different search window sizes, we chose a final window size of both 256 pixels in range and azimuth with a step size between patches of 25 pixels in range and azimuth. This setting was found to be most robust considering the long time interval between data acquisitions. Table 1 lists the TerraSAR-X scenes which were used for the synthetic aperture radar (SAR) offset tracking. Surface velocities for the period 1999/2003 are based on Landsat estimates following the method of Dehecq et al. (2015). The velocity field was obtained from a stack of velocities derived from feature tracking on Landsat-7 band 8 image pairs separated by approximately one year. For the final stack, all available Landsat-7 acquisitions over the period 1999/2003 were used (Dehecq et al., 2015, A. Dehecq, personal communication, March 2016).

2.2. Surface elevation changes

Surface elevation changes (Δh) were calculated between data from the Shuttle Radar Topography Mission (SRTM) acquired in 2000 (Rabus et al., 2003; Farr et al., 2007) and the 2014 TanDEM-X acquisition, which was also employed for the 2013/2014 velocity field (Table 1). Here, we make use of the SRTM C-band DEM with