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Reconstructing glacier retreat since the Little Ice Age in SE Tibet by glacier mapping and equilibrium line altitude calculation

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ABSTRACT

Temperate glaciers in the eastern Nyainqêntanglha Range, southeastern Tibet, are highly sensitive to climate change and therefore of particular high interest for research on late Holocene changes of the monsoonal climate in High Asia. However, because of the remoteness of the area, the scarcity of empirical data, and the challenges to remote sensing work posed by cloud and snow cover, knowledge about the glacier dynamics and changes in this region is still very limited. In this study, we applied a remote sensing approach in which 1964 glaciers were mapped from a Landsat ETM+ scene and subsequently parameterized by DEM-supported measurements. Geomorphological evidence, i.e., trimlines and latero-frontal moraines, were used to obtain quantitative data on the glaciers' morphological characteristics and the changes since the Little Ice Age (LIA) maximum glacier advance. Statistical analysis of glacier length change revealed an average retreat of ~27% and a trend toward stronger retreat for smaller glaciers. An evaluation of different methods to calculate equilibrium line altitudes (ELAs) indicates that an optimized toe-to-ridge altitude method (TRAM) is more suitable than other methods in settings with complex topography and a lack of mass balance measurements. A large number of glacier measurements are crucial for high quality of TRAM results, and special attention has to be paid to different glacier characteristics. In order to determine the best-fitting TRAM ratio value and to test the quality of the calculated ELAs, a remote sensing approach was applied: for each investigated glacier, the altitudes of transient snowlines visible in the late summer Landsat scene were measured from the DEM and compared to TRAM results. The interpolated ELA results show a SE–NW gradient ranging from 4400 to 5600 m asl and an average ELA rise of ~136 m since the LIA. Because of the high spatial resolution of measurements, the ELA distribution reveals topographic effects down to the catchment scale, specifically orographic rainfall and leeward shielding. The interpretation of these patterns reveals that the eastern Nyainqêntanglha Range is influenced by both, the Indian (ISM) and East Asian summer monsoon (EASM). However, the EASM does not reach the western part of the study area. The results indicate that the monsoonal temperate glaciers' high sensitivity to climate change is driven by two double forcings owing to the coincidence of accumulation and ablation phases.

1. Introduction

The Tibetan Plateau is of central importance for the global circulation systems and the regional climate of High Asia (e.g., Murakami, 1987). The Asian summer monsoon is characterized by the double branch system of Indian summer monsoon (ISM) and East Asian summer monsoon (EASM). From May to September, a complex interplay of both pressure gradients is responsible for the transport of humid air masses from the Bay of Bengal (ISM) and the Pacific Ocean (EASM) to the Tibetan Plateau. In particular, the southeastern part of the Tibetan Plateau and its adjoining highlands are characterized by a hydrological gradient of decreasing precipitation toward the inner Tibetan Plateau (Benn and Owen, 1998). Thus, monsoonal summer precipitation is of major importance for the accumulation of the region's glacier ice, which acts as a long-term storage and source for the major rivers of south and southeast Asia supplying water for more than 1.4 billion people (Immerzeel et al., 2010).

Glaciers in the southeastern part of the Tibetan Plateau, especially in the eastern Nyainqêntanglha Range, have a maritime temperature regime and are highly sensitive to climate change (Zhou et al., 1991). Higher ice-layer temperatures lead to reduced nourishment, therefore temperate glaciers show remarkably high ice flow velocities. For

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Abbreviations: AAR, accumulation area ratio; AABR, area-altitude balance ratio; ASTER, advanced spaceborne thermal emission and reflection radiometer; BR, balance ratio; EASM, east Asian summer monsoon; ELA, equilibrium line altitude; GDEM, global digital elevation model; GIC, Glacier Inventory of China; IDW, inverse distance weighted; ISM, Indian summer monsoon; LIA, Little Ice Age; SRTM, shuttle radar topography mission; THAR, toe-to-headwall altitude ratio; TRAM, toe-to-range altitude method; TSAM, toe-to-summit altitude method; TSL, transient snowline.

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example, Zheng et al. (1999) measured flow rates of 438 m/y and 533 m/y for Azha (29°32.05′ N., 96°06.06′ E.) and Minyong (28°26.33′ N., 98°41.01′ E.) glaciers, respectively. In the study area, dynamics of glacier advances and retreats are directly controlled by monsoon intensity and temperature. However, details of the spatiotemporal interaction of climate and glaciers in southeast Tibet are still not fully understood. A major problem is the lack of empirical data: mass balance measurements and meteorological stations are very sparse and data cover only short timespans (e.g., W. Yang et al., 2010b). Furthermore, the meteorological stations are situated in valley bottoms, whereas glaciers are located within the alpine or nival zone. Concluding, the knowledge on local climate and glacier response is as yet very limited. Particularly, the influence of monsoonal systems and precipitation is not yet well understood.

Remote sensing data offers the opportunity to obtain detailed information concerning the modern state of glaciation (Raup et al., 2007; Paul, 2010) and its recent changes (e.g., Bolch et al., 2008). However, the changes before the oldest available satellite imagery from the mid-twentieth century cannot be mapped from ice extents. In order to obtain information about former glacial history, proxy archives have to be used. Geomorphological records such as glacial landforms of former maximal glacier stands and lateral or terminal moraines can serve as archives of changes within the landscape. In contrast to the European Alps, where surveys of glaciology and glacial geomorphology date back until the early twentieth century (e.g., Penck and Brückner, 1909; see Fiebig et al., 2011 for an overview), historical data sets on glaciers in southeast Tibet are scarce. In this context, the so-called Little Ice Age (LIA) is of particular interest. This worldwide cooling period began in the sixteenth century and lasted until the end of the nineteenth century (Grove, 2003). Dendrochronological studies in southeastern Tibet have shown that vegetation succession delineates moraines of the LIA maximum glacier advance (Bräuning, 2006). The outer walls of the LIA moraines are typically covered by successional forests, whereas younger moraines host only few pioneer species. In contrast, the debris-covered glacier tongues are free of higher vegetation species. Because this pronounced vegetation threshold represents a clear marker within the landscape, remote sensing can serve as a promising tool to delineate the spatial extent of glacier retreat since the LIA.

The equilibrium line altitude (ELA) is the theoretical line at which accumulation and ablation are in balance over the period of one year (Porter, 1975; Benn and Lehmkuhl, 2000). Several studies have demonstrated the possibility to derive reliable estimations of present and former ELAs by methods that are based on measurements of geometric parameters of glacial geomorphological features (e.g., Meierding, 1982; Savoskul, 1997). However, the methods based on glacier morphology have been criticized to be rather crude in comparison to ELAs derived from actual mass balance measurements (Benn et al., 2005). It is therefore important to carefully assess the applied ELA method and validate the results (Benn and Lehmkuhl, 2000). The ELA calculations for different time slices represent the relative changes in mass balance over the given time span. In the context of ELA calculations, the LIA maximum is of particular high relevance; it represents the last major turning point in glacial development, switching from an advancing to a retreating regime. Theoretically, at this point all glaciers were in a steady-state, i.e., ice mass and geometry were in equilibrium with climate (Benn and Lehmkuhl, 2000). Taking into account different glacier response times caused by differences in size, topography, etc., the ELA of the LIA maximum represents an important reference level for the evaluation of post-LIA glacier changes (Maisch, 1981). The ELA estimates of previous studies in the eastern Nyainqêntanglha diverge widely: Shi and Li (1981) suggested a range from 4400 to 5200 m asl, whereas Yao et al. (2010) presented ELAs of 3370–5490 m asl for the Yigong Tsangpo and 3560–5980 m asl for the Parlung Tsangpo catchment.

In order to establish links between glacier change and climatic or topographic parameters, the situation at the individual glacier scale has to be analyzed in detail. Detailed glacier mapping has a long scientific tradition and provides insight into each glacier's state (Ashwell, 1982). Haeberli (2004) pointed out that changes in glacier length are among the most reliable and most easily observed terrestrial indicators of climate change. A topographical factor of particular strong influence in subtropical mountain environments is the aspect, which affects the amount of insolation received at the surface. In High Asia, slopes

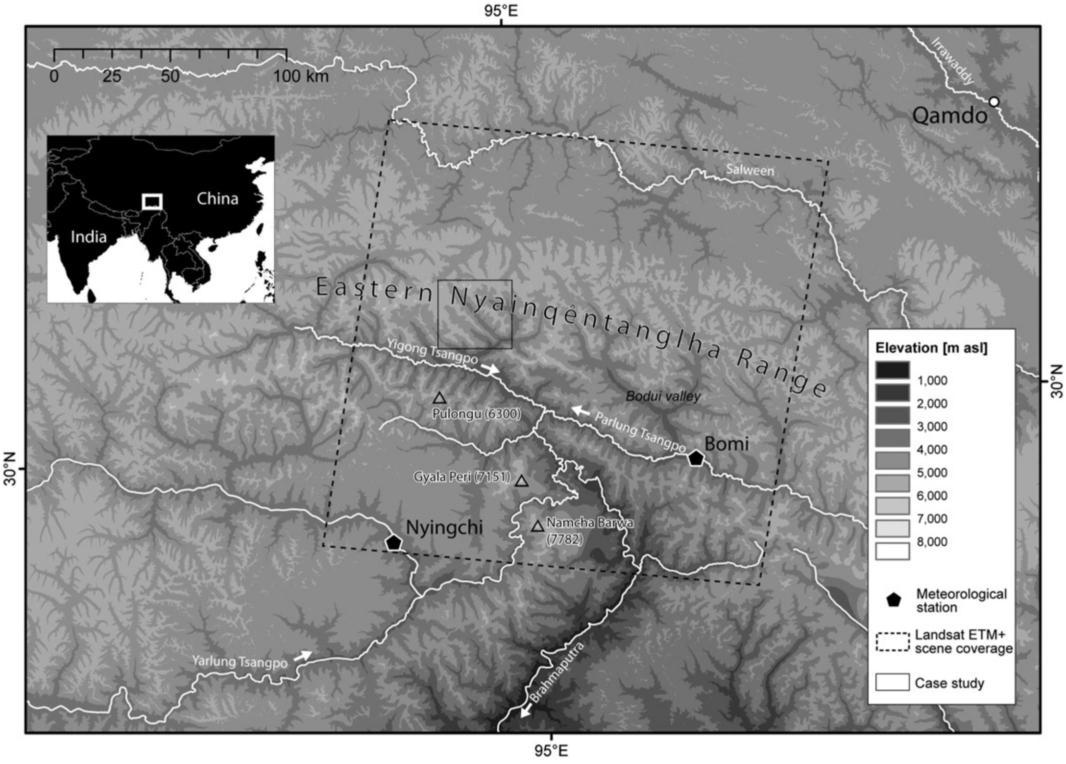

Fig. 1. Study area in southeastern Tibet. Elevations are based on SRTM data.