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Reconstruction of late Holocene glacier retreat and relevant climatic and topographic patterns in southeastern Tibet by glacier mapping and equilibrium line altitude calculation

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Temperate glaciers in the eastern Nyainqêntanglha range, southeastern Tibet, are highly sensitive to climate change and are therefore of particular high interest for research on late Holocene changes of the monsoonal climate in High Asia. However, due to 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 is still very limited. We applied a remote sensing approach that allowed a comprehensive regional glacier survey despite the few available data. Geomorphologic characteristics, distribution and late Holocene changes of 1964 glaciers were mapped from one of the few appropriate late summer satellite images: a Landsat ETM+ scene from September 23, 1999. The glacier dataset was subsequently parameterized by DEM supported measurements. Complex climate-relief-glacier interactions were studied in detail for three large glaciers in neighboring valleys. Despite their spatial proximity, these display strong heterogeneity in terms of catchment morphology, debris cover, and glacier characteristics. The results of this case study then provided the conceptual basis to use geomorphological evidence, i.e. trimlines and latero-frontal moraines, to obtain quantitative data on the changes since the Little Ice Age (LIA) maximum glacier advance. Statistical analysis of glacier length change revealed an average retreat of $\sim$ 40 % and a trend towards 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) outperforms other methods in settings with complex topography and a lack of mass-balance measurements. However, a large number of glacier measurements is crucial for high quality TRAM results and special attention has to be paid to different morphological glacier characteristics: debris-cover, reconstitution, valley floor limitation, and detachment of glacier tributaries, are criteria that prevent reliable ELA calculations. 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: the altitudes of transient snowlines visible in the late summer Landsat scene were measured from the DEM and compared to TRAM results for each glacier. The interpolated ELA results show a southeast-northwest gradient ranging from 4,400 to 5,600 m a.s.l. and an average ELA rise of $\sim$ 98 m since the LIA. Due to the large amount of measurements, the ELA distribution reveals topographic effects down to the catchment scale, i.e. orographic rainfalls and leeward shielding. Contrasting to the expectations for subtropical settings, glaciers on south facing slopes have not retreated strongest and ELAs on south facing slopes did not rise furthest. Instead, highly heterogeneous spatial patterns emerge that show a strong imprint of both, topography and monsoonal dynamics. The interpretation of these patterns provides insights into the monsoonal system and the characteristics of late Holocene glacier change in southeastern Tibet. For example, the ELA distribution reveals that the study area is influenced by both, Indian summer monsoon and East Asian summer monsoon, but that the latter does not reach the Tibetan Plateau.