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Reconstruction of Little Ice Age glacier area and equilibrium line attitudes in the central and western Himalaya

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A B S T R A C T

Glacial changes during the Little Ice Age (LIA) in the Himalayan Mountains are important for understanding changes in the monsoonal and westerly climate of the so-called 'the Third Pole'. However, knowledge of these changes and their dynamics remains limited because of the region's geographical inaccessibility, in addition to geopolitical reasons. In this study, we used high resolution three-dimensional images from Google Earth to identify lateral and terminal moraines as delineators of paleoglacier boundaries, and mapped the boundaries of both modern and LIA glaciers. ArcGIS 9.3 software was applied to map data and to calculate glacier lengths and areas; modern glacier surface elevation data were derived from SRTM (Shuttle Radar Topography Mission) records. Three methods, the toe-to-headwall altitude ratio (THAR), the toe-to-summit altitude method (TSAM), and the toe-to-ridge altitude method (TRAM) were used to estimate equilibrium line altitude (ELA). The transient snowlines (TSL) of ninety-one modern glaciers were acquired using Landsat 8 OLI images in late summer to evaluate the reliability of the calculated ELAs. Our results showed that the total length and total area of two hundred and twenty glaciers in the central and western Himalaya (CWH) had decreased respectively by 35% and 31% since the LIA. The TRAM method was the preferred method for the reconstruction of ELAs. The mean depression of ELAs from the LIA to the first decade of the 21st Century, as reconstructed using the TRAM method, was 123 m. The ELA depression and rate of change of glacier length and glacier area displayed generally increasing trends from west to east along the central and western Himalaya, suggesting that the moisture was most likely transported from an easterly direction. These changes were more intensive on southern than northern slopes, suggesting that southerly and westerly precipitation likely increased over the same period. We speculated that the CWH had been influenced by both the Indian Summer Monsoon (ISM) and Westerlies since the LIA. ISM moisture, as in modern times, was the main factor controlling the distribution of glaciers during the LIA. Further, precipitation carried by the Westerlies likely intensified along southerly pathways along the CWH during the LIA.

1. Introduction

The Himalayan Mountains represent one of the most intensively glacier-occupied areas in the Tibetan Plateau (TP). The climate in this huge mountain system is controlled by both the Indian Summer Monsoon (ISM) and the Westerlies (Yao et al., 2012). Most Himalayan glaciers belong to the "summer-accumulation" type (Yang et al., 2013), and monsoonal summer precipitation makes a major contribution to glacial accumulations (Loibl et al., 2014). The summer period is characterized by the Indian Summer Monsoon (ISM), which transports significant quantities of precipitation to the region (Fujita, 2008a). Glaciers are highly sensitive to any changes in temperature and precipitation. This sensitivity, as exhibited by both modern glaciers and paleoglaciers, has been of especial interest to scientists (Shi, 2002; Owen and Benn, 2005; Fujita, 2008b; Mölg et al., 2013; Kotlia et al., 2012; Yao et al., 2012; Xu, 2014; Xu et al., 2013; Xiang et al., 2014). Research has established that

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Himalayan glaciers have extensively retreated over recent decades (Bagla, 2009; Bolch et al., 2012; Kulkarni et al., 2007; Ma et al., 2010; Yao et al., 2012).

Historical changes in glacier area have been investigated in several regions of the Himalaya (Asahi, 2010; Benn et al., 2005; Benn and Lehmkuhl, 2000; Loibl et al., 2014; Lobil and Lehmkuhl, 2015). In the central and western Himalaya (CWH), the most extensive glaciation occurred during Marine Isotope Stage 3 (MIS3) in response to an intensified ISM (Owen et al., 2005, 2009, 2010). However, spatial variations in glacial change during the LIA, along Himalayan transects, remains largely uninvestigated. The changing areas of modern glaciers on the TP differ significantly according to spatial variations in the levels of precipitation (Yao et al., 2012). Understanding such changes in the Himalaya since the LIA will allow us to obtain a more profound understanding of the mechanisms behind modern and paleoglacial climate change.

Loibl et al. (2014) reconstructed glacier area and ELAs during the LIA in the eastern Himalaya. They suggested that temperate glaciers were highly sensitive to monsoon intensity and temperature owing to the coincidence of the phases of accumulation and ablation. In this study we focused on the reconstruction of glacier area and ELAs during the LIA in the CWH using Google Earth and Shuttle Radar Topography Mission (SRTM) images. We did this to illustrate the possible linkage between glacier retreat and climate change along the CWH.

2. Regional setting and distribution of glaciers

The Himalaya are located on the southern border of the TP, with seven of the highest peaks >8000 m above sea level (asl). This great mountain chain extends over 2400 km in a W-E direction. The boundaries of the eastern, central and western Himalaya remain undefined. The CWH to which this paper refers is located between 80°E and 92°E. Two hundred and twenty glaciers from 13 massifs of the CWH were chosen for the study of glacier change since the LIA. Ten meteorological stations were chosen to analyze variations in precipitation and temperature over the past few decades (Fig. 1). The climate in this region is strongly influenced by both the ISM and the southern branch of the Westerlies (Yao et al., 2012). The moisture transported from the Arabian Sea is obstructed from overriding the high mountains to the north (Bothe et al., 2011), so falls in substantial quantities on the southern slope of the CWH. Therefore, the climate in the CWH, particularly on its northern side, is semi-arid, with low precipitation. Gauge observations, reanalyses and satellite retrievals display a clear declining trend in annual precipitation from east to west along the Himalaya (Maussion et al., 2014; Tong et al., 2014a, 2014b). This is in stark contrast to the wet eastern Himalaya.

From west to east, the chosen massifs are the Naimona'nyi (Gurla Mandhata), Ganglung Gangri, Rachama, Kubi Gangri, Peiku Gangri, Shishapangma, Lapche Kang, Qomolangma (Qomolangma, or Mt. Everest), Chorten Nyima Ri, Chomo Yummo, Kangcheda, Kangkar Pünzum (Gangkhar Puensum) and Kula Gangri (Fig. 1). Information regarding the LIA glaciers studied was collected using Google Earth imagery. One hundred and twenty-five glaciers are north-facing, northwest-facing or northeast-facing, 65 glaciers are south-facing, southwest-facing or southeast-facing, nine glaciers are west-facing, and 21 glaciers are east-facing. Further detailed information is provided in the introduction to each massif. Modern glacier boundaries can be identified clearly from high-resolution Google Earth images. Fig. 2 shows the key features of each glacier across all 13 massifs, as depicted by Google Earth.

Mount Naimona'nyi (81.3°E, 30.4°N) is located in the Nalakankar Himal subrange in southern Tibet. The massif rises from 3800 m asl to 7694 m asl over a distance of 25 km. Eighteen modern glaciers and 16 LIA glaciers have been investigated. Today there are cirques, valley glaciers, and a small ice cap on the massif. The glacial moraines, troughs, cirques and pyramid peaks on the northern and western slopes of the massif were first reported by Ma (1989), and later investigated by Yang et al. (2006) and Owen et al. (2010). Using ^{10}Be surface exposure dating (SED) techniques, Owen et al. (2010) dated the moraines in three valleys, concluding that major glacial advances occurred during MIS 10, MIS 4, MIS 3, the Late Glacial, the Early Holocene, the Neoglacial, and the LIA.

Ganglung Gangri (82.0°E, 30.4°N), Rachama (82.2°E, 30.1°N) and Kubi Gangri (82.8°, 29.7°N), with summit altitudes of 6256 m, 6721 m and 6859 m asl, respectively, are the sources of the Yarlung Tsangpo River. Sixteen modern glaciers and 13 LIA glaciers have been investigated in this massif. Rachama and KubiGangri are located in the eastern part of Ganglung Gangri. Ten modern glaciers

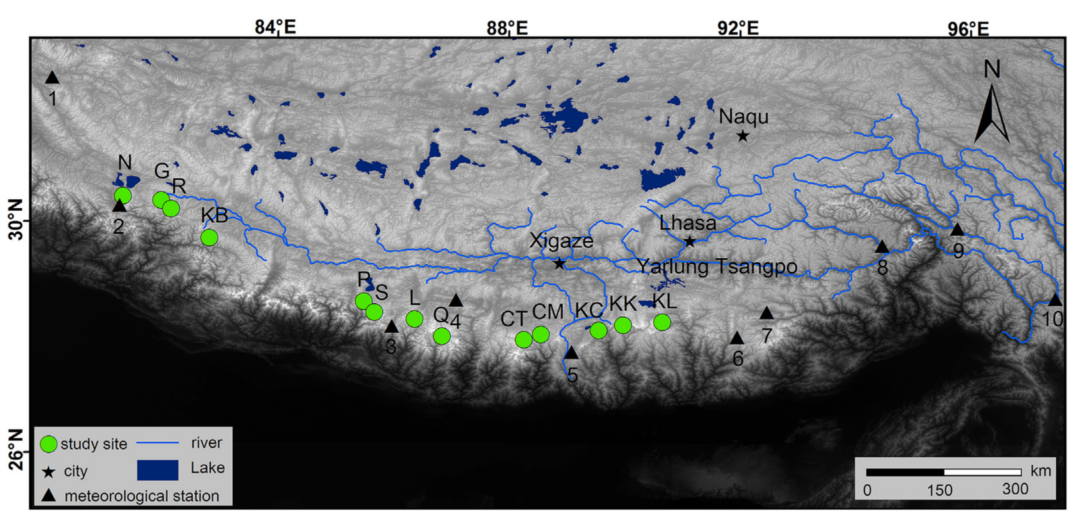

Fig. 1. The location of study sites in the CWH. From west to east, the names of the meteorological stations are: 1, Shiquanhe; 2, Pulan; 3, Nyalam; 4, Dingri; 5, Pali; 6, Cona; 7, Longzi; 8, Linzhi; 9, Bomi; 10, Chayu. Nyalam station (No. 3) is located in the Boqu Valley. N, Naimona'nyi; G, Ganglung Gangri; R, Rachama; KB, Kubi Gangri; P, Peiku Gangri; S, Shishapangma; L, Lapche Kang; Q, Qomolangma; CT, Chorten Nyima Ri; CM, Chomo Yummo; KC, Kangcheda; KK, Kangkar Pünzum; KL, Kula Gangri.