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Topographic controls on the debris-cover extent of glaciers in the Eastern Himalayas: Regional analysis using a novel high-resolution glacier inventory

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ABSTRACT

To better understand the influence of topography on the formation of Himalayan debris-covered glaciers, we manually digitized 5301 glaciers, covering an area of 5691 ± 893 km^2, from high-resolution Advanced Land Observing Satellite imagery, and identified 842 debris-covered glaciers with a debris-covered area of 3839 ± 753 km^2. This estimation of the debris-covered area of these glaciers is a novel approach in the Eastern Himalayas. We investigated the relationship between the debris-covered area and the corresponding potential debris supply (PDS) slopes for the debris-covered glaciers across the region. The PDS slopes on the southern side show better correlation with their debris-covered area formation than those situated on the northern side of the Himalayan barrier, with this correlation weakening toward the western massifs. Further investigation showed that PDS slopes oriented SE to W exert a stronger control on the formation of debris-covered areas, which is related to the diurnal freeze–thaw cycle on the southern slope of the mountain barrier.

1. Introduction

Himalayan glaciers play a crucial role in the maintenance of regional water resources in South Asia (Immerzeel et al., 2013); however, their response to climate change varies spatially (Fujita and Nuimura, 2011; Yao et al., 2012; Cogley, 2016), making accurate assessments of their ongoing and future contributions to water resources difficult. Limited accessibility, primarily due to the rugged terrain and poor socioeconomic conditions, hinder in situ observations in the high mountains, as previous researchers typically relied on the limited number of glaciers located at relatively lower elevations (Tshering and Fujita, 2016). Never-the-less, heterogeneous fluctuations in the mass balance of Himalayan glaciers have been gradually and increasingly revealed by in situ observations (Fujita and Nuimura, 2011; Yao et al., 2012; Zemp et al., 2015; Tshering and Fujita, 2016), remote sensing measurements (Bolch et al., 2012; Kääb et al., 2012; Nuimura et al., 2012, 2017; Gardelle et al., 2013; Ragettli et al., 2016), and numerical modeling (Fujita, 2008; Fujita and Nuimura, 2011; Shea et al., 2015).

A glacier inventory is a basic dataset used in glaciological investigations such as monitoring, modeling, and regional climatic analysis (e.g., Kääb et al., 2012; Gardelle et al., 2013; Sakai et al., 2015). Multiple glacier inventories have been created recently for the high mountains of Asia, including the Randolph Glacier Inventory (RGI: Pfeffer et al., 2014), International Centre for Integrated Mountain Development (ICIMOD, IGI hereafter: Bajracharya et al., 2014a), Glacier Area Mapping for Discharge from the Asian Mountains (GAMDAM, GGI hereafter: Nuimura et al., 2015), and the 2nd Chinese Glacier Inventory (CGI: Guo et al., 2015). However, these various inventories contain discrepancies in terms of the number of glaciers inventoried and their associated areal coverage (Nagai et al., 2016), which may lead to inaccurate regional estimates of water storage across the Himalayas. All of the above-mentioned inventories are based on the relatively coarse-resolution Landsat satellite images (30 m), which do not capture some of the smaller glaciers that are susceptible to disappearing in response to recent climate change (Paul et al., 2013; Ojha et al., 2016).

The contribution of debris cover to the overall evolution of debris-covered glaciers in the Himalayan region is poorly understood (Scherler et al., 2011a; Fujita and Sakai, 2014). The ablation

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zone of most of the glaciers in this region is covered with a debris mantle. Because of the insulating properties of the debris, glaciers covered with a thick debris mantle tend to melt more slowly than those with only a thin debris mantle (Mattson et al., 1993). However, remote sensing analysis suggests comparable surface lowering rates for both debris-covered and debris-free glaciers (Kääb et al., 2012; Nuimura et al., 2012). In the high mountains of Asia, Scherler et al. (2011b) reported that glaciers situated at lower relief zones were primarily nourished by snowfall and thus had little or no debris cover, whereas those having steep accumulation zones had thick debris mantle. In the Bhutan Himalaya, Nagai et al. (2013) found that the south-facing, ice-free head walls above glaciers were the primary contributors to formation of debris-covered area through diurnal freeze–thaw cycles. However, previous studies in the Eastern Himalayas have scarcely dealt with debris-covered areas and their regional features, and the formation of debris-covered areas to local topography has rarely been addressed at the regional scale. This study thus aims to investigate the relationship between topographic settings and the extent of the debris-covered area in the Eastern Himalayas using a newly created high-resolution glacier inventory.

2. Study area, data, and methods

2.1. Study area

We studied both debris-free (hereafter termed the C-glacier, in reference to a clean-type glacier) and debris-covered (hereafter termed the D-glacier) glaciers and their spatial distribution across the Eastern Himalayas (85.0–92.0°E; 27.5–29.0°N) on both sides of the Himalayan barrier, and covering the political territories of Bhutan, India, China, and Nepal (Fig. 1a). Glaciers in the region form at high elevations, ranging from 4000 to 7600 m above sea level (a.s.l) (Bajracharya et al., 2014a), and have been rapidly shrinking over recent decades (Gardelle et al., 2013; Ojha et al., 2016). We divided our study area into four massifs: namely Langtang (LT), Khumbu (KB), Kanchenjunga-Sikkim (KS), and Bhutan (BT). We further categorized the glaciers into southern slope (hereafter termed S-glacier) and northern slope (hereafter termed N-glacier) glaciers, in which the Eastern Himalayas mountain barrier is viewed as a climatic barrier, to understand the role of large mountain ranges in the formation of debris cover on glaciers. This geographical separation closely follows the political boundaries of the neighboring nations, barring a few areas in the western massifs (Fig. 1b).

2.2. ALOS imagery

We created a new glacier inventory for the Eastern Himalayas using images taken by the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM, 2.5-m resolution) and Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2, 10-m resolution), both of which are on board the Advanced Land Observing Satellite (ALOS). All of the PRISM images used in this study were acquired between 2006 and 2011, mostly during the post-monsoon season. In total, 104 (out of 1536 available images) PRISM images and 4 (out of 23 available images) AVNIR-2 images, possessing minimal cloud and snow cover, were selected for glacier delineation. Most of the glaciers (>99%) were delineated from the PRISM images, whereas AVNIR-2 images were used only in those areas where the PRISM images were unavailable. Most of the images (97) were orthorectified using PRISM-derived digital elevation models

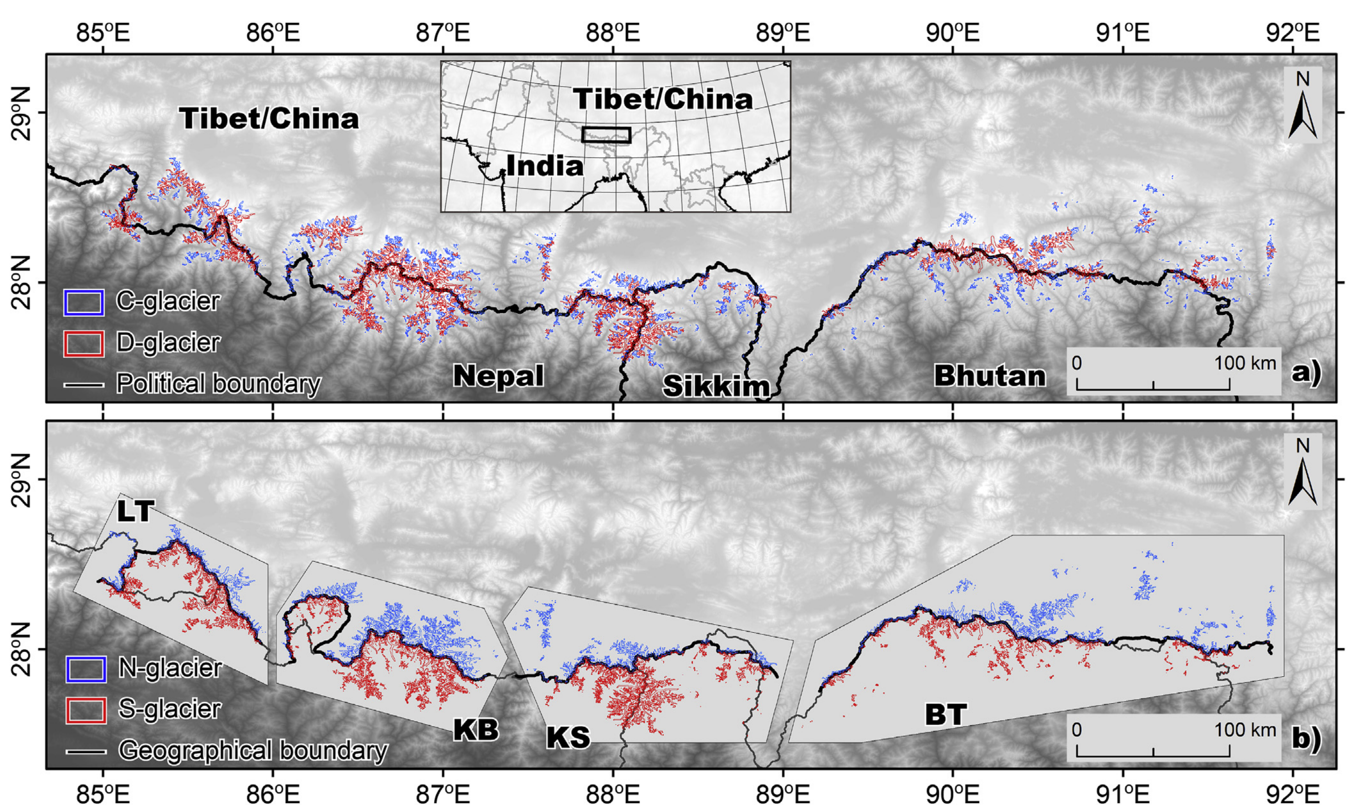

Fig. 1. Spatial distributions of: (a) extent of debris-free (C-glacier) and debris-covered (D-glacier) glaciers across the Eastern Himalayas, and (b) extent of northern-side (N-glacier) and southern-side (S-glacier) glaciers, which are distinguished by the geographical boundary of the Eastern Himalaya mountain barrier. Regional statistics are analyzed for the Langtang (LT), Khumbu (KB), Kanchenjunga-Sikkim (KS), and Bhutan (BT) massifs, whose areas are defined by the light gray polygons.