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Heterogeneous glacial lake changes and links of lake expansions to the rapid thinning of adjacent glacier termini in the Himalayas

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A B S T R A C T

Glacier mass loss in the Himalayas has far-reaching implications for the alteration of regional hydrologic regimes, an increased risk of glacial lake outburst, downstream water resource abundance, and contributions to sea level rise. However, the mass losses of Himalayan glaciers are not well understood towing to the scarcity of observations and the heterogeneous responses of Himalayan glaciers to climate change and local factors (e.g., glacier surge, interacting with proglacial lakes). In particular, there is a lack of understanding on the unique interactions between moraine-dammed glacial lakes and their effects on debris cover on valley glacier termini. In this study, we examined the temporal evolution of 151 large glacial lakes across the Himalayas and then classified these glacial lakes into three categories: proglacial lakes in contact with full or partial debris-covered glaciers (debris-contact lakes), ice cliff-contact lakes, and non-glacier-contact lakes. The results show that debris-contact lakes experienced a dramatic areal increase of 36.5% over the years 2000 to 2014, while the latter two categories of lakes remained generally stable. The majority of lake expansions occurred at the glacier front without marked lake level rises. This suggests that the rapid expansion of these debris-contact lakes can be largely attributed to the thinning of debris-covered ice as caused by the melting of glacial fronts and the subsequent glacial retreat. We reconstructed the height variations of glacier fronts in contact with 57 different proglacial lakes during the years 2000 to 2014. These reconstructed surface elevation changes of debris-covered, lake-contact glacier fronts reveal significant thinning trends with considerable lowering rates that range from 1.0 to 9.7 m/y. Our study reveals that a substantial average ice thinning of 3.9 m/y occurred at the glacier fronts that are in contact with glacial lakes.

1. Introduction

The Himalayan region is one of the most concentrated areas of glacial coverage in the low to mid-latitudes (Mayewski and Jeschke, 1979; Bolch et al., 2012; Kääb et al., 2012). The meltwater from these glaciers is an important contributor to water resources in their downstream basins as well as to global sea level rise (Gardner et al., 2013; Maussion et al., 2014; Huss and Hock, 2015). These glaciers are also sensitive indicators of prevailing and past climate changes (Immerzeel et al., 2010; Loibl et al., 2014). Monitoring their dynamics and estimating melting rates of ice is a crucial task toward the prediction of future water resources in the region (Barnett et al., 2005; Immerzeel et al., 2013). However, glacier fluctuations in the Himalayas are still not well understood, with large uncertainties in observation-based (Kaser et al., 2006; Cogley, 2009) and simulation-based (Oerlemans and Fortuin, 1992) projections of glacier mass loss and sea-level rise.

In situ glacier measurements are largely hampered by the high altitude and remoteness of the region, as well as the vast time costs associated with these measurements (Fujita et al., 2001; Song et al., 2015b). Because of the abovementioned constraints, these measurements are mostly limited to relatively small, debris-free, and easily accessible glaciers with a short observation period (Gardner et al., 2013; Thibert et al., 2013). A number of recent studies based on remote sensing techniques have demonstrated that the Himalayan glaciers have experienced an overall massive ice loss during the past several decades (Liu et al., 2006; Jacob et al., 2012; Kääb et al., 2012; Gardelle et al., 2013; Gardner et al., 2013; Cogley, 2016). However, there is a strong spatial heterogeneity in these ice losses across the region (Fujita and Nuimura, 2011). This spatial variation in glacial mass loss is likely linked to the complex patterns of climate change and regional variability

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(Akhtar et al., 2008), the extreme topographic relief, and the local glaciological conditions (Scherler et al., 2011), e.g., glacier surges, debris cover, interactions with glacial lakes.

Almost all large valley glaciers across the Himalayas have debris cover over their ablation zones (Scherler et al., 2011). Changes of these debris-covered glaciers remain relatively disputable towing to the limited number of in situ measurements and remotely sensed observations of glacier surface elevation, velocities, and their changes. Experimental studies have suggested that thick debris layers suppress glacier melting through insulation, whereas thin debris layers accelerate ice melting because of their thermal properties (Östrem, 1959; Nakawo and Young, 1981; Mattson, 1993). In addition, debris-covered glaciers exhibit highly variable topography, and the development of glacial lakes further complicates an accurate assessment on the rates of glacial thinning. Although some previous studies have reported that heavily debris-covered glaciers in the Himalayas exhibit stable fronts (Scherler et al., 2011), some studies also suggest that the average surface-lowering rates of debris-covered glaciers are comparable to that of debris-free glaciers (Kääb et al., 2012). Many studies have highlighted an evident surface lowering on debris-covered glaciers utilizing remote sensing techniques (Berthier et al., 2007; Bolch et al., 2011; Ye et al., 2015) and in situ measurements (Nuimura et al., 2011).

One of the vastly important factors contributing to rapid glacier tongue recession are the effects that contacted glacial lakes have on the glacier's thermal regime and the subsequent calving rates (Sakai et al., 1998; Richardson and Reynolds, 2000; Quincey et al., 2007; Fujita and Sakai, 2014; Immerzeel et al., 2014). There are many large moraine-dammed glacial lakes at the terminus of debris-covered glaciers in the Himalayas. Several prior studies have revealed that there is a marked increase in the glacial mass loss in the areas of the glacier that are in contact with lakes as compared to other portions of the glacier (Quincey et al., 2007; Sakai et al., 2009; Immerzeel et al., 2014). For instance, the ablation rate of some glaciers in the Nepalese Himalayas was observed to be about 10 times higher at locations where the glacier was in contact with a glacial lake when compared to the average ablation rate of the entire debris-covered zone (Sakai et al., 1998; Fujita and Sakai, 2014). However, a regional assessment of the interactions between glacial lake evolution and contacted glacier termini along with the quantification of mass loss rates of these glacier fronts are lacking for the Himalayas. More observations, particularly for monitoring changes of low-lying glacier tongues in contact with glacial lakes, are needed to understand these spatially heterogeneous changes of debris-covered glacier mass losses, and their potential causes. This study aims to investigate the temporal evolution of glacial lakes and frontal ice thickness changes of debris-covered glacier tongues interacting with glacial lakes across the Himalayas. This improved knowledge of interaction between glacier recession and glacial lake expansion is very helpful in the accurate estimation of glacier mass loss (Fujita and Nuimura, 2011; Bolch et al., 2012) and early recognition of glacial lake outburst flood (GLOF) hazards (Richardson and Reynolds, 2000; Wang et al., 2015).

2. Study area

The Himalayas are an ensemble of mountain ranges that stretch east to west over 2000 km with a north-south extent of 150–400 km. These high mountains are not only the source for several of the world's largest rivers (the Indus, the Ganges, and the Brahmaputra), but they also influence the climate and hydrologic regimes of the adjacent regions (Hasnain, 2002). The Himalayan region is divided into three subregions (Shroder, 2011), that is, the eastern, central, and western Himalayas. The subregional extent definition was referenced in Bolch et al. (2012) and Nie et al. (2013) (as delineated in Fig. 1). The influences of the Indian and southeast Asian summer monsoon decrease, while the moisture supply from the mid-latitude westerlies becomes increasingly more important as you move from east to west in the region. As a result, the eastern Himalaya receives most of its precipitation during the summer and the western regions receive most of their precipitation during the winter (Bookhagen and Burbank, 2010). The extreme rugged topography also exerts a strong influence on the moisture transfer by drying out the southerly air flow and blocking the air masses from travelling farther north, resulting in less precipitation over north slopes than that over the south slopes (Bookhagen and Burbank, 2010).

Himalayan glaciers cover an area of ~22,800 km^2 (Bolch et al., 2012). Most of the glaciers in the eastern and central Himalayas belong to the *summer-accumulation* type, which gain mass mainly from monsoonal snowfall (Bolch et al., 2012). These compare to glaciers in the western region where the winter accumulation is the most important factor (Quincey et al., 2011; Maussion et al., 2014; Song et al., 2015b). The very steep and rugged terrain above the glaciers leads to considerable accumulation by snow avalanching. Around 10% of the total Himalayan glaciers have heavily debris-covered tongues as a consequence of this steep terrain and subsequent avalanche activity (Bolch et al., 2012). The size of these debris zones is highly variable, and the debris thickness can range from a few centimeters (dust or sand) to several meters (Gardelle et al., 2011; Scherler et al., 2011). These debris-covered glaciers are concentrated on the low-lying tongues that are mostly the ablation areas with lower elevations and warmer climate (Scherler et al., 2011; Fujita and Sakai, 2014). Across the Himalayas, glacier termini are often connected to proglacial lakes that store meltwater behind frontal moraines or dead-ice dams (Gardelle et al., 2011).

3. Data and methods

3.1. Landsat imagery for mapping the temporal evolution of glacial lakes

In this study, glacial lake area variations are investigated utilizing multitemporal Landsat images between the years 2000 and 2014 (available at the website: http://glovis.usgs.gov). A detailed description of the ~225 high quality (cloud-free and without heavy seasonal snow cover) Landsat scenes used within this study are listed in Table S-1. We applied a two-step approach to generate the multitemporal glacial lake extent data. In the first step, we adopted the automated water mapping scheme proposed by Li et al. (2011), which integrates (i) a hierarchical image segmentation to optimize local water extractions using the normalized difference water index (NDWI; McFeeters, 1996), and (ii) a rigorous human-interactive quality control component to minimize the mapping uncertainty considering the impact of highly complex mountainous environments caused by mountain shadows, seasonal snow cover, and others. In the global-to-local two-step NDWI histogram segmentation (Li et al., 2011), the final lake outlines were delineated based on different NDWI thresholds adaptive to local lake spectral variations induced by water turbidity, depth, and image acquisition dates. The combined global and local segmentation of the NDWI image favors the flexible threshold setting and effectively reduces the mapping uncertainty caused by spectral differences of different water bodies (Sheng et al., 2016; Song and Sheng, 2016). For missing glacial lakes or inaccurate lake outlines after human inspection, an interactive mapping tool in the environment of ESRI's ArcGIS was developed to facilitate the delineation and editing of lake boundaries from the source Landsat images (Wang et al., 2014).

A semiautomated methodology was adapted based on a glacier inventory data set coupled with a manual inspection through Google Earth imagery in order to classify all mapped lakes according to their spatial relationship with their parent glaciers, which supply the meltwater as well as the geomorphologic characteristics of the individual lake basins. The referenced glacier outline data are from the Randolph Glacier Inventory (RGI; Pfeffer et al., 2014). In the initial step, the lakes are divided into two classes: (i) lakes that are not in direct contact with glaciers (termed as non-glacier-contact lake, NC), and (ii) lakes that are in direct contact with glaciers (termed as glacier-contact lake). The majority of the lakes investigated in this study are located