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

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Abstract

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 owing 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.

Keywords: glacial lake; glacier; debris; Himalaya; remote sensing; climate change

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 (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 owing 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 km² (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).

[Insert Fig. 1 around here]

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, 2016a). 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 in valleys where the glaciers are mostly debris-covered or are partially debris-covered and mixed with clean ice. These lakes are termed as debris-contact lakes (DC) as the third lake classification used in this study. A few glacier-contact lakes are located near the high and steep ice cliffs, or cirques, that are unfavorable for lake expansion. We thus further separated these lakes from other glacier-contact lakes and termed them as cliff-contact lakes (CC). A schematic diagram for the geomorphologic features of these three types of glacial lakes is shown in Fig. 1.

3.2. Satellite altimetry for lake surface elevation measurements

In this study, ICESat and CryoSat-2 altimetry data were used to derive water levels of the studied glacial lakes during the study period of 2003-2014. The ICESat altimeter provides surface elevations from the years 2003 to 2009 within a 70-m diameter footprint at an along-track spacing of 172 m with an accuracy on the order of several to 10 cm (Zwally et al., 2002; Urban et al., 2008). The ICESat elevation measurements have shown good performance at detecting lake level changes in high Asia (Zhang et al., 2011; Kropáček et al., 2012; Biskop et al., 2015). This study used the Release-33 GLA14 ICESat product obtained from the National Snow and Ice Data Center (NSIDC).

The ESA CryoSat-2 was launched in 2010 and carried a radar altimeter named the Synthetic aperture Interferometric Radar ALtimeter (SIRAL; Kleinherenbrink et al., 2014). Its resolution in the along-track direction is about 300 m, and it operates on a 369-day repeat cycle that consists of shifting subcycles of 30 days (Labroue et al., 2012). Thus, the density of CryoSat ground tracks is high and provides for an increased potential to monitor the glacial lakes in the Himalayas. We used Level-2 SIRAL SARIn-mode data (Wingham et al., 2006) from the period July 2010 to June 2014.

We converted the ICESat height data to the height reference system (WGS84 and EGM96) to match the CryoSat-2 and SRTM data sets using the approach of Song et al. (2015c) as the ICESat altimetry measurements are referenced to a different ellipsoid and height datum than the latter two data sets (Song et al., 2015a). A past study confirms that CryoSat-2 and ICESat altimetry data are able to depict the intraannual and interannual variability of lake levels at decimeter accuracy as evidenced by their comparison with gauge-based water level observations at Namco (2005-2012) and Yamzhog Yumco (2003-2013; Song et al., 2015a). A time series analysis of lake levels cannot be conducted as only a few lakes were measured repeatedly with sufficient on-lake footprints owing to the small size of glacial lakes comparing to the satellite altimetry footprints. Therefore, we determined the water level variations of these lakes by comparing satellite altimetry measurements relative to lake levels measured from the SRTM DEM acquired in the year 2000.

3.3. Reconstruction of height variations of lake-contact glacier fronts based on digital elevation model

The version-2 gridded SRTM DEM at a 3 arc-second resolution from the U.S. Geological Survey (USGS) HydroSHEDS database was derived from an 11-day mission from a spaceborne SAR technique flown in February of 2000 (Jarvis et al., 2004; Lehner et al., 2006). Data gaps remain mostly over rugged terrain, and only a few voids are observed over the relatively flat terrain such as the glacier tongues and the area surrounding the glacial lakes. The SRTM DEM data are used here for three objectives: (i) as the height reference (in 2000) to measure water level changes of glacial lakes with ICESat and CryoSat-2 measurements; (ii) to calculate the surface slopes of glacier tongues and valley areas around glacial lakes; and (iii) to reconstruct the change rates of lake-contact fronts of glacier tongues. We overlap the lake boundaries on the DEM to find the surface elevation changes of glacier termini that are in contact with glacial lakes by calculating the height differences (ΔH) of shifted lake shores relative to the lake level, as shown in Fig. 2A, B. This is based on the assumption that water levels of debris-contact proglacial lakes remain virtually stable at interannual timescales through their natural outflow regulations. The rapid expansions of glacier-contact lakes largely depend on the melting and subsequent thinning of the glacier fronts which in turn opens up space for the upstream lake enlargement. We can see from Fig. 2C that these large proglacial lakes have well-developed outlet channels for both non-glacier-contact and debris-contact lakes. All of the 151 lakes in this study were confirmed to have significant outflow by referring to high-resolution Google Earth imagery. We also validated no obvious lake level rises based on ICESat and CryoSat-2 altimetry measurements, and the lakes in contact with debris-covered glaciers exhibit the expansions upstream to the glacier tongues and with the lateral and downvalley boundary unaltered (it will be analyzed in section 4.2 below). Other evidence can be found in one debris-contact proglacial lake in the southeastern Tibetan Plateau that similarly show slight fluctuations with only ~ 1 m derived from repeated ICESat measurements (Song et al., 2016b).

[Insert Fig. 2 around here]

4. Result and analysis

4.1. Evaluation of DEM accuracy at glacial lake terminus

Although the overall absolute accuracy of SRTM DEM data in mountainous areas may be somewhat low, its relative accuracy over flatter terrain (~ 7 -8 m for slopes $< 10^\circ$), such as that around glacial lakes or glacier termini, have been documented to be much more reliable and stable (Toutin, 2002; Fujita et al., 2008; Wang et al., 2012). We evaluated the vertical accuracy of the SRTM DEM by comparing against ICESat altimetry measurements over a 2-km buffer area around the 151 glacial lakes in this study. The ICESat footprints over on-glacier and off-glacier areas were separated to avoid the influences of actual glacier surface elevation variations on the estimates of difference between the ICESat and SRTM DEM measurements.

The histogram of on-glacier and off-glacier elevation differences (Δh) between the SRTM DEM (measured in 2000) and ICESat measurements (2003-2009) is displayed in Fig. 3A. In total, 2088 off-

glacier footprints and 253 on-glacier Δh values were calculated. A small proportion of footprints ($\sim 0.9\%$) with elevation differences >150 m were filtered out as unqualified ICESat measurements that are very likely “contaminated” by cloud cover and/or signal saturation (Kääb et al., 2012). We find that the Δh for most of the footprints fall within a bias of ± 50 m. The mean Δh for the off-glacier areas is 0.7 m and $\sim 70\%$ of these measurements have errors <20 m. In contrast, most on-glacier measurements have a negative bias with a Δh mean of -11.5 m. This suggests that the valley glaciers have experienced substantial melting and thinning. It is evident from Fig. 3B that a strong association can be observed between off-glacier Δh and surface slope, as the linear correlation is statistically significant at the 95% confidence level. The mean Δh is <3 m for slopes $<3^\circ$ and is <7 m for slopes $<10^\circ$. The mean Δh and associated errors at different slope intervals are further summarized in Fig. 3C.

[Insert Fig. 3 around here]

4.2. Area and water level changes of glacial lakes

In this study, we examined 151 proglacial lakes >0.5 km² (note that seven debris-contact glacial lakes that are slightly smaller than 0.5 km² that have rapidly expanded are also included.) across the Himalayas. From these 151 lakes we have further classified them into 79 NC lakes, 17 CC lakes, and 57 DC lakes. A time series of lake surface area variations was derived based on all acquired Landsat images between 2000 and 2014. The change rates vary largely with different glacial lakes. We find that the majority of DC glacial lakes expanded considerably, while CC and NC glacial lakes remained relatively stable. Fig. 4A illustrates the ratios of lake areas observed in circa-2014 to those in circa-2000 for all examined glacial lakes of each of the three classes. The total area of the 57 DC glacial lakes increased by 36.5% from 2000 to 2014, where 21 of which had an areal increase $>50\%$, with the largest areal expansion of $\sim 303\%$. In contrast, the mean expansion percentages for NC and CC lakes are 0.02% and 0.1%, respectively. For most of the expanding DC lakes, the lake boundary grows upstream toward the receding glacier tongue and the lateral and down-valley boundaries remain mostly unchanged (see Figs. 4B and S-1). This implies that the receding and subsiding glacier fronts provide for glacial lake expansion.

The ICESat (2003-2009) and CryoSat-2 (2010-2014) capture a total of 15 and 71 glacial lakes, respectively. Fig. 4 (C–D) shows scatter plots of the ΔH values for all measured lakes separated by the three different lake classifications (NC, CC, and DC). We can clearly find that the mean ΔH values for all lakes are not statistically deviated from zero. Fig. 4C depicts 5 NC lakes, 1 CC lake, and 9 DC lakes that show a mean ΔH of 0.85, 1.03 and 1.3 m, respectively. The same figure shows that ΔH values vary from -1.0 to 2.3 m for the individual lakes. In comparison, Fig. 3D shows 41 NC lakes, 3 CC lakes, and 27 DC lakes with a mean ΔH value derived from CryoSat-2 data of 0.99, -1.47 and 0.8 m, respectively. This same figure shows a larger range of ΔH values from -3.0 to 4.4 m.

[Insert Fig. 4 around here]

4.3. Analysis of thinning debris-covered glacier terminus in contact with glacial lakes

Based on the method introduced in section 3.3, the mean elevation time series of lake-contact glacier fronts for the 57 DC glacial lakes are reconstructed by overlapping Landsat-based waterlines on the SRTM DEM raster. The elevation change trends are linearly fitted for each lake, as shown in Fig. S-2. The lake-contact glacier fronts all show significant thinning trends ($p < 0.05$). However, the decreasing rates vary considerably with different glacier termini, ranging from 1.0 to 9.7 m/y. There are 40 glacier termini with decreasing rates >3 m/y, and 7 with rates >6 m/y. The average rate for the 57 glacier termini is ~ 3.9 m/y. The spatial distribution of the decreasing rates for the different glacier termini in contact with glacial lakes is displayed in Fig. 5. In general, the average lowering rate (4.3 ± 1.2 m/y) in the eastern Himalayas is larger than that in the western Himalayas (4.0 ± 1.6 m/y) as well as in the central Himalayas (3.7 ± 1.7 m/y).

The recession of lake-contact glacier termini was determined to be the combined effect of interactions between glacial lakes and their contacted glaciers, including the melt condition of the glacier terminus and ice flux from the accumulation areas of parent glaciers (Sakai et al., 2000; Kääb et al., 2012; Fujita and Sakai, 2014). Here we examine the correlations between reducing rates of glacier fronts and five potentially linked variables: (i) the area of contacted glacial lakes; (ii) the elevation of the glacial lake, which implies thermal effects varying with lake altitude and lake water temperature; (iii) the area of parent glaciers; (iv) the centerline length of parent glaciers; and (v) the mean slope of the retreated glacier terminus area. These five variables are highlighted in Fig. 5. The scatter plots in Fig. 5A, 5B, and 5D show that lowering rates are positively correlated with glacial lake sizes ($r = 0.32$, $p < 0.05$), are negatively correlated with the glacier centerline length ($r = -0.37$, $p < 0.01$), and are negatively correlated with the area of parent glaciers ($r = -0.29$, $p < 0.05$). Whereas, show rather weak correlation with the altitude of glacial lakes (Fig. 5B). Fig. 5E depicts a weak correlation between lowering rates and the surface slope of glacier tongue areas ($r = 0.18$, $p > 0.1$). This may imply that various factors may affect the rapid thinning of the glacier terminus. However, no further evidence indicates which of these factors could be the dominant factor in the thinning rates.

[Insert Fig. 5 around here]

5. Discussions

5.1. Uncertainties of the reconstruction of glacier termini thinning

The above analyses confirm that the upstream expansion of debris-contact proglacial lakes was mainly caused by the thinning glacier terminus and the subsequent retreat of the glacier fronts. This process provides an opportunity to estimate the height variations of lake waterline-contact glacier fronts through overlapping shifted lake boundaries using historical DEM measurements. It also enables us to conduct a regional investigation of glacier mass loss over the glacial lake-contact glacier termini

across the Himalayas based on currently available satellite measurements. However, this reconstruction method is based on two ideal assumed conditions. The first of which is that the interannual changes in surface water levels of the investigated proglacial lakes are negligible as compared to the vertical variations of the individual lake's glacier fronts. The ICESat and CryoSat-2 altimetric measurements have confirmed slight glacial lake water-level fluctuations of $\sim 1\text{--}2$ m, and these small lake-level fluctuations are caused by the natural outflow regulations through stable lake outlets. However, this assumption may not be suitable for examining developed glacial lakes at the early stages that may be confronted with subsided dams caused by the melting of dead ice below the moraines or moraine blocks. High-resolution Google Earth imagery is used to determine the generally stable lake dams by investigating the stability of the lake's lateral and downstream boundaries. The second assumed condition is that the annual changes of ice below the lakes' waterline are comparable with the upstream expansion of the glacial lakes. Considering the fact that the lake-contact valley glacier tongues examined in this study have relatively flat slopes, and the actual changes of ice below the lake water surface vary with the local terrain, we can infer lake-contact valley glacier tongues with slight interannual differences. The ideal condition is to obtain the lake bathymetry measurements for these lakes; however, it is still very difficult to determine in remote and high-mountain regions, particularly for a regional-scale investigation such as this.

5.2. Comparison of the rapid thinning of lake-contact glacier termini and regional glacier changes

This study reveals a substantial thinning (3.9 m/y on average) over the period 2000-2014 at the debris-covered glacier termini, which are in contact with glacial lakes. The above thinning rate is much more negative than the change rates of glacier surface elevation reported in many earlier studies that are based on various observations at the glacier or regional-scale. For example, Berthier et al. (2007) used DEMs derived from SPOT5 (2004) and SRTM DEM (2000) data and estimated an overall specific mass balance of -0.70 to -0.85 w.e. y^{-1} for glaciers in the Indian Himalaya. A much larger thinning rate of up to -2.0 to -2.5 m/y was observed at lower elevations, and these rates include debris-covered glacial tongues. Kargel et al. (2011) utilized ASTER DEMs from 2001 and 2006 imagery and revealed that the Gangotri Glacier may have thinned by about 5 m over that 5-year period, despite a seemingly stable terminus with a thick debris cover. Bolch et al. (2011) employed multitemporal digital terrain models (DTMs) to investigate the glacier mass balance for 10 glaciers covering an area of about 50 km^2 to the south and west of Mt. Everest, Nepal, over the years 1970 to 2007. They found that despite the thick debris cover, glaciers there have undergone a major mass loss at a rate of 0.32 ± 0.08 m w.e. y^{-1} . A comparison analysis indicates an accelerated mass loss in recent years. Gardelle et al. (2013) investigated a regional-scale glacier mass balance change in the eastern, central, and western Himalaya by comparing DEMs derived from SPOT5 stereo imagery (2008-2011) and SRTM DEM (2000). Their results show moderate mass losses in the eastern and central Himalaya (-0.22 ± 0.12 to -0.33 ± 0.14 m w.e. y^{-1}) and larger losses in the western Himalaya (-0.45 ± 0.13 m w.e. y^{-1}). Regional-scale glacier mass changes based on repeated ICESat laser altimetry for the years 2003-2008/09 were widely investigated (Kääb et al., 2012; Gardner et al., 2013; Neckel et al., 2014; Ji et al., 2015), and those rates vary with different subzones across the Himalayas on the order of about -0.9 to -0.4 m y^{-1} .

Immerzeel et al. (2014) deployed an Unmanned Aerial Vehicle before and after the melt and monsoon season (May and October 2013) in order to measure the mass loss of the debris-covered tongue at the Lirung Glacier in the Nepalese, and their results show a mean negative change of -1.09 m in glacier surface elevation. This larger ice loss in the glacier tongues, regardless of debris cover, could be partly attributed to the higher ablation temperature at these lower altitudes as compared with the debris-free ice in the upper portion. This relationship between ablation temperature and altitude has been confirmed in Fujita and Sakai (2014). We examined in section 4.3 whether or not the lowering rates of different glacier fronts were correlated to their altitudes and did not find a similar conclusion.

5.3. The mechanism of rapid glacier termini thinning in interaction with glacial lakes

The above-reviewed studies also reveal an extremely high spatial heterogeneity in glacier height changes in the Himalayas. Diverse local conditions of glaciers have likely contributed a great deal to the spatiotemporal variability of mass losses. For example, the existence of proglacial lakes plays a large role in the mass loss rate. Unlike Fujita and Sakai (2014), we propose that the interactions with contacted glacial lakes and the ice flux budgets from the accumulation areas of parent glaciers play a larger role in the thinning rates on the glacier fronts than altitude does. This is proved by our moderate correlations between the lowering rates and the centerline length along with the correlations between the area of parent glaciers and glacial lake sizes. Existing studies have stressed the importance of glacial lakes in the accelerated melt of debris-covered glacier tongues (Fujita et al., 2008; Sakai et al., 2009; Fujita and Sakai, 2014; Immerzeel et al., 2014). For instance, in situ measurements suggest that around 69% of the total melt of the Lirung Glacier originates from ice cliffs that only account for 2% of the total glacier area (Sakai et al., 1998). Based on a numerical simulation, Sakai et al. (2009) found that the calving effect of glacier ice has a much stronger influence on accelerating the ice mass loss than ice cliff melting, the latter of which is strongly related to valley wind-driven water current and lake sizes. This may partially explain why lowering rates of glacier fronts increased with the size of proglacial lakes as revealed in this study above. However, the interplay between debris-covered ice, ice cliffs, englacial conduits and voids, and glacial lakes is rather complex. This complexity is caused by various ablation processes (e.g., thermoerosional notching, subaerial calving, flake calving, and subaqueous calving, etc.) and provides further evidence that the quantitative investigations of glacier termini and glacial lakes undertaken in this study are needed to completely understand the relationships mentioned above.

6. Summary

Spatially variable responses of Himalayan glaciers have been stressed in many previous studies. This is a challenging but important topic as a clear knowledge of spatiotemporal variability of these glaciers will affect the quantification of regionwide ice loss rates and those downstream influences on water budgets and sea-level rises. In this study we examined the temporal evolution of large proglacial lakes across the Himalayas and found that their growth is an important local factor that strongly influences the ice melting of contacted glacier fronts. A total of 151 large glacial lakes across the Himalayas were investigated and subsequently broken down into three classes: (i) 79 NC lakes, (ii) 17

CC lakes, and (iii) 57 DC lakes. Our results show that the DC lakes had rapid upstream expansions over the years 2000-2014, with a total areal increase of 36.5%, and that these expansions are closely associated with the retreat and ice-melt-induced lowering of glacier termini. In contrast, the mean expansion rates for NC and CC glacial lakes are only 0.02% and 0.1%, respectively.

The mechanism of glacial lake expansion provides an indirect way of estimating the surface lowering rates of glacier terminus. Thus, we examined the lowering rates of lake-contact glacier fronts by detecting the height variations of their contacted boundaries of proglacial lakes that are reconstructed from the upstream-advancing lake waterlines. The lake-contact debris-covered glacier fronts all show significant thinning trends, and the lowering rates range from 1.0 to 9.7 m/y. The mean lowering rates in the eastern Himalayas (4.3 ± 1.2 m/y) is higher than those rates in both the central (3.7 ± 1.7 m/y) and western Himalayas (4.0 ± 1.6 m/y).

By examining several factors that are potentially linked to glacier tongue melting, we find that the different thinning rates of glacier fronts are negatively correlated with the centerline length and area of parent glaciers and are positively correlated with the size of contacted glacial lakes. We also determined that the rates are not correlated with the altitude and slope of the glacier terminus. We propose that the interactions with contacted glacial lakes and the ice fluxes from the accumulation areas of parent glaciers have a combined control on the thinning rates of the glacier fronts. Future work and a more comprehensive investigation of regional glacial lake evolutions and glacier mass losses are required to systematically discuss their influencing factors (such as glacial lake size, hypsometry, local topography, debris coverage, parent glacier geometry, ice velocity, etc.) that have a major impact on the spatial differences of glacier mass changes in the Himalaya.

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Table and Figure Captions

Fig. 1. A map of Himalayan glaciers and glacial lakes. The glacial lakes are categorized into three groups: 79 non-glacier-contact lakes, 17 cliff-contact proglacial lakes, and 57 debris-contact proglacial lakes. The schematic diagram illustrates the relationship between the three glacial lake types, with the parent glaciers and their geomorphologic characteristics.

Fig. 2. A schematic diagram and satellite imagery illustrating the expansion of glacial lakes and elevation variations of lake-contact glacier fronts. Right: the base image (from Google Earth) was acquired on Oct 12th, 2000; two contrasted lakes (one non-glacier-contact lake and one debris-contact lake) are superimposed with lake outlines derived from Landsat images.

Fig. 3. An evaluation of DEM data accuracy by a comparison with ICESat altimetry measurements. (A) Shows the frequency distributions of DEM measurement biases (Δh : DEM value relative to ICESat measurement) over glacier and off-glacier land; (B) and (C) highlight the relationship between DEM measurement errors and surface slope.

Fig. 4. Areal and water level changes of glacial lakes as measured by satellites imagery acquired during 2000-2014. (A) Comparison of lake areas derived from Landsat imagery acquired in circa-2000 and circa-2014, respectively. The blue, green, and red circles represent the area measurements of three different lake groups: non-glacier-contact, cliff-contact, and debris-contact glacial lakes, respectively; (B) a case study (Lake ID: 143) that shows the upward expansion along with the subsidence of the upstream lake basin caused by glacier melting and retreat; (C-D) the elevation differences (ΔH) of ICESat (2003-2009) and CryoSat-2 (2010-2014) measured lake levels relative to the SRTM DEM-derived lake levels.

Fig. 5. The spatial distribution of change rates of glacial lake-contact glacier terminus thinning and the analysis of the relationship between thinning rates and the following varying factors: glacial lake area (A), glacier-contacted lake surface elevation (B), centerline length of parent glacier (C), area of parent glacier (D), and the slope of retreated glacier terminus area (E).

Fig. 1. Location of Himalayan glaciers and glacial lakes. The glacial lakes are categorized into three groups: 79 non-glacier-contact lakes, 57 debris-contact proglacial lakes and 17 ice cliff-contact lakes. The schematic diagram illustrates the spatial relations of glacial lakes of the above-mentioned three types and parent glaciers and their geomorphologic characteristics.

Figure 2. Schematic diagram and satellite imagery illustrating the expansion of glacial lakes and elevation variations of lake-contact glacier fronts. Right: the base image (from Google Earth at the location $27^{\circ}56'45''\text{N}$, $87^{\circ}55'05''\text{E}$) was acquired on Oct 12th, 2000; two contrasted lakes (one non-glacier-contact lake and one debris-contact lake) are superimposed with lake outlines derived from Landsat images.

Figure 3. Evaluation of DEM data accuracy by comparing with ICESat altimetry measurements. Plot (A) shows the frequency distributions of DEM measurement biases (Δh , SRTM DEM value relative to ICESat measurement) over glacier and off-glacier land; plots (B) and (C) present the relationship between DEM measurement errors and surface slope.

Figure 4. Areal and water level changes of glacial lakes measured by satellites during 2000-2014. (A)

Comparison of lake areas derived from Landsat imagery respectively acquired in circa-2000 and circa-2014. The blue, green and red circles respectively represent the area measurements of three different lake groups: non-glacier-contact (NC), cliff-contact (CC) and debris-contact glacial lakes (DC); (B) case study (Lake ID: 143) for showing the upward expansion with the subsidence of upstream lake basin caused by glacier melting and retreat, the numbers and that are derived from SRTM DEM roughly indicate the elevations of glacial lake surface and adjacent glacier termini measured in 2000; (C-D) elevation differences (ΔH) of ICESat (2003-2009) and CryoSat-2 (2010-2014) measured lake levels relative to DEM-derived lake levels.

Figure 5. Spatial distribution of thinning rates of debris-covered, lake-contact glacier terminus and analysis of the relationship between thinning rates and different factors: glacial lake area (A), glacier-contacted lake surface elevation (B), centerline length of parent glacier (C), area of parent glaciers (D), and slope of retreated glacier terminus area (E).