Glacial lake evolution in the southeastern Tibetan Plateau and the cause of rapid expansion of proglacial lakes linked to glacial-hydrogeomorphic processes

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Abstract: Glacial lakes, as an important component of the cryosphere in the southeastern Tibetan Plateau (SETP) in response to climate change, pose significant threats to the downstream lives and properties of people, engineering construction, and ecological environment via outburst floods, yet we currently have limited knowledge of their distribution, evolution, and the driving mechanism of rapid expansions due to the low accessibility and harsh natural conditions. By integrating optical imagery, satellite altimetry and digital elevation model (DEM), this study presents a regional-scale investigation of glacial lake dynamics across two river basins of the SETP during 1988-2013 and further explores the glacial-hydrogeomorphic process of rapidly expanding lakes. In total 1278 and 1396 glacial lakes were inventoried in 1988 and 2013, respectively. Approximately 92.4% of the lakes in 2013 are not in contact with modern glaciers, and the remaining 7.6% includes 27 (1.9%) debris-contact lakes (in contact with debris-covered ice) and 80 (5.7%) cirque lakes. In categorizing lake variations, we found that debris-contact proglacial lakes experienced much more rapid expansions (~75%) than cirque lakes (~7%) and non-glacier-contact lakes (~3%). To explore the cause of rapid expansion for these debris-contact lakes, we further investigated the mass balance of parent glaciers and elevation changes in lake surfaces and debris-covered glacier tongues using time-series Landsat images, ICESat altimetry, and DEM. Results reveal that the upstream expansion of debris-contact proglacial lakes was not directly associated with rising water levels but with a geomorphological alternation of upstream lake basins caused by melting-induced debris subsidence at glacier termini. This suggests that the hydrogeomorphic process of glacier thinning and retreat, in comparison with direct glacial meltwater alone, may have played a dominant role in the recent glacial lake expansion observed across the SETP. Our findings assist in understanding the expansion

37 mechanism of debris-contact proglacial lakes, which facilitates early recognition of potential

38 glacial lake hazards in this region.

39 **Key words:** glacial lake, Tibetan Plateau, Landsat, ICESat, mountain glacier, climate change

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1 Introduction

In response to rising temperature and changing precipitation, mountain glaciers in High Mountain Asia have been widely observed to have retreated and thinned rapidly in recent decades (Gardner et al., 2013; Kääb et al., 2012; Ke et al., 2015a; Neckel et al., 2014; Song et al., 2014c; Song et al., 2015; Yao et al., 2012), which favors the formation and rapid expansion of glacial lakes (Bajracharya and Mool, 2010; Bolch et al., 2008; Komori, 2008; Richardson and Reynolds, 2000; Shrestha and Aryal, 2011; Song et al., 2014a; Wang et al., 2011b), leading to increased probability of glacial lake outburst floods (GLOFs) (Clague and Evans, 2000; Fujita et al., 2009; Liu et al., 2016; Sakai et al., 2000; Wang et al., 2011a). Hence, glacial lakes are considered as important proxy indicators of regional glacier dynamics and, in certain cases, threaten life and property in downstream valleys (Gardelle et al., 2011; Richardson and Reynolds, 2000).

The southeastern Tibetan Plateau (SETP) has many monsoonal temperate glaciers due to a warm and humid climate (Yang et al., 2008). Recently, numerous studies reported that these glaciers have been melting and thinning faster than continental glaciers in the inner Tibetan Plateau (TP) during the past decade (Kääb et al., 2015; Neckel et al., 2014; Song et al., 2014c; Yang et al., 2010; Yang et al., 2008; Ye et al., 2015). Thus, active glacial processes, combined with abundant rainfall during the monsoon season, pose threats of GLOFs to this region (Wang et al., 2012b). Moreover, construction of a new railway connecting Lhasa (the Tibet Autonomous Region capital of China) and its southeast Nyingchi Prefecture began in 2014 as an extension of the Qinghai-Tibet Railway (<http://www.chinatibettrain.com/>). The planned Lhasa-Nyingchi Railway passes near to a number of glacial lakes, thus early recognition of glacial lake hazards is crucial to the safety of railway construction and operation. Many prior studies emphasized glacial lake inventory and temporal

variations in the Himalayas and Tianshan Mountains (Bajracharya and Mool, 2010; Fujita et al., 2009; Gardelle et al., 2011; Komori, 2008; Liu et al., 2015b; Nie et al., 2013; Quincey et al., 2007; Song et al., 2014a; Wang et al., 2011c; Zhang et al., 2015). However, little is known about glacial lake changes in the SETP, except for small-scale glacial lake monitoring in part of the Boshula Mountain (Wang et al., 2011b) and the Bugyai Kangri (Liu et al., 2015a).

The lack of regional investigation (at least covering one Landsat scene, defined here) of glacial lake changes in the SETP could be largely attributed to the difficulty in obtaining high-quality paired optical images for change detection that are frequently interfered by cloud cover and seasonal snowfalls over the highly glaciated areas and surroundings. The newly launched Landsat-8 satellite with the Operational Land Imager (OLI) onboard extends the Landsat archive to a period of over forty years (Lulla et al., 2013; Roy et al., 2014), and the increasing proportion of land imaged every day of acquisition opportunities for Landsat-8 satellite mission raises the possibility of accessing high-quality images available for monitoring the SETP glacial lake evolution during the past several decades (Sheng et al., 2016). Fortunately, we obtained one pair of nearly cloud-free Landsat images that were acquired by Landsat 5 on 10-09-1988 and by Landsat 8 on 09-28-2013, respectively. It allows us to examine the regional glacial lake evolution across two basins of the SETP during 1988-2013.

In this study, we provide an overview of the distribution and evolution of glacial lakes in the SETP. For rapidly expanding glacial lakes, we further explore the potential cause of the lake expansion. To achieve this goal, we first categorized all examined glacial lakes into different groups and analyzed the associations of lake expansion rates with lake types. As summarized in many previous studies, glacial lakes are generally grouped into two categories, supraglacial lakes and

proglacial lakes (Gardelle et al., 2011; Komori, 2008; Quincey et al., 2007; Reynolds, 2000; Richardson and Reynolds, 2000). The former develop on the glacier surface, expanding through coalescence of small ponds. They tend to form on long, flat and debris-covered valley glaciers at sites of thinning status rather than at retreating termini (Gardelle et al., 2011). Proglacial lakes generally grow by the accumulation of water behind former moraines from melting glaciers upstream (Komori, 2008; Richardson and Reynolds, 2000). Our analyses reveal that the rapid expansions were mostly observed for proglacial lakes in contact with debris-covered glacier tongues (would be analyzed in Result part in detail). Thus, the glacial-hydrogeomorphic processes leading to rapid expansion of this lake type are explored by examining the changes in lake level, the mass loss of parent glaciers (the upstream glaciers whose meltwater supplies the lake) and hydrogeomorphic characteristics of evolved lake bed.

2 Study area

The study area is located in the southeastern Tibetan Plateau, which covers the eastern sections of the Nyainqêntanglha Mountains and the Himalayas. It includes parts of two sub-basins of the Yarlung Zangbo River: Yigong Zangbo Basin and Nyang River Basin (corresponding to one Landsat scene, in the WRS-2 Path/Row of 136/039) (Figure 1). The climate of this region is dominated by two major atmospheric circulation systems (Su and Shi, 2002; Yao et al., 2012). In the dry season (November–April), the southern branch of the mid-latitude westerlies provides little precipitation and cold climate conditions; in the wet season (May–October), the westerlies become weak and the warm-moist Indian monsoon moves northward, bringing heavy rainfall to the region, and the precipitation in the wet season accounts for 60–90% of the annual precipitation (Xu et al., 2008). This region has rather varied terrains and extensive monsoonal temperate

glaciers. The monsoonal temperate glaciers flow more rapidly than continental glaciers in the inner TP, and are more sensitive to climate change and variability due to abundant precipitation and higher ice-layer temperature (Su and Shi, 2002).

[Insert Figure 1 around here]

3 Data and methods

3.1 Study materials

3.1.1 Landsat images for mapping glacial lakes and glaciers

In this study, temporal variations of glacial lake extent are investigated based on multi-temporal Landsat images at a spatial resolution of 30 m (accessed at <http://glovis.usgs.gov>). Two cloud-free images of the scene WRS-2 Path/Row 136/039, acquired on 10-09-1988 (by Landsat 5 TM) and 09-28-2013 (by Landsat 8 OLI), were used for examining regional changes of glacial lakes across the Yigong Zangbo Basin and Nyang River Basin between 1988 and 2013. The basically consistent acquisition dates for the two images may reduce the influence of seasonal lake fluctuations on two-date area comparison. To understand the evolution of rapidly expanding lakes, we selected one typical glacial lake (in contact with debris-covered ice) in the northeastern study area (Figure 1c) and obtained time series of lake area evolution based on all available Landsat images between 1988 and 2013. The selected lake is located in the overlap of WRS-2 Path 135 and Path 136, all Landsat images in Path/Row 136/039 and 135/039 during 1988–2013 without cloud and snow contaminations over the lake areas were collected (totally 25 Landsat scenes, see Table 1).

[Insert Table 1 around here]

3.1.2 ICESat altimetry data

ICESat altimetry data were used to detect inter-annual changes in glacier surface elevation and glacial lake stage during 2003-2009. The ICESat altimeter employs a near infrared (1064 nm) laser to measure elevations within ~70m diameter footprints spaced at 172 m along-track. The elevation dataset can provide elevation measurements with the vertical accuracy of tens of centimeters or better (Urban et al., 2008; Zwally et al., 2002), and has been widely used for measuring surface elevation changes of mountain glaciers (Gardner et al., 2013; Kääb et al., 2012; Neckel et al., 2014) and inland lakes and rivers (Duan and Bastiaanssen, 2013; Phan et al., 2012; Song et al., 2013; Song et al., 2014b; Wang et al., 2013; Zhang et al., 2011).

We used Release-33 ICESat level-2 product (GLA14) provided by the National Snow and Ice Data Center (NSIDC). The GLA14 product contains corrected surface ellipsoidal heights referenced to the TOPEX/Poseidon ellipsoid and Earth Gravity Model (EGM)-2008 geoid heights, saturation flags and other information. The ICESat tracks passing over the selected lake and nearby mountain glaciers are shown in Figure 1. In the pre-processing stage, the latitude, longitude and elevation of footprints were extracted by the GLAS Visualizer and NSIDC GLAS Altimetry elevation extractor Tool (NGAT).

3.1.3 Glacier inventory data

Glacier extents over our study area in previous glacier inventories were mainly derived from aerial photographs and historical maps, and have quality issues such as geometrical distortions or overestimated glaciated area due to seasonal snow cover (Pfeffer et al., 2014). The CGI version-2 was released recently, but there were few updates in part of the SETP region due to the limited

acquisition of cloud-free images (Guo et al., 2015). This study uses a new glacier inventory, which was compiled based on Landsat images acquired between 2011-2013 (mostly from Landsat 8 OLI images acquired in 2013), coherence images derived from PALSAR (Phased Array type L-band Synthetic Aperture Radar) sensor, and SRTM DEM (Ke et al., 2016). In the new glacier inventory, debris-free ice and debris-covered glacier tongues were mapped separately. For the former, debris-free masks generated from segmentation of multi-temporal Normalized Difference Snow Index (NDSI) images were mosaicked to ensure minimum glaciated area (excluding seasonal snow cover). As the debris-covered glacier tongues show very low PALSAR coherence and have relatively gentle slopes, the potential glacier tongues covered with supraglacial debris were extracted by overlaying segmented coherence maps, a slope map and vegetation and water masks. The vegetation and water masks were generated from normalized difference vegetation index (NDVI) and normalized difference water index (NDWI) maps based on the same Landsat scenes, respectively. Only debris-covered glaciated areas which were connected with debris-free ice were selected as the final debris-covered glacier tongues. In compiling the new glacier inventory, most thresholds used for the segmentation were based on histogram distributions of image values, and most of the processing steps were semi-automated and pixel-based (Ke et al., 2016). The generated glacier data has a high consistency with the recently published Randolph Glacier Inventory (RGI) 5.0 inventory in the SETP (the version of RGI inventory has not been published when our data were generated) (Nuimura et al., 2015). Through visual inspection by referring to Landsat false-color composites, the debris-covered ice parts were separately identified and provide valuable information for distinction of different types of glacier lakes in this study.

3.1.4 Digital elevation model (DEM) data

DEM data were obtained to serve as the topographic reference when using multi-date ICESat measurements to estimate surface elevation changes of glacial lakes and glaciers and investigating the altitudinal distribution of glacial lakes. This study uses the version-2 gridded SRTM DEM acquired on February 2000 from the Consultative Group on International Agricultural Research (CGIAR) website (<http://srtm.csi.cgiar.org/>). This version was preferred because it contains no horizontal misalignment between DEM raster and ICESat (Kääb et al., 2012; Neckel et al., 2014). Although there are a few data gaps in this version due to radar shadow and layover effects associated with the InSAR techniques in generating the DEM, mostly over rather rugged high-mountain terrain, almost no data gaps are observed over relatively flat terrains such as the glacier tongues and surroundings where glacial lakes are distributed. The SRTM elevations are orthometric heights with respect to the WGS-84 ellipsoid and the EGM 96 vertical datum.

3.2 Methods

3.2.1 Mapping glacial lakes

Lake mapping is a prerequisite for examining glacial lake distribution and temporal variations. Various methods have been proposed for mapping water bodies in previous studies, such as conventional supervised spectral classification (Johnston and Barson, 1993), manual delineation (Wang et al., 2012b; Wang et al., 2011b), spectral transformation method (Sawaya et al., 2003), decision tree (Gardelle et al., 2011), object-oriented classification (Li et al., 2011), and water or snow indices (McFeeters, 1996). Here we applied two steps to generate our glacial lake inventory. 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 NDWI (McFeeters, 1996), and (ii) a DEM-based terrain analysis to minimize the impact of mountain shadows. In order to calculate valid NDWI values, raw digital numbers in all Landsat images were calibrated to Top-of-Atmosphere (TOA) reflectance (similar performances to atmospheric corrected images in mapping these glacial lakes) (Chander et al., 2009).

Figure 2 illustrates the main procedures of our automated lake mapping step. First, a mask of potential glacial lake areas was generated by a global-level threshold segmentation from a combination of NDWI and other auxiliary variables such as near infrared (NIR) and shortwave infrared (SWIR) bands, and topographic factors (thresholds shown in the right panel of Figure 2) in order to constrain commission errors due to melting ice. Following Quincey et al. (2007), DEM-derived surface slope for potential lake areas was required to be less than 10° . A loose initial NDWI threshold is set at -0.05 to minimize omission of lakes during the global-level filtering. For each potential lake segmented by this global NDWI threshold, a buffer zone (about 2-4 times lake area varying with the lake sizes) was built to refine the local threshold using the NDWI distribution within this buffer (four cases illustrated in plots A-D of Figure 2 left-bottom). This local-level segmentation was conducted iteratively until the fine-tuned water extent stabilized (with the areal variations less than 1% for most lakes). As a result, the final lake boundaries were delineated based on different NDWI thresholds adaptive to local lake spectral variation induced by water turbidity, depth and image acquisition dates (A-C in Figure 2). In this study, only glacial lakes occupying more than five pixels ($\geq 0.0045 \text{ km}^2$) are kept and analyzed below, as smaller lakes might pose much weaker potential threats to downstream regions and have larger uncertainties in lake mapping.

[Insert Figure 2 around here]

Following the automated lake mapping, a human-interactive quality control was performed to correct remaining mapping errors. We identified false and missing lakes by overlapping mapped lake features on the source Landsat images and high-resolution Google Earth images. False lakes, mainly identified as mountain shadows and river segments, were manually removed. For missing glacial lakes, 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). Furthermore, via the “spatial join” tool of ArcGIS, cross-validation and modification for each glacial lake was conducted based on our lake mapping results from the two dates.

In the southeastern Tibetan Plateau, most glaciers are steep and there is a considerable turnover between accumulation and ablation, thus few supraglacial lakes are observed. Only two supraglacial lakes were identified in the 1988 image. According to the spatial relations with parent glaciers, proglacial lakes include the lakes in contact with glaciers (termed as glacier-contact lake, hereinafter) or not (non-glacier-contact lake). For these glacier-contact lakes, some are in contact with debris-covered ice (termed as debris-contact lake) as many valley glaciers in the SETP have long and relatively gentler tongues and thus tend to be covered or partially covered by debris; others are located in steep-sided debris-free glacier cirques where no enough space favor the lake enlargement (termed as cirque lake). The classification of all glacial lakes based on our mapped glaciers and glacial lakes were further confirmed by referring to high-resolution Google Earth images.

3.2.2 Measuring surface elevation variations of glacier and glacial lake

As the ICESat altimetry data is referred to the Topex/Poseidon ellipsoid and EGM 2008 datum, all

ICESat measurements were converted to the height reference system of WGS84 ellipsoid and EGM96 geoid (the same as used in SRTM DEM data) with reference to the geoid height provided by NGA/NASA (<http://earth-info.nga.mil/GandG/wgs84/gravitymod/>). Bilinear interpolation was used to extract the SRTM DEM elevations at the footprint location of each ICESat measurement. The elevation difference (dh) between each ICESat estimate and SRTM DEM ($I_{hgt} - I_{srtm}$) represents the elevation change at the sampled footprint. As in similar earlier studies (Kääb et al., 2012; Ke et al., 2015b; Neckel et al., 2014), a threshold of 150 m was applied to filter obvious errors of dh probably due to cloud cover and atmospheric noise.

The glacier extent generated in Section 3.1.3 was used as a mask to extract ICESat footprints as on-glacier and off-glacier samples. The off-glacier footprints were limited within a 10 km buffer outside glacier areas. Water bodies such as glacial lakes were excluded from the off-glacier extent. The annual trends of surface elevations were determined through robust linear fitting of all dh values in fall (October/November) seasons during 2003–2009. Trends in dh were estimated for glacier zones above and below the mean equilibrium line altitude (ELA), which is estimated to be at around 5000 m (Ke et al., 2016). The overall error in surface elevation change trends was computed as the root of sum of squares (RSS) of the robust fitting estimates. The off-glacier trend was calculated in the same way as the on-glacier trend by employing all ICESat measurements in the same ground track (not shown in the figure).

4 Result and analyses

4.1 Spatial distribution characteristics of glacial lakes

A total of 1278 and 1396 glacial lakes larger than 0.0045 km² were identified in the two study

basins for 1988 and 2013, respectively. Several large lakes located in downstream valleys that were not formed by glacial processes, such as Basongcuo Lake (earthquake-induced dammed lake) and man-made reservoirs, were excluded in our analyses. 92.4% (1290) of the lakes mapped in 2013 (Figure 1b) are not contacted with glaciers, most of which are distributed in valleys downstream. In particular, lakes which are densely located in the southern Nyang River basin are not replenished by glacial meltwater but by seasonal snow meltwater and precipitation, as there are no modern glaciers distributed there. These lakes might have been formed by ancient glacier erosion (shown in Figure S1). The remaining 7.6% includes 27 (1.9%) lakes in contact with debris-covered ice (debris-contact lake) and 80 (5.7%) cirque lakes. In comparison, debris-contact glacial lakes evolve towards larger sizes (0.36 km^2 on average) than cirque lakes (0.12 km^2 on average) as the former are generally developed in long and less steep valleys.

We further examine the altitudinal distributions of lake size and count (derived from SRTM DEM) in Figure 3. The histograms of lake altitudes exhibit an approximately normal distribution. Over the two study basins, the altitudes of glacial lakes range from 3300 m to 5600 m. More than 95% lakes are concentrated in the altitude belt of 4300–5400 m. Different from the count-altitude distribution, lake sizes at lower altitudes tend to be larger due to the wider valleys and gentler terrain. Besides, the altitudinal distributions of glacial lakes are differentiated between the two basins. In the Nyang River basin, the majority of glacial lakes (~ 86% in count) are distributed in the altitude belt from 4400 m to 5250 m, while in the Yigong Zangbo basin, ~ 83% lakes are distributed between 4700 m and 5400 m. The higher altitudinal distribution of glacial lakes in the northwestern basin (Yigong Zangbo) could be largely related to higher average glacier altitudes due to the decrease in precipitation towards the interior of the plateau.

[Insert Figure 3 around here]

4. 2 Temporal evolution of glacial lakes during 1988–2013

As most lakes examined here belong to the proglacial type, their locations remain basically stable during 1988–2013, which differs from the supraglacial lakes investigated in the Karakorum, Himalayas and Khan Tengri-Tumor Mountains, which are ephemeral and vary in location from year to year (Gardelle et al., 2011; Liu et al., 2015b; Ye et al., 2009). This enables us to better analyze the temporal evolution of each glacial lake during the study period. Table 2 shows the count and area of glacial lakes of different types at the two study dates. From 1988 to 2013, glacial lakes in the SETP show obvious increases in both area and count. In total, the number of lake increases from 1278 in 1988 to 1396 in 2013. This change involves 129 newly-formed lakes and 11 disappeared lakes. There are 1267 lakes observed at both dates at the same locations (termed as co-existing lakes, hereinafter). The total area of glacial lakes increases by 8.07 km², with an expansion of 9.43%. The co-existing lakes have an expansion of 6.30 km² in area, which accounts for 78.07% of the total area increase.

Variations of lake area and count show differences between different groups (Table 2). The non-glacier-contact lakes constitute the majority of the total lake area and count in both dates. However, the expanding percentages have large differences between the glacier-contact and non-glacier-contact lakes. Of the 1267 co-existing glacial lakes, 1213 non-glacier-contact lakes expand by 2.61% (1.94 km²) in area, while 49 cirque lakes expand by 6.82% (0.36 km²) and 15 debris-contact lakes expand by 74.77% (4.01 km²). Most of the non-glacier-contact lakes, located downstream, remain unchanged, and the total area of non-glacier-contact lakes larger than 0.1 km²

(137 lakes, 46.74 km² in 1988) only increase by 1.18 km² (0.10 % yr⁻¹). Among 129 newly-formed lakes, 31 cirque lakes and 12 debris-contact proglacial lakes increase by 0.68 km² and 0.55 km², respectively, which totally account for over half of area increase of the newly formed lakes. The average size of new debris-contact lakes is 2-5 times larger than those of cirque lakes and non-glacier-contact lakes. Additionally, 11 lakes disappeared during the study period, including two supraglacial lakes on debris-covered ice and nine non-glacier-contact lakes, which cause a total decrease of 0.22 km² in area.

[Insert Table 2 around here]

4.3 Exploring cause of the rapid expansion of debris-contact proglacial lakes

We have shown in Section 4.2 that debris-contact proglacial lakes experienced more rapid expansion than the other two lake types. Here one typical example is provided to further illustrate the contrast between non-glacier-contact and debris-contact lakes. Two large glacial lakes are highlighted in Figure 4. Both lakes receive a large amount of glacial meltwater, and have outlets and outflow river channels clearly visible in Google Earth imagery. However, the debris-contact lake experienced a considerable expansion by 206% (0.37 km²) from 1988 to 2013, while the non-glacier-contact lake remained nearly unchanged (1.58 km² in 1988 to 1.52 km² in 2013).

[Insert Figure 4 around here]

In order to investigate the evolution and driving mechanism of debris-contact proglacial lakes, we selected one glacial lake in contact with debris-covered ice near Mount Kona Kangri in the eastern Yigong Zangbo Basin (shown in Figure 1c). Figure 5 shows inter-annual variations of the selected lake from 1988 to 2013 derived from all available Landsat images (refer back to Section 3.1.1 and

Table 1). During the study period, the lake expanded dramatically by 132.5% (0.91 km²) in inundation area. By overlapping the evolving lake outlines on the image of 1988 (Figure 5 left), we clearly see that lake expanded upstream, a phenomenon similarly observed in most other debris-contact proglacial lakes.

[Insert Figure 5 around here]

Many prior studies have tried to identify the driving mechanisms of spatio-temporal heterogeneity of glacial lake evolution across these mountainous regions. In general, an expanding lake is considered to have an unbalanced water budget, with the water inputs (glacial meltwater and precipitation) outweighing outputs (evaporation or discharge). Thus temperature, precipitation and evaporation are commonly considered as major climatic factors controlling the changes of glacial lakes. Although accelerated temperature rises and precipitation changes have resulted in retreat and thinning of many mountain glaciers, few studies have provided convincing evidence of an association between glacial lake evolution and temperature and precipitation variability (Gardelle et al., 2011; Nie et al., 2013; Wang et al., 2011b). Based on field measurements or glacial-hydrological modelling, some studies inferred that the development of moraine-dammed glacial lakes might be largely related to glacier retreat (implying a possible increase in lake basin capacity), or alternatively to the downwasting of debris-covered ice (Quincey et al., 2007; Quincey et al., 2005; Richardson and Reynolds, 2000; Yamada, 1998). The glacier-contact proglacial lakes expand upstream by promoting calving and subaerial melting at the glacier terminus (Gardelle et al., 2011). Although the interaction between glacier lake and parent glacier has been discussed in previous studies, there is still no direct evidence to reveal how the glacier influences the glacial lake evolution (whether by influencing lake's water budget or controlling the

lake bathymetry), especially for dramatically expanding glacial lakes in contact with debris-covered ice in the study area.

To explore the cause of rapid expansion of debris-contact proglacial lakes in the SETP, we here hypothesize two driving mechanisms, as illustrated in Figure 6. In the first mechanism (mechanism A), the expansion of lake area is induced by considerable water gains with increasing glacial meltwater outweighing the discharge, which could lead to a large water level rise (Figure 6a); in the second mechanism (mechanism B), the lake level remains stable at the inter-annual timescale due to the natural regulation of water discharge via channels or englacial conduits; and the lake area expansion (mostly advancing upstream) is a direct consequence of debris subsidence with the melting and retreat of contacted glacier tongues (Figure 6b).

[Insert Figure 6 around here]

We estimate the changes of water level and glacial meltwater amount from parent glaciers for the selected lake. As shown in Figure 7a, parent glaciers of the selected lake experienced evident thinning from 2003 to 2009 over both ablation ($-2.19 \pm 0.39 \text{ m yr}^{-1}$) and accumulation areas ($-0.72 \pm 0.15 \text{ m yr}^{-1}$). The mean change rate is estimated at $-0.83 \pm 0.12 \text{ m yr}^{-1}$, which is comparable with the thinning rate ($-0.81 \pm 0.32 \text{ m yr}^{-1}$) over the entire eastern Nyainqêntanglha and Hengduan Mountains reported by Neckel et al. (2014). By referring to the thinning rate (assuming the glacier density to be 900 kg m^{-3}), the estimated net meltwater from parent glaciers (166.27 km^2 , based on Landsat imagery acquired in 2013) amounts to approximately $0.124 \pm 0.018 \text{ km}^3 \text{ yr}^{-1}$, which is equivalent to a water level rise of up to about 26.5 m yr^{-1} for the lake considering no additional contribution of precipitation and no water outflow.

Therefore, assuming that mechanism A is true, the lake water level could rise considerably due to the increasing glacial meltwater supply. However, as derived from the repeated ICESat altimetry measurements (Figure 7b), the water level of the selected lake remained nearly stable during 2003–2009 with only minor fluctuation of ~ 1.1 m about the mean lake surface (3995.9 ± 3.8 m a.s.l., in February 2000) with reference to SRTM DEM. The water level fluctuation and water slope (within 0.5m, measured by ICESat footprints along the lake) is negligible compared to the tens of meters of DEM-derived relief upstream of the lakeshore (see Figure S2). Such lake area expansion, i.e., with shoreline advancing considerably towards the upstream glacier terminus, obviously contradicts the observed constant lake levels, unless it parallels with a substantial debris subsidence at the glacier terminus (as illustrated in mechanism B). The better supported mechanism B reveals that the geomorphological alteration in the upstream lake basin induced by glacial thinning and melting likely dominates the increase of direct meltwater inflow in contributing the rapid expansion for these debris-contact proglacial lakes across the SETP.

Due to the sparse coverage of ICESat tracks over the study area and small size of glacial lakes, only the selected lake was measured repeatedly. Despite the limited lake level measurements, 13 out of 15 debris-contact proglacial lakes have unaltered lateral and down –valley boundaries but have expanded up-valley, which further supports mechanism B. In comparison with debris-contact glacial lakes, the cirque lakes are mostly developed in steep-sided cirques that are unfavorable sites for the limited enlargement of lake extent despite the ice melting.

According to the above analysis, expansion of debris-contact proglacial lakes mainly depends on the subsidence of upstream debris with glacier melt and recession. Hence we further examine the subsidence rate of debris-covered glacier termini after 2000 by comparing DEM-measured

elevation differences of the upper-shoreline (see Figure S2) relative to “stable” lake water surface. Figure 7b shows the elevation variations of the glacier terminus at the upper lakeshore during 2000-2013. Using robust regression fitting, we estimate that the lake-contacted debris (glacier termini) dropped at the rate of $3.82 \pm 0.18 \text{ m yr}^{-1}$. This indicates that the debris-covered ice was thinning at much greater rates than debris-free ice at higher altitudes (Figure 7a).

[Insert Figure 7 around here]

5 Discussions

5.1 Comparing with previous studies on glacial lake evolution of other regions

Many analyses on glacial lake evolution in this study are comparable with the results reported in earlier studies for other regions (Gardelle et al., 2011; Liu et al., 2015a; Nie et al., 2013; Wang et al., 2011b; Wang et al., 2011c). During the past several decades, glacial lakes experienced notable expansions, and the newly-formed glacial lakes far exceed disappeared lakes in both count and area. In comparison with the newly-formed lakes, the expansion of co-existing glacial lakes has larger contribution to the net area increase. For example, Nie et al. (2013) found that more than 80% of lake expansions in the central Himalayas were attributable to the growth of glacial lakes co-existing over the four investigated dates (1990, 2000, 2005 and 2010). Wang et al. (2011b) reported that co-existing and newly-formed glacial lakes in the Boshula Mountain contributed ~67% and ~33% to the net area expansion, respectively, and the moraine-dammed lake expansions contributed the majority of total area increase. Besides, the temporal evolution of glacial lakes showed strong spatial heterogeneity, varying with different regions and lake types, which could be tightly associated with the spatially variable glacier changes. Gardelle et al. (2011) examined

glacial lake evolution in seven regions of the Hindu Kush Himalaya (HKH) and found that glacial lakes in the east (India, Nepal and Bhutan) expanded more rapidly during 1990–2009 than those in the west (Pakistan and Afghanistan). In the Boshula Mountain of the SETP, the expansion rate for moraine-dammed glacial lakes is about $0.77 \text{ \% yr}^{-1}$ from the 1970s to 2009 according to Wang et al. (2011b), which is less than half of the observed rate for glacier-contacted lakes ($1.76 \text{ \% yr}^{-1}$, including cirque lakes and debris-contact proglacial lakes) during 1988-2013 in our study area, or even one fourth of the expansion rate of debris-contacted lakes ($2.99 \text{ \% yr}^{-1}$). In our study area, the 27 (~2% of the whole examined lakes in count) debris-contact proglacial lakes account for about 54% of total increase in lake area, and exhibit much more active evolution than cirque lakes and non-glacier-contact lakes during 1988-2013.

5.2 Uncertainties of elevation measurement of glaciers and glacial lakes

The investigation of elevation changes of glacial lakes and debris-covered ice depends critically on the reliability of ICESat measurements and DEM data. The ICESat altimetry data have been widely applied to monitor inland lake dynamics with centimeter-level accuracy (Song et al., 2014b; Urban et al., 2008; Wang et al., 2013). In this study, although there are only several (3–6) on-lake footprints for each ICESat campaign, their measured lake surface elevations have very small biases from each other (with the standard deviation of 0.05- 0.29 m). It implies that ICESat altimetry measurements on the glacier lake are acceptable in this study. The accuracy of several freely available DEM datasets (e.g., ASTER DEM and SRTM DEM) has been assessed at global and regional scales. It was widely reported that the DEM data have low accuracy in mountainous areas. Toutin (2002) reported that the root-mean-square errors (RMSEs) of DEM data are linearly correlated with the terrain slope, and the increase in RMSE with terrain slope is clear for the

SRTM DEM. Fujita et al. (2008) evaluated the relative accuracies of SRTM and ASTER DEM with GPS ground surveys for monitoring glacial lakes in the Lunana region, Bhutan Himalaya: in spite of the relatively higher RMSEs of 11.0 m for ASTER and 11.3 m for SRTM over the whole surveying area, the data accuracy around lakes, riverbeds and glacier terminus is obviously better due to flatter terrain; the RMSE of SRTM DEM for slopes below 10° is less than 8 m. The similar accuracy of DEM has also been confirmed over the Longli Co basin of southeast Tibet by Wang et al. (2012a): the RMSE of the SRTM DEM for slopes below 5° is around 7.5 m. We evaluate the used SRTM DEM measurements by inter-comparing with ICESat altimetry data over the study area (excluding the glaciated areas and glacial lakes). As shown in Figure S3, the strong associations of relative accuracy of DEM data with land surface slope are found, with a mean bias less than 5 m over slopes below 5° . For the selected lake, the mean slope of upstream debris-covered ice is $5.35^\circ \pm 1.51^\circ$. Thus, compared to the considerable elevation variations of lake-contact debris, the uncertainty of SRTM DEM data is basically acceptable in this study.

6 Summary

In this study, we conducted a regional investigation of the spatial distribution and temporal evolution of glacial lakes in the SETP from 1988 to 2013, and explored the potential cause of rapid expansion of debris-contact proglacial lakes. Glacial lakes were extracted using a hierarchical segmentation method, which delineates lake boundaries using different NDWI thresholds that are well adapted to various water spectral conditions by segmenting NDWI histogram for each lake. The automated mapping result was validated and corrected by comparing the source Landsat images and high-resolution Google Earth imagery with the assistance of an interactive mapping tool. A total of 1278 and 1396 glacial lakes ($\geq 0.0045 \text{ km}^2$) were inventoried

in 1988 and 2013, respectively. Among these lakes (in 2013), 92.4% of lakes are not in contact with modern glaciers. The remaining 7.6% includes 27 (1.9%) debris-contact lakes and 80 (5.7%) cirque lakes. 95% of lakes (in count) are concentrated in the altitude belt of 4300–5400 m. Glacial lakes in the Yigong Zangbo Basin (the northern study area) have relatively higher altitudes than those in the Nyang River Basin, mainly due to the decrease in precipitation towards the interior of the plateau.

Between 1988 and 2013, glacial lakes in the study area experienced obvious increases in both area and count. The number of glacial lakes increased by 118, involving 129 newly-formed lakes (2.33 km²) and 11 disappeared lakes (0.22 km²). The total area increased by 8.07 km² (9.43%). The co-existing lakes (identified in both 1988 and 2013) exhibit a total expansion of 6.30 km² in area, which contributes 78.07% to the total area increase of our analyzed glacial lakes. Among these co-existing lakes, debris-contact lakes showed a much higher expansion (74.77%) than cirque lakes (7.41%) and non-glacier-contact lakes (2.61%). Most non-glacier-contact lakes remained relatively stable.

We further explored the cause of the rapid expansion of debris-contact proglacial lakes by examining the mass balance of parent glaciers and elevation changes of lake surfaces and debris-covered glacier termini of one typical debris-contact lake based on ICESat altimetry and SRTM DEM. Our case study shows that the rapid expansion of debris-contact lake was mainly caused by the altered geomorphometry of upstream lake basin that results from the subsidence of lake-contact debris with glacier melting and thinning. This mechanism was verified by the observed stable lake water levels and evolved lake outline morphometry. It was shown that expansion of these debris-contact lakes primarily occurred towards the upstream direction rather

472 than in the lateral and downstream directions. On the contrary, most non-glacier-contact lakes
473 located in the downstream valleys remained generally unchanged due to their stable lake
474 bathymetry and outlet. This study helps us better understand the glacial-hydrogeomorphic
475 processes of debris-contact glacial lake evolution in the SETP. Continued monitoring is
476 indispensable for early recognition of potential glacial lake hazards due to ongoing glacier retreat
477 in this region.

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Table and Figure Captions

Table 1. Landsat images used for investigating glacial lakes and glaciers in this study.

Table 2. Statistics of temporal variations in count and area (km²) for different types of glacial lakes in the study area.

Figure 1. Location of the study area. (a), the geographical location of study area in High Mountain Asia; (b), topographical characteristics and distribution of mountain glaciers and glacial lakes in the two targeted river basins; (c), one typical debris-contacted glacial lakes (marked as Lake1) for investigating glacial-hydrological processes, and the yellow tracks indicate the ICESat footprints.

Figure 2. Procedure of automated lake mapping. Step 1, preparation of multi-spectral Landsat images including the conversion of radiance value to TOA reflectance; Step 2, generation of NDWI image and other auxiliary variables including surface slope ($<10^\circ$), NIR (<0.15) and SWIR (<0.05) bands; Step 3, threshold segmentation of NDWI (≥ -0.05) and other images; Step 4, the local-level NDWI histogram threshold segmentation.

Figure 3. Altitudinal distributions of glacial lakes in count and area for two sub-basins: Nyang River basin and Yigong Zangbo basin.

Figure 4. Contrast of temporal evolution between selected non-glacier-contact and debris-contact glacial lakes during 1988–2013. The background shows the Landsat-8 image acquired on September 28, 2013, with the false-color RGB composite of Band 7-5-3.

Figure 5. Temporal evolutions of the selected debris-contacted lake during 1988–2013. Left: lake boundaries derived from time-series Landsat images (Note: evident boundary changes were

observed in the upstream direction); right panel: time series of inundation areas between 1988 and 2013. Red lines refer to the linear regression fitting within the 95% confidence interval.

Figure 6. Schematic diagrams illustrating the glacial-hydrogeomorphic process of debris-contact proglacial lake expansion. In mechanism A (a), the lake expansion is hypothesized to be caused by rising water level with the supply by increasing glacial meltwater; in mechanism B (b), the lake level remains relatively stable, and the lake enlargement in the upstream direction is caused by geomorphological alteration of upstream lake basin with debris subsidence due to ice melting and thinning.

Figure 7. Comparison of change patterns in surface elevations over different parts of glaciers (a), and measured elevation changes of lake water surface (from ICESat altimetry, in orange color) and upper-lakeshore debris subsidence for the selected glacial lake (b). The blue line in plot (b) indicates the linear fit of upper-lakeshore DEM.

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Research purpose	Acquisition date (mm/dd/yyyy)	Satellite/Sensor	WRS-2 Path/Row
Investigation of glacial lakes and glaciers over the whole study area	10/09/1988	Landsat 5/TM	136/039
	09/28/2013	Landsat 8/OLI	136/039
	04/15/1996	Landsat 5/TM	135/039
	07/21/1999	Landsat 7/ETM+	135/039
	09/23/1999	Landsat 7/ETM+	135/039
	10/25/1999	Landsat 7/ETM+	135/039
	05/04/2000	Landsat 7/ETM+	135/039
	05/12/2000	Landsat 5/TM	135/039
	10/02/2000	Landsat 5/TM	136/039
	10/22/2001	Landsat 5/TM	135/039
	11/15/2001	Landsat 7/ETM+	135/039
	06/10/2002	Landsat 5/TM	136/039
	10/17/2002	Landsat 7/ETM+	135/039
	07/24/2003	Landsat 5/TM	135/039
	05/07/2004	Landsat 5/TM	135/039
Investigation of typical glacial lake and its parent glacier terminus (including the above two scenes)	11/06/2004	Landsat 5/TM	136/039
	09/06/2005	Landsat 5/TM	136/039
	10/24/2005	Landsat 5/TM	136/039
	04/14/2007	Landsat 5/TM	135/039
	04/30/2007	Landsat 5/TM	135/039
	07/05/2008	Landsat 5/TM	135/039
	03/21/2010	Landsat 5/TM	135/039
	08/31/2011	Landsat 5/TM	135/039
	08/04/2013	Landsat 8/OLI	135/039
	08/11/2013	Landsat 8/OLI	136/039

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666

667 Table 2. Statistics of temporal variations in count and area (km²) for different types of glacial

668 lakes in the study area.

lake type	co-existing lakes at the two dates				newly-formed lakes		disappeared lakes	
	count (1267)	area (km ²)			count (129)	area (km ²) (2.33)	count (11)	area (km ²) (0.22)
		1988 (85.02)	2013 (91.32)	changes (7.41%)				
cirque lake	49	5.28	5.64	6.82%	31	0.68	/	/
debris-contact lake	15	5.35	9.36	74.77%	12	0.55	/	/
supraglacial lake	/	/	/	/	/	/	2	0.02
non-glacier-contact lake	1213	74.38	76.32	2.61%	86	1.10	9	0.20

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