A regional-scale assessment of Himalayan glacial lakes changes using satellite observations from 1990 to 2015

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Abstract

The Himalaya, the world's highest mountain ranges, are home to a large group of glaciers and glacial lakes. Glacial lake outburst floods (GLOFs) in this region have resulted in catastrophic damages and fatalities in the past decades. The recent warming has caused dramatic glacial lake changes and increased potential GLOFs risk in the Himalaya. However, our knowledge on the current state and change of glacial lakes in the entire Himalaya is limited. This study maps the current (2015) distribution of glacial lakes across the entire Himalaya and monitors the spatially-explicit evolution of glacial lakes over five time periods from 1990 to 2015 using a total of 348 Landsat images at 30 m resolution. The results show that 4950 glacial lakes in 2015 cover a total area of $455.3 \pm 72.7 \text{ km}^2$, mainly located between 4000 m and 5700 m above sea level. Himalayan glacial lakes expanded by approximately 14.1% from 1990 to 2015. The changing patterns of supraglacial lakes and proglacial lakes are rather complex, involving both lake disappearance and emergence. Many emergent glacial lakes are found at higher elevations, especially the new proglacial lakes, which have formed as a result of glacier retreat. Spatially heterogeneous changes of Himalayan glacial lakes are observed, with the most significant expansion occurring in the southern slopes of the central Himalaya. Increasing glacier meltwater induced by the Himalayan atmospheric warming is a primary cause for the observed lake expansion. This study provides primary data for future GLOF risk assessments. A total of 118 rapidly expanded glacial lakes are identified as potential vulnerable lakes for the priority of risk assessment.

Keywords: Landsat, glacial lake, glacier, climate change, Himalaya

1. Introduction

Glaciers are a key indicator of terrestrial climate change and serve as important water resources in mountainous areas [Kääb *et al.*, 2012]. The Tibetan Plateau (TP) and its vicinity contain the largest number of glaciers outside of the Antarctic and Arctic [Gardner *et al.*, 2013; Yao *et al.*, 2012]. During the past decades, the glaciers in the Himalaya showing the most negative mass balances have been observed in TP region [Bolch *et al.*, 2012; Kääb *et al.*, 2012; Yao *et al.*, 2012]. Such a continued change will affect regional water availability [Immerzeel *et al.*, 2013], accelerate glacial lake evolution [Linsbauer *et al.*, 2016; Zhang *et al.*, 2015] and increase the risk of glacial lake outburst floods (GLOFs) causing catastrophic destructiveness and fatalities in the downstream regions [Ng *et al.*, 2007; Nie *et al.*, 2013; Quincey *et al.*, 2005; Yao *et al.*, 2012]. The Himalaya (Figure 1) is known as one of the major GLOFs-vulnerable regions in the world [Carrivick and Tweed, 2016; Ives, 1986; Liu *et al.*, 2014a; Liu *et al.*, 2014b; Quincey *et al.*, 2005; Wang *et al.*, 2012a; Worni *et al.*, 2013; Yamada and Sharma, 1993]. According to a glacio-hydrological model [Immerzeel *et al.*, 2013], continuous glacial retreat may potentially accelerate GLOFs in the Himalaya in the future.

Due to the low accessibility of glacial lakes, remote sensing provides the most feasible technique for monitoring and detecting vulnerable glacial lakes in high mountain areas [Buchroithner, 1995; Buchroithner and Bolch, 2015; Huggel *et al.*, 2002; Quincey *et al.*, 2007]. The Landsat series of satellites provide the longest temporal and spatial record for earth surface observation since their first launch in 1972. The successful launch of Landsat 8 on February 11 2013 extends the Landsat record into four decades [Roy *et al.*, 2014], with advantages of new spectral bands, high signal-to-noise ratios and improved image acquisition capability [Roy *et al.*, 2014]. Landsat products are an important source of data for climate change studies, and have been

widely used in the cryospheric sciences in the Himalaya [Bhardwaj *et al.*, 2015; Bolch *et al.*, 2008; Buchroithner, 1995; Buchroithner and Bolch, 2015; Gardelle *et al.*, 2011; Liu and Mayer, 2015; Robson *et al.*, 2015]. The expansion of glacial lakes in the Bhutan Himalaya (eastern Himalaya) [Jain *et al.*, 2015; Komori, 2008] and in the Mount Everest region of Nepal [Bajracharya and Mool, 2009] were revealed by remote sensing data, but only for several representative lakes. The Chinese Himalaya glacial lakes expanded by 29.7% based on topography maps from 1970s and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images from the 2000s [Wang *et al.*, 2012b]. A total of 251 glacial lakes $>0.01 \text{ km}^2$ were identified and mapped over the Indian Himalaya using Landsat images in circa 2000 and Satellite Pour l'Observation de la Terre (SPOT) images in circa 2010 [Worni *et al.*, 2013]. The spatiotemporal dynamics of supraglacial ponds across nine glaciers in the Everest region (central Himalaya) were revealed by different fine-resolution satellite imageries from 2000 to 2015 [Watson *et al.*, 2016]. Different data sources and spatial resolutions may result in uncertainties in glacial lake change analysis. Landsat images acquired in 1990, 2000 and 2009 were employed to map glacial lake distributions and evolution at seven sites of the Hindu Kush Himalaya [Gardelle *et al.*, 2011]. A systematic investigation of glacial lakes using the consistent 30 m spatial resolution of Landsat image from 1990 to 2010 over four time periods was reported in the central Himalaya [Nie *et al.*, 2013]. Glacial lakes in 1990, 2000 and 2010 were investigated by manual digitization for the High Mountain Asia [Zhang *et al.*, 2015]. An automated algorithm was developed and applied to delineate glacial lakes from Landsat images in circa 1990, circa 2000 and 2009 across the Himalaya, and an accelerated expansion was reported (2.74% 1990-2000, and 4.16% 2000-2009) [Li and Sheng, 2012]. These studies increase the knowledge on Himalayan glacial lake changes.

However, no previous studies have made a systematic investigation for glacial lakes of the entire Himalaya, both about their latest distribution status and spatial-temporal heterogeneity of changes. Glacial lakes inventory covering the entire Himalaya with a historic record up to present is crucial for assessment of regional-scale glacial-climate changes and GLOF risks [Zhang *et al.*, 2015]. Local people and the scientific community are particularly concerned about charting the development of glacial lakes, which may be prone to sudden catastrophic drainage. Most historical GLOF events in the Himalaya (Figure 1) originated from moraine-dammed glacial lakes. One of the most serious disastrous GLOF events was the outburst flood from Lake Cirenmaco that destroyed a downstream hydropower plant, roads, bridges, and resulted in hundreds of fatalities [Chen *et al.*, 2007; Wang *et al.*, 2016]. The potential risk assessment of glacial lakes in the Himalaya has been discussed [Bolch *et al.*, 2008; Wang *et al.*, 2012a; Wang *et al.*, 2015a; Worni *et al.*, 2013]. The expanding rate of glacial lakes is one of the most important indicators of potential outburst hazards [Wang *et al.*, 2012a]. Glacial lake sizes and their potential flood volumes directly control the severity of a hazard [Fujita *et al.*, 2013; Worni *et al.*, 2013]. Meanwhile, monitoring glacial lake changes at regional scales, especially considering the Himalaya as a whole, is essential to the assessment of climate change impacts [Nie *et al.*, 2013]. Glacial lake inventories should be validated using rigorous quality control processes to reduce or avoid the impacts of clouds, mountain shadows and other sources of error [Sheng *et al.*, 2016]. The validated glacial lake inventory can be employed to identify rapidly expanding glacial lakes for the priority of hazardous risk assessment. The distribution and spatial heterogeneity of rapidly expanding glacial lakes in the entire Himalaya should be further explored.

To this end, objectives of this study include: 1) to employ Landsat 8 images to investigate the up-to-date glacial lake distribution in the whole Himalaya in 2015; 2) to map glacial lake changes

and their regional heterogeneity across the Himalaya using consistent Landsat images of five episodes (ie., 1990, 2000, 2005, 2010 and 2015); 3) to identify the rapidly expanding lakes, providing fundamental information for early recognition of GLOF hazards; 4) to improve the understanding on relationship between glacial lake, glacier and climate change in the Himalaya.

2. Materials and methods

2.1. Study area

The study area covers the entire Himalaya, running about 2400 km from its northwest to southeast. The Himalaya are located around the southern rim of the TP, occupying an estimated area of ~0.65 million km² (Figure 1) and containing glaciers with a total area of ~22, 800 km² [Bolch *et al.*, 2012]. The Himalaya are the source of the world's major rivers, including the Indus, the Brahmaputra and the Ganges. The distribution of glaciers and equilibrium line altitudes are mainly under the dominance of the Indian monsoon and the Westerlies with limited influence from the East Asian monsoon [Yao *et al.*, 2012]. Precipitation regimes are driven by the Indian monsoon in summer and by the mid-latitude westerlies in winter [Bohner, 2006]. The precipitation pattern is characterized by a north-south gradient due to the orographic barrier of the Himalaya and an east-west gradient because of the westerly weakening of the Indian monsoon [Bookhagen and Burbank, 2006; Maussion *et al.*, 2014; Worni *et al.*, 2013]. Mean annual air temperature and precipitation from 1979 to 2014 are, respectively, 1.0 °C and 66.1 mm at Shiquanhe station in western Himalaya, 5.9 °C and 657.3 mm at Nyalam station in central Himalaya, and 0.4 °C and 442.6 mm at Yadong station in eastern Himalaya (Figure 1).

Figure 1 Location of study area and distribution of Himalayan glaciers and glacial lakes in 2015

2.2. Data

A total of 348 Landsat Thematic Mapper (TM), Thematic Mapper Plus (ETM+) and Landsat 8 Operational Land Imager (OLI) images with a spatial resolution of 30 m were downloaded from the United States Geological Survey (USGS) and the Global Land Cover Facility, and used to map lake extents in 1990, 2000, 2005, 2010 and 2015. It is difficult to obtain images covering the whole study area in a given year due to the highly frequent cloud cover across the region [Burns and Nolin, 2014; Nie *et al.*, 2010; Nie and Li, 2011]. All available high-quality images were acquired primarily within ± 1 years of the mapping years at the five episodes (Figure 2). For example, the circa 2000 data spanned from 1999 to 2001. A total of 85 Landsat 8 images spanning 2013-2015 were employed to produce the circa-2015 lake dataset (50 images acquired in 2015). Landsat 8 is more effective in lake mapping than the previous Landsat sensors due to its improved sensor and enhanced image acquisition plan [Sheng *et al.*, 2016]. To reduce the effect of seasonal variability,

images in similar seasons were selected, mainly in autumn and early winters (325 out of the 348 images). Hydrological data observed at the downstream of Rongbuk Glacier in the central Himalaya reveal the ablation period of glaciers is mainly from June to August and river discharge decreases gradually from September onwards [Liu *et al.*, 2006; Nie *et al.*, 2013]. Thus, glacial lake change during autumn and early winter is minor in this area. Using images from autumn and early winter, therefore, reduces the effect of acquisition date differences on glacial lake changes.

Figure 2 Statistics of Landsat images employed by year (a) and month (b)

Other datasets used are: i) meteorological data from the China Meteorological Administration; ii) precipitation data of Global Precipitation Climatology Project (GPCP) [Adler *et al.*, 2003; Huffman *et al.*, 2009] provided by NOAA/OAR/ESRL at <http://www.esrl.noaa.gov/psd/>; iii) China Glacier Inventory data [Guo *et al.*, 2015]; iv) the Randolph Glacier Inventory [Pfeffer *et al.*, 2014]; and v) Global Land Ice Measurements from Space (GLIMS) Glacier Inventory Data [Armstrong *et al.*, 2011]. Glacier datasets were used to extract glacial lake attributes. Based on the GLIMS Glacier Inventory Data, a buffer distance of 10 km from the nearest glacier termini [Wang and Ding, 2013; Zhang *et al.*, 2015] was adopted to determine the extent of glacial lakes in this

study. Glacial lakes further than 10 km from the nearest glacier termini were excluded due to an assumed weak interaction with current glaciers [Zhang *et al.*, 2015]. In addition, Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) with a 3-arc second (90 m) resolution [Jarvis *et al.*, 2008] was employed to identify the altitudinal characteristics of mapped lakes. The absolute vertical accuracy of the SRTM DEM is 16 m (90%) [Rabus *et al.*, 2003; Surazakov and Aizen, 2006]. The SRTM DEM has been evaluated specifically for the Lunana region, Bhutan Himalaya and southeast Tibet, and was shown to provide reliable data for glacial lake assessment [Fujita *et al.*, 2008] and hydraulic modeling of GLOF [Wang *et al.*, 2012c].

2.3. Methods

Glacial lake extents for 1990, 2000, 2005 and 2010 were extracted using automatic object-oriented mapping and human inspection methods as reported by Nie *et al.* [2013]. Glacial lake data in 2015 from Landsat 8 images was generated using an advanced automated adaptive lake mapping method [Li and Sheng, 2012; Sheng *et al.*, 2016; Wang *et al.*, 2014]. In both of the automatic extraction methods, the Normalized Difference Water Index (NDWI) [Mcfeeters, 1996] was calculated to derive glacial lake extent. Both the automated mapping methods include pre-processing of image data, object segmentation and conversion of raster data into vector format. The difference between these two mapping methods is that the object-oriented mapping first employed edge-based segmentation algorithms to generate entities and set a single threshold to extract the lakes from all the entities, while the second method employed a two-step threshold segmentation to extract each lake boundary [Song and Sheng, 2015]. Both the automatic mapping methods produced good outputs as inspected according to the source images. Quality assurance and quality control (QA/QC) procedures included three steps: 1) visual inspection and correction for each lake at one episode based on Landsat images and Google Earth high-resolution images; 2)

cross-check of glacial lake data at five episodes according to multi-temporal images; and 3) topology validation for lake mapping, including repeat removal, elimination of small sliver polygons. Misidentifications of extracted lake extents due to cloud cover, snow cover, lake ice and topographic shadows were manually modified using alternative images of better quality. QA/QC procedures helped to eliminate the effects of cloud contaminations, mountain shadows, and snow and ice covers. We set the minimum mapping unit to nine pixels or 0.0081 km². The centroid of each lake was calculated as the unique label point for tracing the changing characteristics of individual lakes across the five episodes. Accuracy assessment of the mapping process is difficult due to the lack of field measurements of glacial lakes in the Himalaya [Gardelle *et al.*, 2011]. The uncertainty of glacial lake area is typically estimated in previous research by the linear error and the lake's perimeter [Fujita *et al.*, 2009; Salerno *et al.*, 2012; Zhang *et al.*, 2015]. Here an error of ± 0.5 pixels was used to calculate the area uncertainty of glacial lakes using the method reported by Salerno *et al.* [2012]. The dynamic cross-validation and QA/QC procedures are time-consuming, but are essential to maximize the quality of glacial lake change detections.

All glacial lakes are preliminarily classified into three types based on the relationships to their 'mother' glaciers: (1) supraglacial lakes, developed on glacier surface; (2) pro-glacial lakes, connected with glaciers and usually dammed by moraines; and (3) unconnected glacial lakes, not directly in contact with current glaciers [Gardelle *et al.*, 2011; Salerno *et al.*, 2012]. Unconnected glacial lakes are further categorized into glacier-fed and non-glacier-fed lakes [Zhang *et al.*, 2015] based on the existence of one or more current glaciers in the basin according to glacier inventory data.

3. Results

3.1. Distribution of glacial lakes between 1990 and 2015

Across the entire Himalaya, there were 4549 glacial lakes ($398.9 \pm 65.3 \text{ km}^2$) in 1990, 4671 lakes ($421.2 \pm 67.8 \text{ km}^2$) in 2000, 4691 lakes ($431.4 \pm 68.5 \text{ km}^2$) in 2005 and 4723 lakes ($442.3 \pm 69.6 \text{ km}^2$) in 2010. Our lake mapping technique based on Landsat-8 images reveals 4950 glacial lakes in 2015, with a total area of $455.3 \pm 72.7 \text{ km}^2$ (Table1). Most glacial lakes are less than 0.1 km^2 (4007, Figure 3a) in 2015, but larger lakes (area $> 0.1 \text{ km}^2$) contribute 71.3% to the total area (Figure 3b).

Figure 3 Frequency (a) and area (b) of Himalayan glacial lakes in various size classes

Of the 4950 glacier lakes in 2015, 173 (5.6 km^2) were supraglacial, 534 (137.7 km^2) were proglacial, 2705 (209.9 km^2) were unconnected glacier-fed and 1538 (102.1 km^2) were non-glacier-fed (Table 1).

Glacial lakes in the Himalaya show distinct altitudinal distributions. Lake's number and size show similar distribution patterns against elevation (Figure 4a). The altitudes of all glacial lakes mapped in 2015 ranged from 3000 m a.s.l. (above sea level) to 6000 m a.s.l., with 93%

between 4000 m a.s.l. and 5700 m a.s.l. and a mean altitude of 4913 m a.s.l.. However, the four types of lakes exhibit differences in their altitudinal distributions (Figure 4b). The proglacial lakes have the highest mean elevation (5161 m), followed by unconnected glacier-fed glacial lakes (5017 m), then supraglacial lakes (4917 m) and finally non-glacier-fed glacial lakes (4645 m).

Figure 4 Altitudinal distribution of Himalayan glacial lakes in 2015: (a) frequency and area distribution of glacial lakes; (b) altitudinal characteristics of each type of lakes

3.2. Complex changing patterns

In general, Himalayan glacial lakes expanded rapidly between 1990 and 2015, but the expansion varied between different periods and lake types. During the study period, total number of glacial lakes increased by 401, and the total area expanded by 56.4 km² (14.1%). The glacial lakes expanded areally at a rate of 0.56% per year between 1990 and 2000, 0.48% between 2000 and 2005, 0.51% between 2005 and 2010, 0.59% between 2010 and 2015 respectively. Comparing different types of glacial lakes, we found that proglacial lakes contributed most to the total

expansion of Himalayan glacial lakes, with an increasing area of 46.9 km² (expanded by 51.6% and contributed 83.1% to the total expansion) from 1990 to 2015 (Table 1). Supraglacial lakes expanded by 4.4 km² with a rate of 367.3% between 1990 and 2015 while non-glacier-fed glacial lakes stayed stable over the five episodes. Unconnected glacier-fed glacial lakes expanded a little by 5.4 km² (2.7%).

Table 1 Count (area, km²) of glacial lakes by types between 1990 and 2015[†]

Types		1990	2000	2005	2010	2015	1990-2015
Glacier-fed	Unconnected	2674(204.4)	2738(211.4)	2743(211.6)	2750(212.3)	2705(209.9)	31(5.4)
	Proglacial	308(90.8)	343(105.2)	353(114.2)	373(123.6)	534(137.7)	226(46.9)
	Supraglacial	29(1.2)	52(2.3)	57(3.2)	63(4.3)	173(5.6)	144(4.4)
Non-glacier-fed		1538(102.5)	1538(102.3)	1538(102.4)	1537(102.1)	1538(102.1)	0(-0.3)
Sum		4549(398.9)	4671(421.2)	4691(431.4)	4723(442.3)	4950(455.3)	401(56.4)

[†]Note: unconnected represents for glacier-fed glacial lakes without ice contact

3.2.1. Changes in proglacial lakes and supraglacial lakes

Proglacial lakes and supraglacial lakes experienced the biggest changes. Individual glacial lake changes were traced using their unique labels across the five episodes. Quite a few disappeared and many emerged between 1990 and 2015. The key difference between the two lake types is that proglacial lakes remained relatively stable while supraglacial lakes experienced dramatic spatial-temporal changes.

Most proglacial lakes existed as perennial lakes in all the monitoring periods, coded 1990-2000-2005-2010-2015 (Table 2). Figure 5 shows four typical proglacial lakes that existed in all the five episodes and expanded continuously. Just a few proglacial lakes disappeared over the 25 years, however more lakes emerged, especially in the year of 2015 (163 lakes).

In contrast, supraglacial lakes are highly variable in location, shape and size, as described in previous studies [Benn *et al.*, 2001; Gardelle *et al.*, 2011]. Small but dynamic supraglacial lakes were more dependent on climate change, sometimes appeared and disappeared due to coalescence or spillway. Figure 6 shows rapid changing supraglacial lakes on four debris-covered glaciers.

Some supraglacial lakes became perennial lakes on the debris-covered glaciers (Table 3), such as Lalaga Glacier and Rongbuk Glacier (Figure 6). The dominant change among supraglacial lakes was the newly emergent lakes in 2015 (Table 3). In general, supraglacial lakes in the Himalaya demonstrate high temporal and spatial variability and rapid expansion in the past 25 years.

In summary, considering the Himalayan glacial lake changes as a whole, this analysis confirms that it is on the debris-covered parts of glaciers where glacial lakes evolved the most, including new formation, expansion and disappearance.

Table 2 Matrix of time serial changes of proglacial lakes in the Himalaya between 1990 and 2015*

Changing codes	1990	2000	2005	2010	2015	1990-2015 change
1990	1(0.01)	N/A	N/A	N/A	N/A	-1(-0.01)
1990-2000	1(0.1)	1(0.2)	N/A	N/A	N/A	-1(-0.1)
1990-2000-2005-2010	2(0.1)	2(0.1)	2(0.1)	2(0.1)	N/A	-2(-0.1)
1990-2000-2005-2010-2015	304(90.6)	304(103.2)	304(111.5)	304(120)	304(124.2)	0(+33.6)
2000	N/A	2(0.04)	N/A	N/A	N/A	N/A
2000-2005-2010-2015	N/A	34(1.6)	34(1.9)	34(2)	34(4.8)	+34(+4.8)
2005-2010-2015	N/A	N/A	13(0.7)	13(0.7)	13(0.9)	+13(+0.9)
2010-2015	N/A	N/A	N/A	20(0.7)	20(0.9)	+20(+0.9)
2015	N/A	N/A	N/A	N/A	163(7.0)	+163(+7.0)
Sum	308(90.8)	343(105.2)	353(114.2)	373(123.6)	534(137.7)	+226(+46.9)

*Note for Table 2 and Table 3: each value expresses Count (area, km²) of glacial lake; Time serial changes were calculated based on the existence of each glacial lake at five time points, for example, code 1990 means that the lakes only appeared in 1990 and disappeared after 1990; Gray backgrounds represent disappearing lakes by 2015, code 1990-2000-2005-2010-2015 with olive green background represents the same perennial lakes at multi-time points and light orange backgrounds represent newly emergent lakes after 1990; N/A: Not available; each value keeps one decimal place, however, we have to retain two decimal places in case of the appearance of 0.0

Table 3 Matrix of time serial changes of supraglacial lakes in the Himalaya between 1990 and 2015

Changing codes	1990	2000	2005	2010	2015	1990-2015 change
1990	10(0.3)	N/A	N/A	N/A	N/A	-10(-0.3)
1990-2000	4(0.1)	4(0.1)	N/A	N/A	N/A	-4(-0.1)
1990-2000-2005	2(0.1)	2(0.5)	2(0.9)	N/A	N/A	-2(-0.1)
1990-2000-2005-2010	2(0.2)	2(0.2)	2(0.2)	2(0.2)	N/A	-2(-0.2)
1990-2000-2005-2010-2015	10(0.4)	10(0.6)	10(0.6)	10(0.6)	10(0.6)	0(+0.2)
1990-2000-2005-2015	1(0.1)	1(0.02)	1(0.01)	N/A	1(0.03)	0(-0.07)
2000	N/A	11(0.2)	N/A	N/A	N/A	N/A
2000-2005	N/A	2(0.1)	2(0.1)	N/A	N/A	N/A
2000-2005-2010	N/A	8(0.2)	8(0.4)	8(1.7)	N/A	N/A
2000-2005-2010-2015	N/A	11(0.4)	11(0.6)	11(0.8)	11(0.8)	+11(+0.8)
2000-2015	N/A	1(0.05)	N/A	N/A	1(0.7)	+1(+0.7)
2005	N/A	N/A	5(0.1)	N/A	N/A	N/A
2005-2010	N/A	N/A	9(0.2)	9(0.3)	N/A	N/A
2005-2010-2015	N/A	N/A	6(0.2)	6(0.2)	6(0.3)	+6(+0.3)
2005-2015	N/A	N/A	1(0.03)	N/A	1(0.05)	+1(0.02)
2010	N/A	N/A	N/A	8(0.2)	N/A	N/A
2010-2015	N/A	N/A	N/A	9(0.4)	9(0.4)	+9(+0.4)
2015	N/A	N/A	N/A	N/A	134(2.7)	+134(+2.7)
Sum	29(1.2)	52(2.3)	57(3.2)	63(4.3)	173(5.6)	144(4.4)

Figure 5 Evolution of typical proglacial lakes with the background of Landsat images: (a) Lake Ganglongco (85.8392° E , 28.3212° N), (b) Kangxico (85.8697° E, 28.3607° N), (c) Cirenmaco (86.0658° E, 28.0674° N), (d) Bailangco (90.7871° E, 28.0889° N)

Figure 6 Temporal and spatial changes of supraglacial lake (date [yyyymmdd]) on the debris-covered glaciers: (a) Lalaga Glacier (85.5727°E, 28.4465°N), (b) Ngozumpa Glacier (86.6941°E, 28.0021°N), (c) Rongbuk Glacier (86.8627°E, 28.1134°N) and (d) Tsojo Glacier (90.1614°E, 28.1285°N); Glacier outlines in light blue are from glacier inventory dataset.

3.2.2. Newly emergent and disappeared glacial lakes

Considering lakes as a whole across all five episodes, there were 475 newly emergent glacial lakes and 134 disappeared lakes, including 74 lakes that were observed in 1990 but had perished by 2015.

Figure 7 Altitudinal characteristics of disappeared lakes and newly emergent lakes between 1990 and 2015 by count (a) and area (b)

Newly emergent lakes had higher mean and median altitudes than those of disappeared lakes. New lakes were mainly located between 4200-5800m (count greater than 10) while most disappeared lakes ranged between 4200-5500m (count greater than 10). Their areal distributions were almost consistent with their numerical distributions (Figures 7a and 7d). The mean altitude of newly emergent lakes (5090 m, with the standard deviation of 419 m) was slightly higher than that for disappeared lakes (4840 m, with the standard deviation of 493 m). The median altitude of newly emergent lakes was higher than that for disappeared lakes (5150 m vs. 4850 m). These

analyses imply that new glacial lakes are emerging at higher altitudinal zones of the Himalaya due to glacial retreat and down-wasting caused by lasting global warming [Immerzeel *et al.*, 2013; Yao *et al.*, 2012]. The formation of new glacial lakes at higher elevation is consistent with the observations in the Southern Alps [Salerno *et al.*, 2014] and Cordillera Blanca [Emmer *et al.*, 2016]. Upward development of newly emergent glacial lakes will also increase the mean altitude of all Himalayan glacial lakes.

3.3. Regional heterogeneity in spatial distribution and temporal evolution of glacial lakes

The changes over time in both lake number and area vary from region to region across the Himalaya (Figures 8 and 9). On the northern side of the Himalayan main range, glacial lakes are fewer in number but with a larger mean size (0.10 km^2) than those on the southern side (0.08 km^2). There are also regional differences in the number and area of glacial lakes between the central, eastern and western Himalaya, with the greatest number and area in the central part, and the smallest in the western part (Table 4). According to the expansion rate between 1990 and 2015 (as shown in Figure 9), glacial lakes in the southern Central Himalaya showed the most rapid expansion (23.0%), followed by the northern Central Himalaya (13.7%) and the southern side of the eastern Himalaya (11.1%). The expansion rate of glacial lakes in the western Himalaya was the lowest (5.0%).

Table 4 Distribution of glacial lakes between the northern side and southern side across the Himalayan regions

Region	Count in 2015 (all lakes)		Area (km^2) in 2015 (all lakes)		Count in 2015 (REGL [†])	
	North	South	North	South	North	South
Central Himalaya	839	1104	117.4	86.3	35	33
Eastern Himalaya	502	1050	66.0	96.8	13	23
Western Himalaya	979	476	50.0	38.8	10	4
Total	2320	2630	233.4	221.9	58	60

[†]REGL represents rapidly expanded glacial lakes

Figure 8 Density distribution of glacial lakes in 2015 (point density parameters: neighborhood settings = 10 cell (rectangle shape), cell size = 4 km); spatial distribution of rapidly expanded glacial lakes and historical GLOF events in the Himalaya (potential vulnerable areas of GLOFs in orange boxes)

Figure 9 Regional difference of glacial lake expansion across the Himalaya

3.4. Rapidly expanding glacial lakes

Moraine dam failures associated with previously documented GLOFs were usually preceded by rapid lake expansions, such as Lugge Tsho [Ageta *et al.*, 2000]. Therefore, we need to pay particular attention to those rapidly expanding lakes that imply a higher GLOF risk. Three factors are selected to identify the rapidly expanding glacial lakes in this study. First, the annual expansion rate needs to be greater than 1% from 1990 to 2015 according to a previous study [Nie *et al.*, 2013]. Second, lakes should be proglacial lakes that are moraine-dammed and supplied directly by glacial melt water [Gardelle *et al.*, 2011; Wang *et al.*, 2012a; Wang *et al.*, 2015b], as all historical GLOF events in the Himalaya are moraine-dammed glacial lakes, which are vulnerable to outburst [Liu *et al.*, 2014b; Wang *et al.*, 2012a]. Third, the minimum lake size should be 0.1 km^2 , which is usually

selected as the threshold to identify the Himalayan glacial lakes posing considerable risk [Wang *et al.*, 2012a].

A total of 118 proglacial lakes are identified as rapidly expanding lakes across the Himalaya in 2015 (Figure 8 and last two columns in Table 4). The distribution of our rapidly expanding lakes is highly consistent with historical GLOF events that occurred in the Himalaya. For example, in two orange rectangles in Figure 8, there are 51 rapidly expanding lakes and there have been 43 historical GLOF events. These two areas should be considered as potential vulnerable areas of GLOFs and deserve particular attentions. The selected glacial lakes are more vulnerable to GLOFs than other glacial lakes, and deserve a higher priority in term of the continuous monitoring and hazardous risk analysis. The number and area of rapidly expanding lakes are spatially heterogeneous (the last two columns Table 4). More than 50% of these glacial lakes are located in the central Himalaya. In the eastern Himalaya, more vulnerable glacial lakes are distributed on the southern side. However, in the western Himalaya, more rapidly expanding lakes are located in the northern side. Our dataset of the selected key glacial lakes for hazard risk assessment can provide insight to the allocation of social resource in hazard mitigation.

4. Discussions

4.1. Climate and glaciers as factors driving glacial lake changes

Climate warming and its induced glacier retreat play a primary role in glacial lake changes in the Himalaya. Temperature rises have been reported in many previous studies. Warming in the Mount Everest region, central Himalaya, was more significant than in other regions in China [Yang *et al.*, 2006]. A total of 12 meteorological stations near the main range of the Himalaya showed a significantly consistent warming between 1979 and 2014 (Table 5). The mean warming rate of air temperature was 0.4 °C/10a. Negative mass balance of glaciers and continuous glacier

retreat were reported in the central Himalaya, western Himalaya and eastern Himalaya based on modeling estimations, remote sensing and in-situ observations [Bolch *et al.*, 2012; Fujita and Nuimura, 2011; Yao *et al.*, 2012]. Temperature rise was considered as the main driving force for glacial retreat and downwasting in the Himalaya [Bolch *et al.*, 2012; Nie *et al.*, 2010; Yao *et al.*, 2012]. The net glacier melt runoff is likely to rise until 2050 according to a glacio-hydrological model run for two Himalayan glaciated watersheds [Immerzeel *et al.*, 2013]. The enhanced glacier ablation is likely to be the prominent cause for glacial lake expansion in the Himalaya.

Table 5 Used meteorological stations near the Himalaya and trends in air temperature and precipitation between 1979 and 2014

Station	Longitude/latitude	Sub-region	Elevation (m)	Data period	Temperature		Precipitation	
					°C/10a	Adj. R ²	mm/10a	Adj. R ²
Shiquanhe	80.08°E/32.50°N	WH	4279	1979-2014	0.60	0.51	0.01	-0.03
Burang	81.25°E/30.28°N	CH	4900	1979-2014	0.47	0.41	-7.88	0.00
Nyalam	85.96°E/28.18°N	CH	3810	1979-2014	0.31	0.35	-34.06	0.03
Tingri	87.08°E/28.63°N	CH	4300	1979-2014	0.41	0.51	15.68	0.02
Latse	87.60°E/29.08°N	CH	4000	1979-2014	0.47	0.60	27.30	0.06
Xigaze	88.88°E/29.25°N	EH	3836	1979-2014	0.37	0.49	19.56	0.00
Yadong	89.08°E/27.73°N	EH	4300	1979-2014	0.28	0.26	12.45	0.00
Gyangze	89.60°E/28.91°N	EH	4040	1979-2014	0.33	0.42	0.39	-0.03
Nagarze	90.40°E/28.96°N	EH	4432	1991-2014	0.48	0.31	18.09	-0.02
Cona	91.95°E/27.98°N	EH	4280	1979-2014	0.41	0.45	14.47	0.03
Lhunze	92.46°E/28.41°N	EH	3860	1979-2014	0.21	0.24	10.13	0.00
Mainling	94.21°E/29.21°N	EH	2950	1991-2014	0.52	0.50	-55.70	0.12

Note: WH, CH and EH represent the western Himalaya, central Himalaya and eastern Himalaya, respectively; the minus fitting values of adj. R² mean no good fitting.

Figure 10 Precipitation trend derived from GPCP data and meteorological stations in the Himalaya

Precipitation in the Himalaya in general shows decreasing trends based on GPCP gridded data confirmed by in-situ observation data. The GPCP data are improved by combining satellite data and gauge observations [Huffman *et al.*, 2009]. GPCP precipitation data show a decrease in the Himalaya from 1979 to 2010 [Yao *et al.*, 2012]. Extending precipitation data to 2014, Figure 10 shows a continuing decreasing trend across most of the Himalaya from 1979 to 2014. This trend is confirmed by precipitation data at three stations at Burang, Nyalam and Mainling. The increasing trend of precipitation from GPCP data is also verified by the stations at Yadong, Latse, Xigaze, Nagarze and Cona. The weakening Indian monsoon is the key driving factor to the precipitation decrease in the Himalaya [Wu, 2005; Yao *et al.*, 2012]. The declining supply of precipitation to glacial lakes has led to a general shrinkage of most non-glacial-fed lakes (Table 1), which has also been reported for the Central Himalaya by Salerno *et al.* [2016]. Thus, glacial meltwater is the dominant contributor to glacial lake expansion in the Himalaya.

The sensitivity of glaciers to climate change controls the spatially heterogeneous wastage of Himalayan glaciers [Fujita and Nuimura, 2011; Maussion *et al.*, 2014; Yao *et al.*, 2012]. Glacier mass loss [Bolch *et al.*, 2012] [Kääb *et al.*, 2015], and retreat [Bolch *et al.*, 2012; Yao *et al.*, 2012] are clearly different across the central, eastern and western Himalaya. The response of Himalayan glaciers to climate change is also strongly affected by spatially variable debris cover [Scherler *et al.*, 2011]. Spatially heterogeneous recession of glaciers may also explain the regional difference in Himalayan glacial lake evolution.

Himalayan glacial lake expansion features the enlargement of proglacial lakes (Table 1). The lakes of this type appear to have sufficient space to develop as a result of terminal retreat of the connected glaciers. The regional difference in the evolution of glacial lakes reflects the complex interaction between glaciers and glacial lakes. Proglacial lakes are in direct contact with the

retreating glaciers, which not only provide the melt water but also leave the expansion space for the glacial lakes [Song *et al.*, 2016; Wang *et al.*, 2015b]. Here we assume that areal expansion at the top of proglacial lakes is equal to the planar area of terminal retreat of the connected glaciers. The terminal retreat rate of glaciers contacted with glacial lakes between 1990 and 2015 is at a maximum in the central Himalaya (29.1 km²), especially in the northern side of this region, and at a minimum in the western Himalaya. Proglacial lakes connected with glacier ice transmit thermal energy to the terminal ice and accelerate the melting and retreat of glaciers [Sakai *et al.*, 2009]. The expansion of proglacial lakes is driven by sub-aerial melting, water-line melting and ice calving [Gardelle *et al.*, 2011]. Obviously, quite a few larger proglacial lakes result in very high terminal retreats of glaciers due to particularly high rates of thermal erosion in water-line melting. The difference in the terminal retreat of glaciers is likely to be in accordance with the largest size of glacial lakes in the north of the central Himalaya and the smallest size of glacial lakes in the western Himalaya. At this point, the proglacial lakes are a good indicator to the glacier retreat and regional difference of glacier changes. This study provides evidence that glaciers contacted with glacial lakes across the entire Himalaya shows significant regional heterogeneity.

The impact of climate on glacial lakes is rather complex. Besides, the darkening of Himalayan glaciers caused by the incorporation of black soot particles [Ming *et al.*, 2012; Xu *et al.*, 2009] is considered to be another important contributor to accelerate the glacial melting. The quantitative assessment of the interaction between glaciers and glacial lakes still needs to be further investigated based on long-term glacier mass balance data and glacial lake evolution data in this area.

4.2. Mapping and classification of glacial lakes

Landsat images with a consistent spatial resolution were employed in lake mapping, which reduced the uncertainty associated with data sources, but the effects of topographical shadows, snow cover, and clouds on the lake mapping remained key sources of errors [Nie *et al.*, 2010; Zhang *et al.*, 2015]. Repeated observations in the same areas were used to remove these effects. Most images used were either cloud free or with low cloud coverage (less than 15% in percentage). To reduce terrain shadows, images acquired in September and October were preferred for lake mapping due to their high solar altitude angles. The unique label point of individual glacial lakes linked the same lake at five episodes and generated a change code for each lake (Tables 2 and 3). The change code can help to identify and correct the mistakes resulted from lake mapping. Crosschecking of glacial lake data at five episodes improved the quality of mapping and strongly supported the analysis of glacial lake change.

The classification of glacial lake types is affected by the accuracy of glacier inventory data. The various glacier inventory data [Armstrong *et al.*, 2011; Guo *et al.*, 2015; Pfeffer *et al.*, 2014] are not consistent at quite a few places due to their differences in acquisition date, spatial resolution of image source, and mapping methods. In lake mapping, we compared the three glacier datasets in accordance with Landsat images to optimally identify the appropriate boundary of glacier and confirm the type of glacial lakes. The Landsat 8 OLI imageries of high quality effectively help us in understanding the spatial extents of glaciers and glacial lakes in case of the displacement of the glacier boundaries. Glacier retreat was also considered in the process of classification of glacial lakes. For example, it is obvious that some proglacial lakes became unconnected glacial lakes because the continuous glacier retreats are clearly observed in the images from 1990 to 2015. The formation of pro-glacial lakes is closely associated with the evolution of supraglacial lakes [Salerno *et al.*, 2012], and the conversion that some supraglacial

lakes became pro-glacial lakes (moraine-dammed lakes) have been observed in the previous research [Bajracharya and Mool, 2009] and our study. This implies that we should fully consider the dynamic evolution of glacial lakes and glaciers in the process of classifying lake types.

4.3. Minimum mapping unit

Generally, a smaller minimum mapping unit produces a greater number of glacial lakes. In this study, a minimum mapping unit is set to 0.0081 km². Other research selected 0.0001 km² [Salerno *et al.*, 2012], 0.0027 km² [Zhang *et al.*, 2015], 0.0036 km² [Gardelle *et al.*, 2011] or 0.0045 km² [Li and Sheng, 2012] as the minimum mapping unit. Our result indicates that 8.1% of glacial lakes belonged to the size class 0.0081-0.01 km², which only took up 0.79% of the total area. It is obvious that the minimum mapping unit has a significant effect on the total number of glacial lakes, however it affects the total area only slightly. All the analysis on the supraglacial lakes, disappeared glacial lakes and newly emergent glacial lakes are based on this minimum mapping unit. This explains why we report 173 supraglacial lakes in 2015 through the Himalaya, while Salerno *et al.* [2012] investigates 437 supraglacial lakes in 2008 only in the vicinity of Mount Everest region based on the minimum mapping unit of 0.0001 km².

The minimum mapping unit also affects the uncertainty. Measuring the uncertainty is dependable on the linear error and the perimeter of glacial lakes [Salerno *et al.*, 2012]. The error for small shapes is proportionally larger than that for large shapes at the same resolution. The error is 45% for supraglacial lakes with a mean area of 0.003 km² [Salerno *et al.*, 2012]. The mean area of glacial lakes in the Himalaya is 0.09 km². The uncertainty calculated using this method is possibly overestimated. An improved method for measuring the uncertainty of glacial lakes is needed urgently in the future.

4.4. Seasonal variation of glacial lakes

This study mainly employs Landsat images in autumn and early winter and reveals the long-term changing pattern of glacial lakes within these seasons. Significant seasonal change of supraglacial lakes [Miles *et al.*, 2017; Watson *et al.*, 2016] is not detected in this study. Satellite images acquired during the summer should be added to conduct the analysis of seasonal changes, which are strongly restrained by the extremely low availability of useful satellite data due to the high incidence of cloud cover during the ablation period in the Himalaya. This study only reveals the expansion of supraglacial lakes in the fall and early winter.

4.5. Potentially dangerous GLOF lakes

In this study, we provide up-to-date basic data of glacial lakes for further risk assessment in the entire Himalaya and identify the rapidly expanding glacial lakes for future priority monitoring. About 10 GLOF events occurred in the Himalaya after 2000 that resulted in severe socio-economic loss [Bajracharya and Mool, 2009; Liu *et al.*, 2014a; Yao *et al.*, 2014]. A recent event occurred on June 17, 2013 in the central Himalaya [Das *et al.*, 2015]. GLOF events are usually triggered by avalanche, rockslide or calving [Bolch *et al.*, 2008; Bolch *et al.*, 2011; Buchroithner, 1995; Ives, 1986; Somos-Valenzuela *et al.*, 2014; Worni *et al.*, 2013]. We agree with others [Röhl, 2008; Salerno *et al.*, 2012] that the rapid expansion and potential risk of glacial lakes should be explained at an individual scale combined with appropriate field survey and simulation analysis. We draw particular attention to the rapidly expanding glacial lakes, especially those within the potential vulnerable areas (orange boxes in Figure 8) where historical GLOFs occurred frequently; here the glacial lakes are storing massive energy for potential catastrophic hazards in the event of dam failure. Glacier shrinkage might accelerate under the current warming conditions [Yao *et al.*, 2012]. In that case, glacial lakes will continue to expand and the risk of GLOFs may increase in the Himalaya.

5. Concluding remarks

This study provides a latest complete inventory of Himalayan glacial lakes in 2015 based on Landsat 8 images. The patterns of glacial lake evolution in the entire Himalaya are revealed in a systematic way by using the Landsat images in the past 25 years at the consistent spatial resolution of 30 m.

Himalayan glacial lakes have experienced a rapid expansion since 1990, especially in terms of the enlargement of proglacial lakes. The specific evolution process of each glacial lake is recorded by using Landsat images. It is clear that the evolution of glacial lakes is a complex process, involving a significant number of disappeared but also newly emergent lakes. We find that newly emergent glacial lakes are developing at higher elevations in response to the temperature rise. Regional differentiation in occurrence and evolution of glacial lakes is apparent across the whole Himalaya. Glacial lakes in the southern side of the central Himalaya expanded most rapidly. Spatially heterogeneous recession of Himalayan glaciers resulted in the rapid expansion of glacial lakes and the spatial heterogeneity of their evolution.

The developed Himalayan glacial lake database is expected to serve the further assessment of GLOF hazard risk. A total of 118 rapidly expanding glacial lakes are identified as vulnerable lakes that need further assessments of their hazard risk and potential influence due to their increasing energy and relative instability. Continued monitoring and detailed analysis of the Himalayan glacial lakes with high possibility of potential flood events are currently urgent tasks, including by collecting more remote sensing observations and field survey.

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