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

Yong Nie [a,b,*], Yongwei Sheng [b], Qiao Liu [a], Linshan Liu [c], Shiyin Liu [d], Yili Zhang [c], Chunqiao Song [b]

[a] Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, Sichuan 610041, China
[b] Department of Geography, University of California, Los Angeles (UCLA), Los Angeles, CA 90095, USA
[c] Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[d] State Key Laboratory of Cryosphere Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

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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 GLOF 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 ± 72.7 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.

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 (Fig. 1) is known as one of the major GLOF-vulnerable regions in the world (Carrivick and Tweed, 2016; Ives, 1986; Liu et al., 2014a, 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) was revealed by remote sensing data, but only for several representative

* Corresponding author.
E-mail address: nieyong@imde.ac.cn (Y. Nie).

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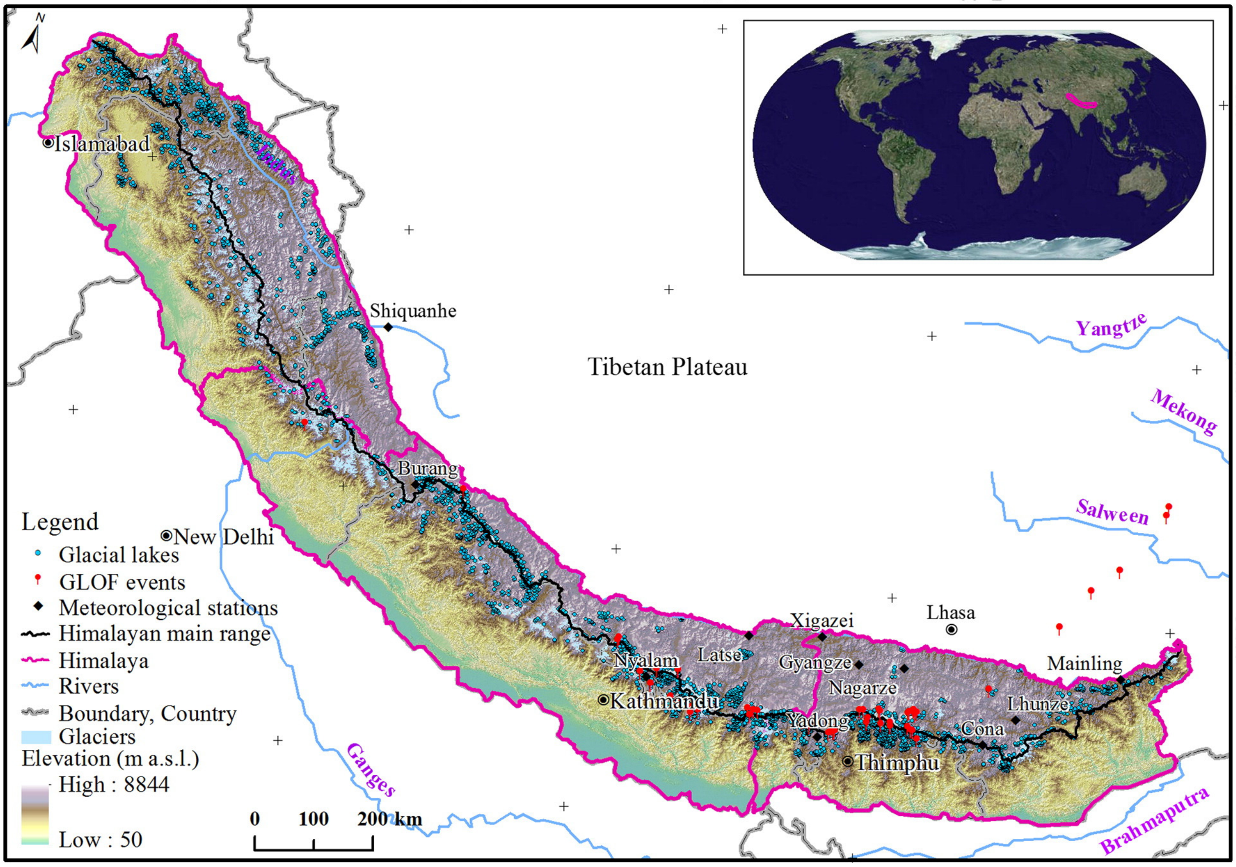

Fig. 1. Location of study area and distribution of Himalayan glaciers and glacial lakes in 2015.

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 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 (Fig. 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, 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 (i.e., 1990, 2000, 2005, 2010 and 2015); 3) to identify the rapidly expanding lakes, providing fundamental information for early recognition of GLOF hazards; and 4) to improve the understanding on relationship between glacial lake, glacier and climate change in the Himalaya.