Global and Planetary Change 111 (2013) 246–257

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Glacier and glacial lake changes and their relationship in the context of climate change, Central Tibetan Plateau 1972–2010

Xu Wang [a,b], Florian Siegert [b,c], Ai-guo Zhou [a,d,*], Jonas Franke [c]

[a] School of Environmental Studies, China University of Geosciences, 388 Lumo Road, Wuhan 430074, China
[b] Biology Department II, GeoBio Center, Ludwig-Maximilians-University, Grosshadenerstr. 2, Planegg-Martinsried, Munich 82152, Germany
[c] Remote Sensing Solutions GmbH, Isarstr. 3, Baierbrunn 82065, Germany
[d] State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, 388 Lumo Road, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 22 November 2012
Revised 23 August 2013
Accepted 23 September 2013
Available online 1 October 2013

Keywords:
Central Tibet Plateau
Glacier
Lakes
Climate change
Remote sensing

ABSTRACT

The alpine ecosystem of the Western Nyainqentanglha region, located in the Central Tibetan Plateau, has experienced a lot of changes in the context of climatic change. The long data record of remote sensing data allowed us to evaluate spatio-temporal change in this remote area. The ecosystem changes of the Western Nyainqentanglha region were detected by using Landast MSS/TM/ETM+, Hexagon KH-9, Glas/ICESat, SRTM3 DEM remote sensing data and GIS techniques. The area of glacier lakes was delineated by visual interpretation, while for the inland lake by image classification. The change of glacier thickness was obtained by Glas/ICESat data of 2004 and 2008. Results show high variation in extent of glaciers and lakes with increased temperature and precipitation in the past 40 years. These variations include glacial retreat, increased water level of inland lakes and increased number of glacier lakes to higher altitudes. Glaciers lost 22% of its coverage from 1977 to 2010, and the annual shrinkage rate accelerated in the last decade compared with the previous time period of 1977–2001. In average, the thickness of the monitored glaciers reduced by 4.48 m from 2004 to 2008 with an annual rate of 1.12 m. From 1972 to 2009, the number of new formed glacier lakes increased by 150 and the area of glacier lakes increased by 173% (4.53 km^2). At the same time, the surface area of the largest salt lake in Tibet expanded by 4.13% (80.18 km^2). These variations appear to be associated with an increase in mean annual temperature of 0.05 °C per year, and an increase in annual precipitation of 1.83 mm per year in the last four decades. By analyzing the relationship between the decreased glacier area and the increased number and extent of lakes in the vertical zones over the past 40 years, there is a high correlation of 0.81. These results indicate that the climate change has great impacts on glaciers and glacier lakes on the central Tibetan Plateau. Further detailed investigations are required to understand the contribution of melting water and precipitation to the water cycle and the complicated hydrological relationship between the characteristics of glaciers and glacier lakes and climate warming in this alpine region.

1. Introduction

The global climatic changes have significantly affected the cryosphere in many regions of the world (Paul et al., 2002, 2004; Bolch, 2007; Nie et al., 2010). Melt-off of mountain glaciers will further substantially contribute to the sea level rise. Mountainous and highland regions are highly sensitive to local climate change, and they are the amplifier for climate change (Hoelzle et al., 2007; Wang et al., 2008; Owen et al., 2009). As the “Third-Pole” on the earth, the Tibetan Plateau (TP), with an average elevation of more than 4000 m asl, is the highest and most extensive highland in the world and is also the headstream of major Asian rivers. Tibetan Plateau's climate showed a significant increase in temperature and precipitation in most regions over the past decades, especially in the Eastern and Central parts of the TP (Du and Ma, 2004; Xu et al., 2008; You et al., 2009). Glacier, ice and snow cover 17% of the Great Himalayan area and shrink faster than the world average (Dyurgerov and Meier, 2005). The glacier lakes also increased in number and extent in the Himalaya (Wang et al., 2011). Glacier melting and precipitation increase tend to accelerate water cycling and improve the local ecological environment at this stage (Gong et al., 2006; Cheng and Wu, 2007; Jin et al., 2009; Kang et al., 2010). Effective mitigation of the water hydrological impacts on societies as well as assessing glacier-related hazards require a large-scale survey of glaciers, glacier lake dynamics and a better understanding of their relationship. Due to the large extent and difficult accessibility of remote mountainous terrain, the analysis of historical and recent satellite data is the only tool to study and monitor environmental changes in the long term.

There is ample evidence that in recent years climatic changes have affected the geological environment on the Tibetan Plateau. More than

* Corresponding author at: School of Environmental Studies, China University of Geosciences, 388 Lumo Road, Wuhan 430074, China. Tel.: +86 02767883060.
E-mail addresses: jorrywangxu@hotmail.com (X. Wang), siegert@rssgmbh.de (F. Siegert), aiguozhou@cug.edu.cn (A. Zhou), franke@rssgmbh.de (J. Franke).

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http://dx.doi.org/10.1016/j.gloplacha.2013.09.011

80% of the glaciers in Western China experienced a retreat during the past decades (Liu et al., 2006). The surface water level of inland lakes annually increased by 0.2 m on the Tibetan Plateau during 2003–2009 (Phan et al., 2012). There have been recent efforts to document the glacier loss and shrinkage in the Western Nyainqentanglha range (WNR) in particular (Zhang et al., 2004; Pu et al., 2006; Wu and Zhu, 2008; Bolch et al., 2010b). However, few studies focused on glacier area changes, change of glacier surface elevation, change of glacier lakes and their relationship to hypsography. In this study we examined the glacier and glacier lake changes and analyzed their characteristics in regard to elevation using satellite data and a digital elevation model over the period of 1972–2010. We focused on the change in (1) the extent of the glacier area and its spatial distribution; (2) the glacier surface elevation change; (3) the number and locations of natural lakes occurring after glacier retreat, and (4) the relationship of glacier and glacier lakes in the hypsography in the WNR area.

2. Materials and methods

2.1. Study site, regional climate change

The Western Nyainqentanglha area is located in the center of the Tibetan Plateau and extends in a NE–SW direction (Fig. 1). The average altitude of the WNR is about 5500 m with the highest peak having an altitude of 7111 m. The study site is bordered by the northern part of the Gangdise mountain range in the SE and by the Namco Lake in the NW. The mountain range divides the watershed of the Namco Basin and the Lhasa River Basin. The NW exposed area is situated on the SE edge of a semi-arid alpine climatic zone and leeward to the summer monsoon on the NW slope, snow-melt and glacier-melt water feed the Namco Lake, which was once the largest salt lake in Tibet and which is now the second largest lake (Zhang et al., 2012). The SE is located windward to the summer Monsoon. Melt water drains towards the Lhasa River and subsequently into the Brahmaputra River.

This region experiences a typical monsoon climate which is dominated by the Southeast monsoon from May to September in summer and prevailing westerly winds in winter. The precipitation varies largely between the dry and wet seasons. Much of the precipitation (80–90%) occurs in the warm (rainy) seasons (from May to September) (Fig. 2). The cold season is generally dry.

The nearest meteorological stations Bange, Damxung and Lhasa were used to analyze climate trends during the last four decades. We collected the precipitation and temperature data from 1971 to 2010. The mean annual temperature in Bange station, about 55 km west of Namco lake, is −0.62 °C, and the mean annual precipitation is 329 mm. Damxung, situated at the Eastern foot of the Nyainqentanglha Range, has a mean annual temperature of 2.13 °C and a precipitation of 460 mm. The mean annual temperature in Lhasa, about 80 km east of the Nyainqentanglha Range, is 8.3 °C, and the mean annual precipitation is 437 mm. Over the last four decades, the mean annual precipitation of the three meteorological stations increased by 1 mm per year, while the mean annual temperature increased by 0.053 °C per year (Fig. 3). The precipitation showed an increase in fluctuation over the last decades, and the mean annual temperature in the study area showed a significant warming trend.

Compared to the time period of 1971–1990, there is a clear acceleration in warming in the past twenty years. The trend is 0.035 °C per year during 1971–1990 and 0.08 °C per year from 1990 to 2009. While precipitation is 1.043 mm per year in the period of 1971–1990 it is 2.403 mm per year during 1991 and 2009. The data indicates that the air becomes warmer and moister in this region.

2.2. Data and processing

Landsat MSS/TM and ETM+ scenes were used for the analyses, since the Landsat mission provides historical data back to the mid 1970s. Due to different seasonal and inter-annual snow conditions, cloud coverage, and data gaps, there are only a very limited number of satellite images available for the study area. By comparing all available images that have been acquired during the study period, the most appropriate scenes were chosen for the analysis (Table 1). Although there is a little snow cover on several glaciers on the image of 2010, we could take the image of 2009 as a reference to delineate the snow-covered glaciers.

The images were provided by the United States Geological Survey (http://glovis.usgs.gov/). For MSS data, the geometric correction was performed using the Auto-sync model of ERDAS Imagine with an

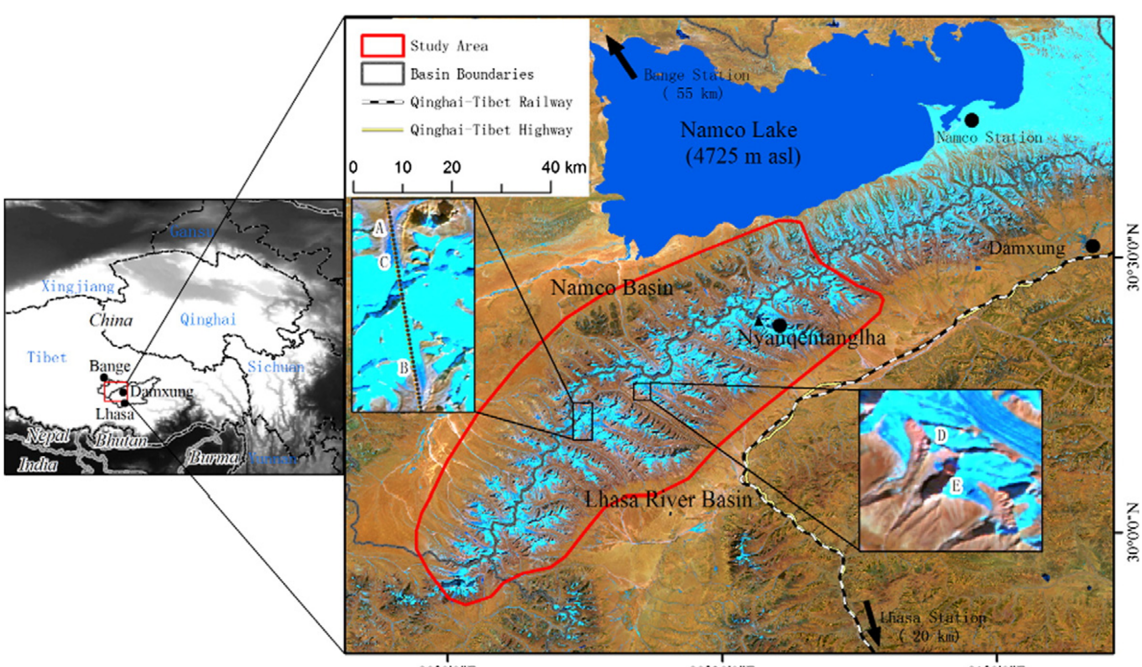

Fig. 1. Location of the study area in central Tibetan Plateau.