Quaternary Research 85 (2016) 25–33

Contents lists available at ScienceDirect

Quaternary Research

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

Changes in glacier extent and surface elevations in the Depuchangdake region of northwestern Tibet, China

Zhiguo Li [a,b,*], Lide Tian [b], Hongbo Wu [c], Weicai Wang [b], Shuhong Zhang [d], Jingjing Zhang [a], Xuexin Li [a]

[a] Department of Environment and Planning, Shangqiu Normal University, Shangqiu, China
[b] Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China
[c] School of History and Tourism, Shaanxi University of Technology, Shaanxi Hanzhong 723000, China
[d] Department of Life Science, Shangqiu Normal University, Shangqiu, China

ARTICLE INFO

Article history:
Received 27 March 2015
Available online 14 January 2016

Keywords:
Glacier variations
Remote sensing
Transition zone
Depuchangdake region

ABSTRACT

Remote sensing data, including those from Landsat Thematic Mapper/Enhanced Thematic Mapper Plus (TM/ETM+), the Shuttle Radar Topography Mission Digital Elevation Model (SRTM4.1 DEM), and the Geoscience Laser Altimeter System Ice, Cloud, and Land Elevation Satellite (Glas/ICESat), show that from 1991 to 2013 the glacier area in the Depuchangdake region of northwestern Tibet decreased from 409 to 393 km^2, an overall loss of 16 km^2, or 3.9% of the entire 1991 glacial area. The mean glacier-thinning rate was -0.40 ± 0.16 m equivalent height of water per year (w.e./yr), equating to a glacier mass balance of -0.16 ± 0.07 km^3 w.e./yr. Total mass loss from 2003 to 2009 was -1.13 ± 0.46 km^3. Glacier retreat likely reflects increases in annual total radiation, annual positive degree days, and maximum temperature, with concurrent increases in precipitation insufficient to replenish glacial mass loss. The rate of glacier retreat in Depuchangdake is less than that for Himalayan glaciers in Indian monsoon-dominated areas, but greater than that for Karakoram glaciers in mid-latitude westerly-dominated areas. Glacier type, climate zone, and climate change all impact on the differing degrees of long-term regional glacial change rate; however, special glacier distribution forms can sometimes lead to exceptional circumstances.

Introduction

The Tibetan Plateau and bordering mountains (TPB) contain the largest concentration of glaciers outside of the Polar Regions (Yao, 2008) and are often referred to as the world's "Third Pole." Glacial changes in the TPB can alter atmospheric circulation patterns and affect agriculture, power generation, and the water supplies of the 1.5 billion people that live in the region (Immerzeel et al., 2010; Piao et al., 2010; Qiu, 2010). In addition, rising meltwater streams and expanding areas of glacial meltwater-fed lakes caused by glacier retreat have deeply impacted local ecosystems and flooded pastures (Yao, 2010). Therefore, alongside scientific interest, understanding glacial change has important socioeconomic and political implications.

Previous research has defined the extent of glacier retreat varies across the TPB and has shown systematic differences in glacier status between Himalaya and Karakoram (Yao et al., 2012; Gardner et al., 2013). Most glaciers in the eastern, central and western Himalaya have decreased in extent since the 1970s (Ye et al., 2008; Li et al., 2011; Wang et al., 2015a), which likely reflects rising temperatures and decreasing precipitation (Yao et al., 2012; Wiltshire et al., 2014; Yang et al., 2014). Mass loss has been higher in western Himalaya than in eastern and central Himalaya (Gardelle et al., 2013). In contrast, Karakoram glaciers have remained stable or advanced over the same period (Hewitt, 2005; Kaab et al., 2012; Yao et al., 2012; Gardelle et al., 2013; Gardner et al., 2013; Neckel et al., 2014). This pattern, which was first highlighted by Hewitt (2005) and is known as the Karakoram Anomaly, and contrasts markedly with a worldwide decline in mountain glaciers. The Karakoram Anomaly is attributed to increased snowfall and cooling at high altitudes (Hewitt, 2005; Wiltshire et al., 2014; Yang et al., 2014).

The transition zone between the Himalaya and Karakoram (TZHK) is bordered to the west by Jammu–Kashmir and Himachal Pradesh, on the east by Depuchangdake, on the south by Ayilariju, and on the north by Xiongcaigangri. Glaciers in Himachal Pradesh are shrinking (Gardelle et al., 2013; Mir et al., 2014), while those in Jammu–Kashmir have decreased, increased or fragmented, or have not change in extent from 1962 to 2001, with most glaciers apparently stable from 2001 to 2009 (Ghosh et al., 2014). A 5.6% glacier area loss (6.5 km^2) occurred between 1980 and 2010 in the Shyok Basin, with small glaciers retreating and large glaciers advancing, especially during the last decade (Bajracharya et al., 2015). Ayilariju glaciers along the southern border of the TZHK are retreating comparatively rapidly (Li et al., 2015a), while the Xiongcaigangri and neighboring glaciers on the northern border of the TZHK are retreating relatively slowly (Brahmbhatt et al., 2015; Li et al.,

* Corresponding author at: Department of Environment and Planning, Shangqiu Normal University, Shangqiu, China.
E-mail address: lizhiguo999999@163.com (Z. Li).

http://dx.doi.org/10.1016/j.yqres.2015.12.005
0033-5894/

2015b). However, although glacier volume change across the region had been reported in the TPB using remote sensing data (Kääb et al., 2012; Gardelle et al., 2013; Gardner et al., 2013; Neckel et al., 2014) and field observations (Yao et al., 2012), mass change in Depuchangdake glaciers has not been reported.

Investigating glacial changes in the TZHK may help to reveal the roles and processes driving the spatial heterogeneity of glacier change, i.e., how and why glaciers change from retreating to advancing states across the TPB. Our study focused on glacier area changes from 1991 to 2013 in the Depuchangdake region of the Tibetan Plateau. In particular, glacier mass balance changes from 2003 to 2009 were identified and possible control mechanisms were considered.

Study area

The Depuchangdake region is situated on the northwestern edge of the Tibetan Plateau, east of the Karakoram, northeast of the Western Himalaya, and south of West Kunlun (Fig. 1). Asian monsoons and westerly cyclones influence the climate of the Depuchangdake region, and local glaciers have been classified as polar continental-type (Shi, 2008). Depuchangdake glaciers provide fresh water for Jiezechaka, Longmu, Woerba and Lumajiangdong lakes (Fig. 1). According to Landsat image obtained in1991, 303 glaciers lie within the study area, comprising a total area of ~409 km^2, and with a mean glacier area of ~1.35 km^2 at the time of mapping. Glacier areas for Jiezechaka, Longmu, Woerba and Lumajiangdong lakes in the Depuchangdake regions are 134, 26, 100, and 149 km^2, respectively.

The mean equilibrium-line altitude (ELA) for glaciers in the Depuchangdake region is ~5900 m above sea level (asl; Shi, 2008; Yao et al., 2012). The mean annual air temperature and precipitation from 1961 to 2013 were ~0.71°C and 70.6 mm, respectively, as measured at Shiquanhe station (a national reference climatological station at 32°30′N/80°08′E, 4279 m asl).

Data and methods

Remote sensing data

Landsat Thematic Mapper/Enhanced Thematic Mapper Plus (TM/ETM+) images were used to extract glacier extent values and to monitor glacier changes. A total of 7 images were used to interpret glacier status in 1991, 2001, and 2013 (Table 1). Cloud cover in the 1991 TM, 2001 ETM+, and 2013 ETM+ images was < 4% and did not occur over the glaciers; thus, cloud cover had little impact on the delineation of glacier outlines. In addition, 7 other images from 2002 to 2009 were used to classify glacier surface cover and determine density parameters, i.e., firn, snow, and glacier ice, which helped to calculate glacier volume changes. All of the images used for area extraction were acquired near the end of the ablation season and had nearly no cloud cover. Either one or two additional images were taken at approximately the same time to provide reference data for determining seasonal snow cover and data gaps. Landsat images were provided by the U.S. Geological Survey (USGS; http://glovis.usgs.gov) and the Global Land Cover Facility. We used manual digitization to delineate glacier boundaries, as recommended by Raup et al. (2007) beacuse this provided the best tool for extracting reliable information from satellite images.

Glaciers were separated according to ridgelines generated from the Shuttle Radar Topography Mission Digital Elevation Map (SRTM 4.1 DEM) and Google Earth. The SRTM DEM was obtained in February 2000, and this dataset contains ~80% of Earth's surface elevation data at a spatial resolution of 90 m. The SRTM 4.1, whose study area data gaps were processed by Reuter et al. (2007), was selected and obtained from the Consultative Group on International Agricultural Research-Consortium for Spatial Information (CGIAR-CSI; http://srtm.csi.cgiar.org/). The SRTM DEM was also used to yield various glacier parameters, including elevation, slope, and aspect.

Ice, Cloud, and Land Elevation Satellite (ICESat) and Global Land Surface Altimetry satellite (GLAS) data were used to examine glacier change. GLA01 (release version 33) and GLA14 (release version 34) data were downloaded from the U.S. National Snow and Ice Data Center (NSIDC; http://nsidc.org/data/icesat/data.html). A total of 768 GLAS footprints (Fig. 2) for the glaciated areas of the study region were collected between 26 February 2003 and 10 October 2009. The methods of Wang et al. (2015b) were used to correct saturation elevations caused by the slope and roughness of the ICESat products. Next, glacier surface cover classifications and density parameters, i.e., firn, snow, and glacier ice surface area, were computed on the basis of GLAS waveforms and corresponding Landsat TM/ETM images from the same year. Then, glacial mass balance in each 300-m altitudinal zone was calculated using the formula of Wang et al. (2015b):

$$b_m = \frac{1}{S_m}\left(s_{\text{snow}} \times \rho_{\text{snow}} \times \Delta\bar{h}_{\text{snow}} + s_{\text{firn}} \times \rho_{\text{firn}} \times \Delta\bar{h}_{\text{firn}} + s_{\text{ice}} \times \rho_{\text{ice}} \times \Delta\bar{h}_{\text{ice}}\right) \quad (1)$$

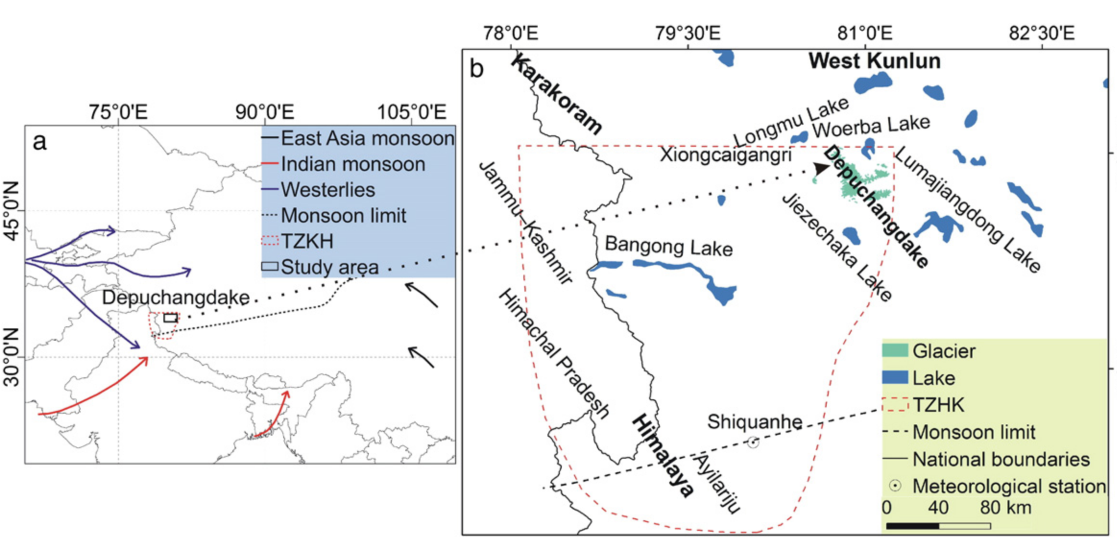

Fig. 1. Study region maps showing the distribution of glaciers and the Shiquanhe meteorological station. (a) Location of the study area within the Tibet Plateau region. Arrows denote westerly and monsoon moisture paths. The dashed line denotes the mean monsoon margin (after Chen et al., 2008), which fluctuates with season and year. (b) Overview of the study area and Shiquanhe station overlain on the digital elevation model (DEM).