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An inventory of glacial lakes in the Third Pole region and their changes in response to global warming

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ABSTRACT

No glacial lake census exists for the Third Pole region, which includes the Pamir-Hindu Kush-Karakoram-Himalayas and the Tibetan Plateau. Therefore, comprehensive information is lacking about the distribution of and changes in glacial lakes caused by current global warming conditions. In this study, the first glacial lake inventories for the Third Pole were conducted for ~1990, 2000, and 2010 using Landsat TM/ETM+ data. Glacial lake spatial distributions, corresponding areas and temporal changes were examined. The significant results are as follows. (1) There were 4602, 4981, and 5701 glacial lakes (>0.003 km^2) covering areas of 553.9 ± 90, 581.2 ± 97, and 682.4 ± 110 km^2 in ~1990, 2000, and 2010, respectively; these lakes are primarily located in the Brahmaputra (39%), Indus (28%), and Amu Darya (10%) basins. (2) Small lakes (<0.2 km^2) are more sensitive to climate changes. (3) Lakes closer to glaciers and at higher altitudes, particularly those connected to glacier termini, have undergone larger area changes. (4) Glacier-fed lakes are dominant in both quantity and area (>70%) and exhibit faster expansion trends overall compared to non-glacier-fed lakes. We conclude that glacier meltwater may play a dominant role in the areal expansion of most glacial lakes in the Third Pole. In addition, the patterns of the glacier-fed lakes correspond well with warming temperature trends and negative glacier mass balance patterns. This paper presents an important database of glacial lakes and provides a basis for long-term monitoring and evaluation of outburst flood disasters primarily caused by glacial lakes in the Third Pole.

1. Introduction

The Tibetan Plateau (TP) and surrounding mountains have the largest store of ice outside the Alaskan, Arctic, Antarctic, and Greenland regions and have been designated the Third Pole (Qiu, 2008; Yao et al., 2012a), although the size of single glacier is relatively small. The Third Pole covers a total glacial area of approximately 100,000 km^2 that includes more than 46,000 glaciers (Yao et al., 2012a, 2012b; Pfeffer et al., 2014). Recent attention has focused on lakes because most glaciers in the Third Pole have exhibited a negative mass balance in recent decades (Bolch et al., 2012; Yao et al., 2012a, 2012b), excluding a slight mass gain or balanced mass budget for the Western Kunlun (Neckel et al., 2014; Kääb et al., 2015) and Karakoram (Bolch et al., 2012; Gardner et al., 2013). According to the second Chinese glacier inventory dataset, the glacial area in the interior plateau and western China decreased by 9.5% (767 km^2) and 18% (approximately 9000 km^2), respectively, between the 1970s and the 2004–2011 period (Guo et al., 2014; Wei et al., 2014). Rapid warming in recent decades has occurred not only with respect to air temperatures (+0.036 °C/year), but also in relation to land surface temperature (+0.03 °C/year) (Zhang et al., 2014a). These rates exceed the global mean surface temperature rate (0.011 °C/year) from 1951 to 2012 (IPCC, 2014). The accelerated retreat of glaciers and enhanced precipitation have resulted in an increase in the number of lakes (>1 km^2), an expansion of lake area (Zhang et al., 2014b), and rising lake levels (and a consequent increase in water storage) (Zhang et al., 2011; 2013a; Phan et al., 2012).

Previous studies have focused primarily on the census and changes for large lakes (>1 km^2) (Ma et al., 2010; Zhang et al., 2014b). Phan et al. (2013) reported that 244 of 900 lakes supplied with glacial runoff were directly fed by 25.3% of the total glacier area. Song et al. (2014) demonstrated that rates of water level among lakes fed by discharged glacier meltwater were similar to those of lakes not supplied with glacier meltwater, demonstrating that precipitation is the dominant factor for rising lake levels. The reported water area of these individual lakes was generally larger than that of glacial lakes; moreover, these lakes were typically located farther from glaciers. Salerno et al. (2012) also demonstrated that lakes not connected to glaciers in the Mount Everest region were affected more heavily by precipitation-induced runoff than by glacial melt.

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Glacial lakes can be classified into three categories: supra-glacial lakes (ponds), which are situated in the lower ablation areas; pro-glacial lakes, which include lakes that are connected to glacier termini; and lakes disconnected from but in close proximity to glaciers (Ageta et al., 2000; Salerno et al., 2012). All three glacial lake types within the TP and surrounding area were examined in this study.

Glacial lakes are more sensitive to climate change and affect outburst flood disasters more heavily than larger lakes or lakes located farther from glaciers. Moraine-dammed lakes are susceptible to glacial lake outburst floods (GLOFs) because unconsolidated moraine dams were formed largely from the advancement of glaciers during the Little Ice Age (Randhawa et al., 2005). GLOFs in the Himalayas originate at high altitudes and can travel long distances, potentially damaging downstream infrastructures (Chen et al., 2007; Osti and Egashira, 2009; Liu et al., 2014). Some of the most significant GLOFs occurred in the Himalayas and caused considerable damage (Rai, 2005; Vuichard and Zimmermann, 1986; Wang et al., 2014; Worni et al., 2013). GLOFs from moraine-dammed glacial lakes have been assessed and modeled in several previous studies (Thompson et al., 2012; Wang et al., 2012; Osti et al., 2013; Westoby et al., 2014). Temperature fluctuations strongly influence GLOF characteristics (Liu et al., 2013).

Most previous investigations of glacial lake changes have been conducted in the Himalayas, and large areal expansions with regional differences have been reported (Mool et al., 2001; Bolch et al., 2008; Gardelle et al., 2011; Govindha Raj et al., 2012; Li and Sheng, 2012). For example, Imja Tsho, one of the best-studied glacial lakes, expanded from 0.028 km^2 in 1962 to 1.257 km^2 in 2012 and increased in depth by 18 m between 2002 and 2012 (Somos-Valenzuela et al., 2014). Ye et al. (2009) showed that the area of supra-glacial lakes over the debris-covered terminus of the Rongbuk glacier on Mount Qomolangma in the Himalayas increased 13 times between 1974 and 2008. Wang et al. (2014) observed that glacier-fed lakes have expanded significantly and that non-glacier-fed lakes have remained stable in the Poiqu River basin of the central Himalayas. Gardelle et al. (2011) examined glacial lake changes in the Hindu Kush Himalaya between 1990 and 2009 and determined that lakes have expanded considerably in the east (Bhutan, Everest and West Nepal) compared with those in the west (Hindu Kush and Karakoram). Moreover, Worni et al. (2013) presented a glacial lake inventory for the Indian Himalayas and conducted a detailed risk assessment for the region. However, no glacial lake census has been performed for the entire Third Pole region. Therefore, a comprehensive inventory with mapped and classified glacial lakes within the Third Pole is needed for the identification and risk assessment of potential hazards.

The objectives of this study are to (1) map glacial lakes in the Third Pole region for three time periods (~1990, 2000, and 2010) using Landsat archives (30-m pixel size), (2) examine the spatial distribution of glacial lakes and corresponding areas and temporal changes over the past 20 years, and (3) evaluate whether glacier melt or precipitation was the primary cause of glacial lake expansion. The boundary of the study area was derived from the Shuttle Radar Topography Mission Digital Elevation Models (SRTM DEMs) using an altitude of ≥ 2,500 m, which covers the Pamir-Hindu Kush-Himalayas and the Tibetan Plateau.

2. Data and methodology

The Landsat satellites first launched in 1972 have generated the longest temporal record of space-based surface observations (Roy et al., 2014). The Landsat Thematic Mapper (TM) (since 1982) and Enhanced Thematic Mapper (ETM+) (since 1999) have a spatial resolution of approximately 30 m for visible through middle infrared channels (Loveland and Dwyer, 2012). Landsat data have been used widely to map glaciers and glacial lakes globally due to their high spatial resolution and accessibility (Bolch et al., 2010; Mergili et al., 2013; Xu et al., 2013). Given the small size of glacial lakes and consistent coverage of Landsat data, Landsat TM/ETM+ images for ~1990, 2000, and 2010 with a temporal range of 10 years were used in this study.

Landsat Level 1 Terrain (corrected) (L1T) images of 151 scenes for each study period (i.e., ~1990, 2000, and 2010) and for the entire study area were downloaded via a web portal (http://glovis.usgs.gov/); additional details are presented in Table 1. The glaciers are primarily located in the Pamir-Hindu Kush-Karakorum-Himalayan and Hengduan Shan/Eastern Nyainqentanghla regions; however, glaciers are also distributed in small portions of each scene in the interior plateau. Fewer than 10 scenes did not include a glacier.

The Landsat data selected for lake delineation were generally from the months July through November of ~1990, 2000, and 2010. During this period in each year, Landsat images featured less perennial snow coverage, and lake has a larger area following glacier-induced runoff and monsoon-induced precipitation. Data were extended to adjacent years when cloud obscuration and snow coverage were high during the targeted study year; in particular, the eastern TP and Himalayan regions are characterized by high daily snow cover. The maximum time span of the selected Landsat data was two years, including the preceding and subsequent years. Some Landsat images for winter months were also included when data for adjacent years were unavailable. Landsat data for ~2010 were determined from data for years 2009 to 2011 (i.e., year 2010 ± 1; Table 1). Data span the 1999–2002 period for ~2000. Data were difficult to select for ~1990; therefore, the time span for ~1990 was expanded from 1987 to 1996, and the majority of images (76%) used were obtained during 1990 ± 2.

Fig. 1 shows the Landsat data used in the study. The data predominantly spanned the July–November period of ~1990 (83%), 2000 (80%), and 2010 (89%), with 4, 10, 20, 18, 22, and 14% of the scenes imaged during July, August, September, October, November and December, respectively.

Cloud, snow, and mountain shadows in the Third Pole region can complicate automated image classification of glacial lake boundaries. Hence, glacial lakes were carefully identified and manually digitized by a single expert. Although labor-intensive, this method guaranteed consistent examination and high quality control. Glacial lakes in each scene were identified and interpreted using ArcGIS. ArcMap was synchronized with Google Earth to examine lake boundaries and types (i.e., glacier-fed or non-glacier-fed). Synchronization was critical because the higher spatial-resolution images used in Google Earth, including SPOT 5 (spatial resolution of 2.5 m), GeoEye (1.65 m), and Quickbird (2.62 m) images, can improve the identification of lakes and their boundaries. Synchronization assured that the glacial lakes in any single image were detected and delineated quickly. The derived lake boundary vector files were then converted to KML format and loaded into Google Earth for visual examination and comparison. The files were edited further using ArcGIS if any error was identified. A buffer polygon of glaciers for the study area based on the Randolph Glacier Inventory (RGI v3.2) was produced first. Buffer distances of 20, 15, 10, and 5 km were tested to determine the tradeoff between including nearly all glacial lakes and excluding glacier-fed lakes located farther from glacier termini. Finally,

Table 1
Landsat data for the years ~1990, 2000, and 2010 used in this study.

Acquired date	Number of scenes	Percentage of scenes	Sensor	Repeat cycle (days)	Pixel size (m)
1990 (1987–1996)	151	76% (1990 ± 2)	TM	16	30
2000 (1999–2002)	151	100% (2000 ± 2)	ETM+	16	30
2010 (2009–2011)	151	100% (2010 ± 1)	TM/ETM+	16	30

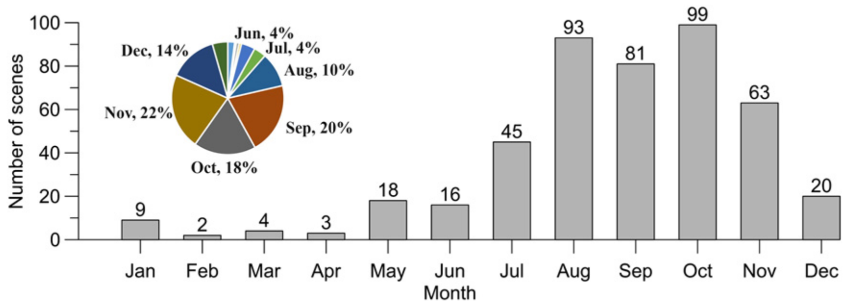

Fig. 1. Number of Landsat TM/ETM+ images used for each month of the study period from ~1990 to 2010.

a buffer distance of 10 km was determined to be optimal; this distance was also used in a previous study (Wang et al., 2013). Moreover, lakes located near buffer boundaries were intentionally included manually.

Lakes were classified as glacier-fed or non-glacier-fed based on whether glacier meltwater discharged into the lake with the help of Landsat images and Google Earth verification. Final lake vector files were reprojected to an Albers Equal-Area Conical coordinate system and then combined for the entire study area. Finally, glacial lake inventories for ~1990, 2000, and 2010 were determined individually; lake changes were examined and evaluated.

The smallest detectable glacial lakes of more than three pixels, i.e., 0.0027 km^2, in the Landsat TM/ETM+ data were included (Gardelle et al., 2011; Wang et al., 2013). In addition to cloud and snow coverage, the accuracy of glacial lake areas can be affected by the spatial resolution of satellite data. Several studies have demonstrated that the accuracy of data derived from satellite imagery is within approximately 0.5 pixels (O'Gorman, 1996; Fujita et al., 2009; Salerno et al., 2012). The uncertainty of the glacial lake area was estimated in this study as an error of ±0.5 pixels on either side of the delineated lake boundary.

3. Results

3.1. The number and area of glacial lakes

In total, 4602, 4981, and 5701 glacial lakes were identified using the data obtained for ~1990, 2000, and 2010, respectively, in the study area at a maximum distance of 10 km from glacier boundaries (Fig. 2). The total area of glacial lakes also increased with time, i.e., 553.9 ± 90, 581.2 ± 97, and 682.4 ± 110 km^2 in ~1990, 2000, and 2010, respectively, with a much faster increase during the last 10 years than the first 10 years. The data suggest that there were 3350 glacier-fed lakes (73% of all glacial lakes) covering a total area of 440.2 km^2 (79%) in ~1990, 3641 glacier-fed lakes (73%) covering a total area of 467.6 km^2 (80%) in ~2000, and 4260 glacier-fed lakes (75%) covering a total area of 556.9 km^2 (82%) in ~2010. Glacial lakes covering areas less than 0.1 km^2 dominated in number (68%), as shown in the Fig. 3 inset. The spatial distribution of glacial lakes in the Third Pole and subregions is presented in Fig. 3.

Table 2 presents the number and area of glacier-fed lakes for ~1990, 2000, and 2010. The Brahmaputra (39%), Indus (28%), and Amu Darya (10%) basins include more lakes and larger lakes than the other basins. All lakes in the Qaidam Basin and Hexi Corridor are glacier-fed. Fig. 4 shows the elevation distribution for glacial lakes in ~2010. Glacial lakes were situated within the elevation range of 2400–6000 m. Most lakes were located at elevations exceeding 3600 m. The dominant elevation of the lake distribution was 4000–5600 m.

3.2. Glacial lake changes

In total, 379 (291) and 720 (619) new lakes (glacier-fed) appeared between ~1990 and 2000 and between ~2000 and 2010, respectively (Fig. 2). Glacier-fed lakes exhibited total area increases of 27.4 and 89.3 km^2, significantly greater than the area changes of -0.1 and 11.9 km^2 for non-glacier-fed lakes between ~1990 and 2000 and between ~2000 and 2010, respectively. Table 2 shows that glacier-fed lakes were dominant in number and area in every basin. Moreover, the number and total area of glacier-fed lakes generally increased.

Fig. 5 illustrates an example of lake changes in the central Himalayas from ~1990 (2000) to 2010. The majority of glacial lakes were moraine-dammed lakes that expanded with the retreat of glaciers. Fifteen glacial lakes are present in this region. Clearly, changes in glacial lake boundaries and areas were more pronounced between ~2000 and 2010 than between ~1990 and 2000 (Fig. 5 inset).

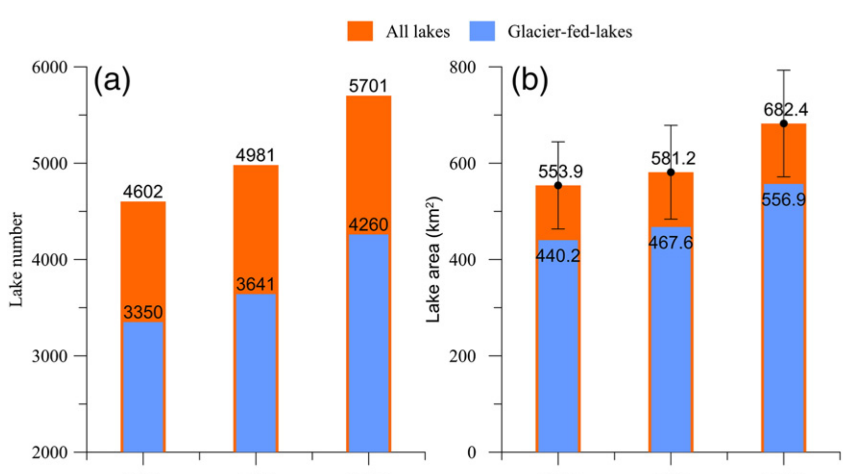

Fig. 2. (a) Number and (b) area of all lakes located at a maximum distance of 10 km from the nearest glacier and for glacier-fed lakes in ~1990, 2000, and 2010.

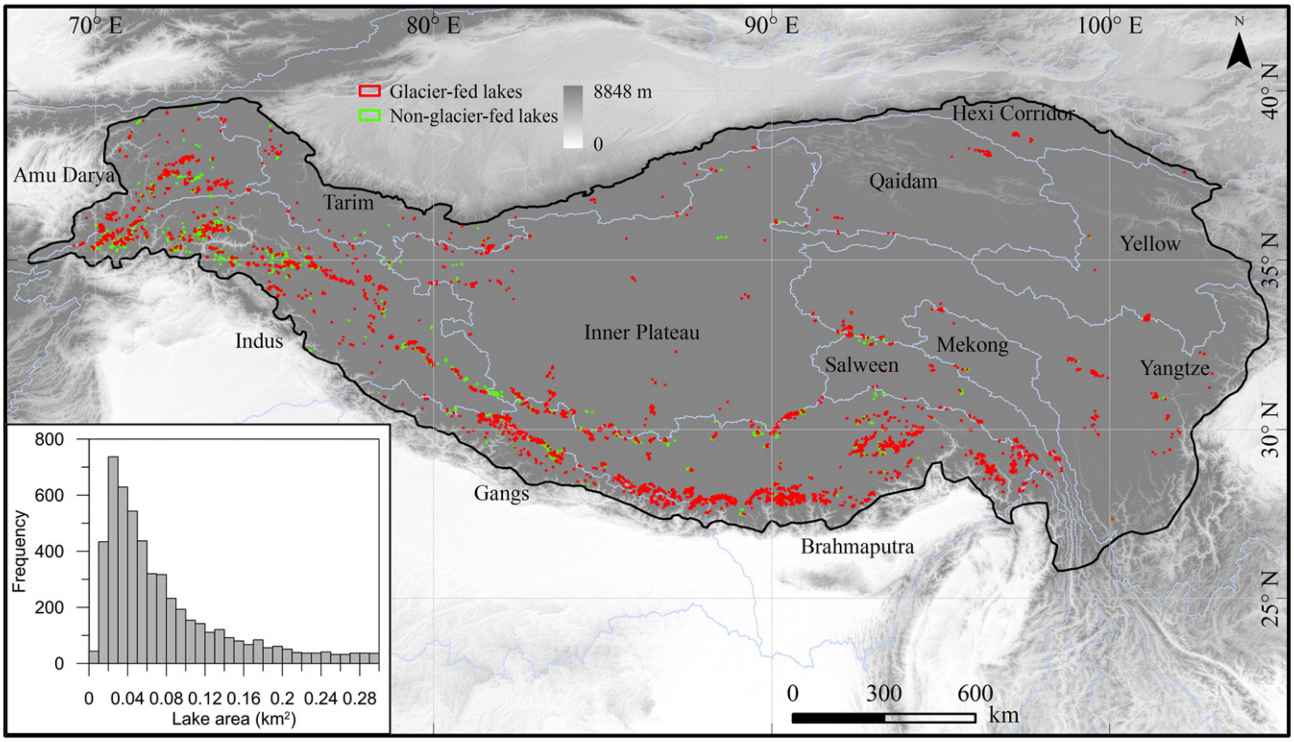

Fig. 3. Distribution of glacial lakes located at a maximum distance of 10 km from the nearest glacier in ~2010. The inset shows a lake area histogram with a bin width of 0.01 km^2. The study area was divided into the 12 great basins, including the Amu Darya, Tarim, Indus, Inner Plateau, Qaidam, Hexi Corridor, Yellow, Yangtze, Mekong, Salween, Brahmaputra, and Ganges basins.

3.2.1. Average area changes by size scale

Changes in glacial lake area can be attributed to lake size, lake-glacier distances, water recharge method (glacier-fed and non-glacier-fed), and elevation gradients. Glacial lake sizes range from 0.003 to 3 km^2 in this census. Two large well-studied glacial lakes, Thso Rolpa and Imja Tsho, had areas of 1.56 and 1.15 km^2 in 2010, respectively, indicating a rapid expansion in area since ~1960 (Chalise et al., 2006; Somos-Valenzuela et al., 2014). Fig. 6 shows an overall increase in area between ~1990 and 2010 and between ~2000 and 2010 regardless of lake size, with some decreases in lakes sizes of 0.3–0.8 km^2 and of greater than 1.0 km^2 between ~1990 and 2000. In addition, smaller lakes exhibited more significant area changes, particularly lakes smaller than 0.05 km^2. Lake sizes of 0.05–0.2 km^2 also exhibited more rapid area changes, i.e., > 6%, over the last decade.

3.2.2. Average area changes based on the distance between lakes and glaciers

Average glacial lake area changes were divided into three categories based on lake distance (10, 5, and 2 km) from a glacier boundary of the RGI. Fig. 7 shows that glacial lake area expansion was more rapid during the period ~2000–2010 (slightly > 20%) than during ~1990–2000 (<20%). Lakes located the shortest distance (2 km) from glaciers exhibited the greatest degree of area expansion between ~1990 and 2010, although only slight differences were recorded for ~2000–2010.

For ~2010, glacial lakes were classified as supra-glacial and pro-glacial lakes either connected or disconnected from a glacier terminal (Fig. 7-d). Lakes attached to glaciers exhibited the most significant mean area changes, i.e., 53.1 ± 5.6%. Lakes disconnected from glaciers exhibited a moderate mean area change of 25.1 ± 1.3%, whereas those

Table 2
Glacial lake number and area (with uncertainty) in ~1990, 2000, and 2010 for the 12 large basins in the Third Pole. Values in parentheses denote the corresponding number and area (km^2) of glacier-fed lakes.

Basin name	1990		2000		2010	
	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)
Amu Darya	500 (374)	54.0 ± 8.9 (39.9 ± 6.6)	556 (423)	58.8 ± 10.0 (44.7 ± 7.6)	594 (451)	65.8 ± 10.9 (50.3 ± 8.3)
Tarim	82 (68)	11.4 ± 1.6 (9.0 ± 1.3)	89 (79)	11.3 ± 1.7 (8.9 ± 1.4)	123 (108)	16.9 ± 2.5 (13.9 ± 2.1)
Indus	1295 (653)	111.7 ± 20.9 (65.3 ± 11.4)	1530 (808)	130.1 ± 24.9 (79.5 ± 14.2)	1607 (868)	141.6 ± 26.4 (88.8 ± 15.5)
Inner Plateau	275 (201)	28.9 ± 4.6 (19.9 ± 3.2)	300 (226)	31.4 ± 5.0 (22.4 ± 3.6)	352 (266)	38.3 ± 6.1 (27.6 ± 4.4)
Qaidam	16 (16)	1.4 ± 0.3 (1.4 ± 0.3)	23 (23)	2.2 ± 0.4 (2.2 ± 0.4)	31 (31)	3.1 ± 0.6 (3.1 ± 0.6)
Hexi Corridor	9 (9)	1.4 ± 0.2				
(1.4 ± 0.2)	10 (10)		1.6 ± 0.2 (1.6 ± 0.2)	11 (11)	2.0 ± 0.3 (2.0 ± 0.3)	
Yellow	13 (11)	2.8 ± 0.4 (2.7 ± 0.4)	15 (13)	2.8 ± 0.4 (2.7 ± 0.4)	15 (13)	3.0 ± 0.4 (2.9 ± 0.4)
Yangtze	146 (132)	19.3 ± 3.0 (17.6 ± 2.7)	140 (128)	18.2 ± 2.9 (16.8 ± 2.7)	192 (177)	22.4 ± 3.7 (20.7 ± 3.4)
Mekong	28 (25)	3.3 ± 0.6 (1.6 ± 0.4)	31 (28)	3.6 ± 0.7 (2.0 ± 0.5)	34 (31)	3.8 ± 0.7 (2.3 ± 0.5)
Salween	81 (66)	17.2 ± 2.2 (12.9 ± 1.7)	91 (74)	18.0 ± 2.4 (13.7 ± 1.9)	131 (114)	22.0 ± 3.1 (17.8 ± 2.6)
Brahmaputra	1863 (1562)	272.4 ± 41.1 (242.2 ± 35.9)	1902 (1594)	265.4 ± 41.1 (239.3 ± 36.1)	2247 (1883)	317.3 ± 48.7 (285.6 ± 42.8)
Ganges	294 (230)	30.3 ± 5.2 (26.3 ± 4.3)	294 (248)	36.3 ± 5.9 (33.0 ± 5.2)	364 (298)	45.8 ± 7.3 (41.4 ± 6.3)

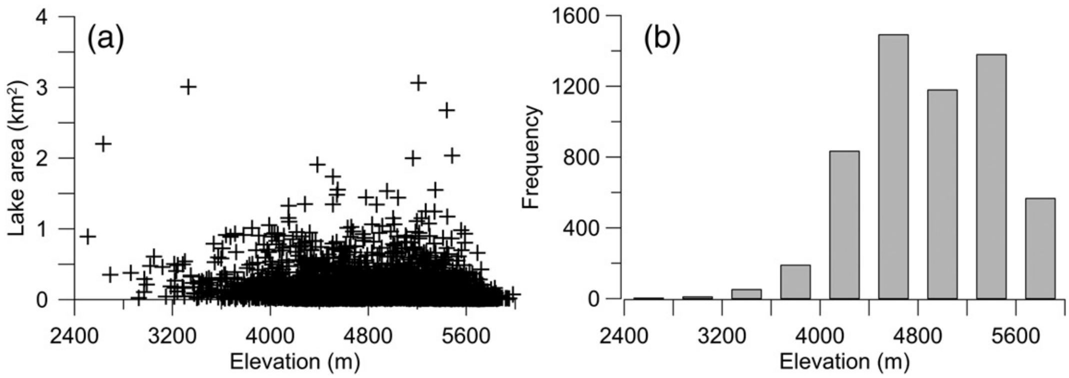

Fig. 4. (a) Area of individual lakes located at a maximum distance of 10 km from the nearest glacier versus elevation and (b) lake elevation histogram using lake data in ~2010.

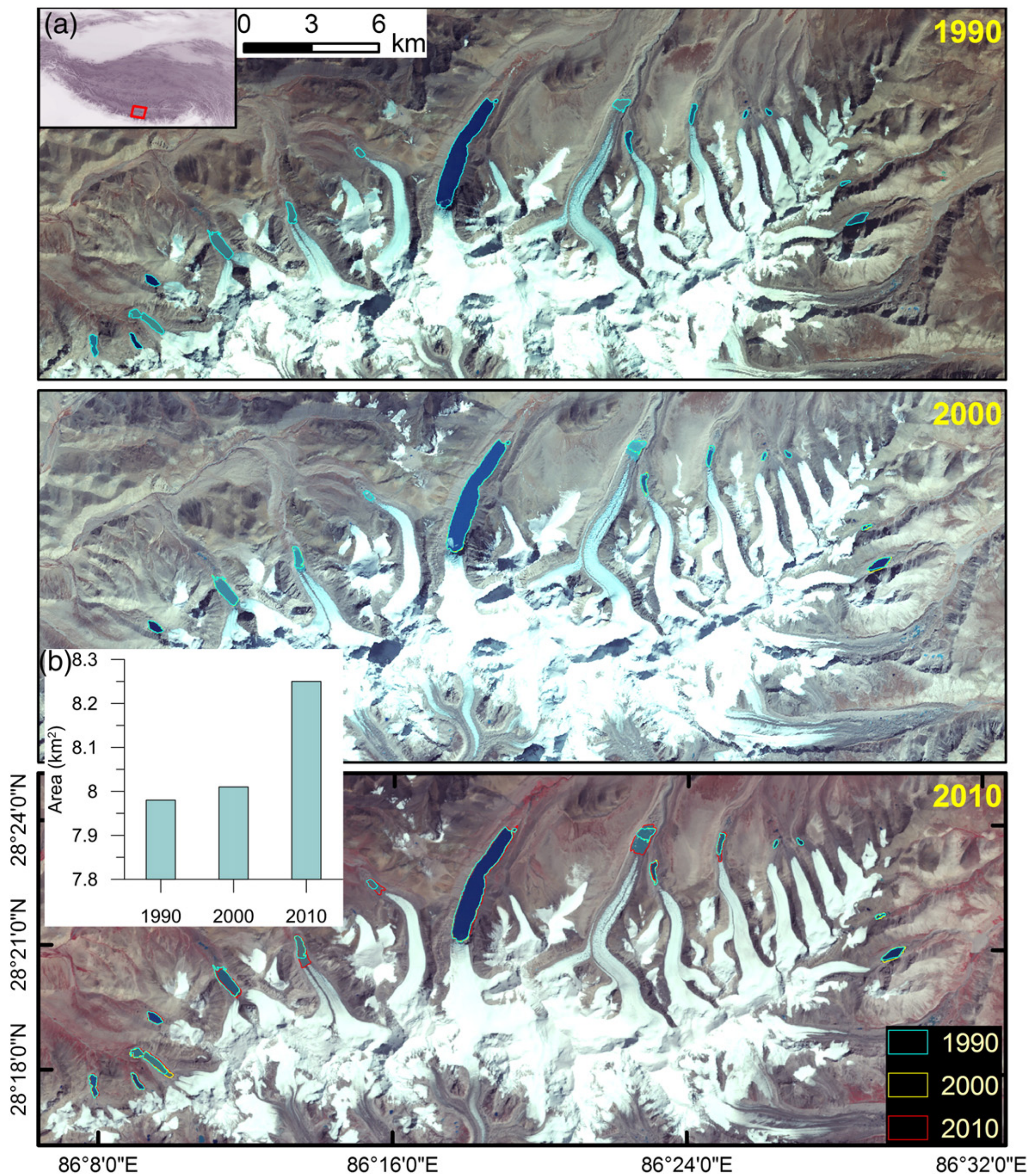

Fig. 5. Glacial lake expansion from ~1990 to 2010. The example includes 15 glacial lakes indicating lake outline changes. The inset shows (a) the location of these glacial lakes and (b) the total lake area in ~1990, 2000, and 2010.

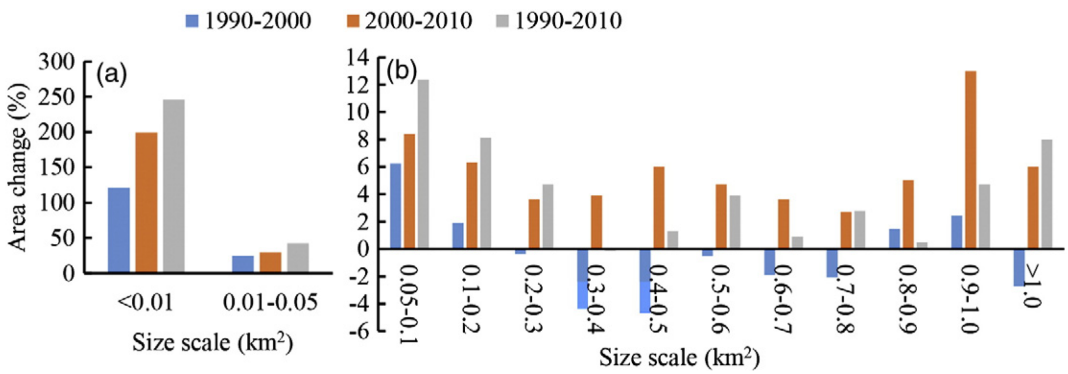

Fig. 6. Average area changes for glacial lakes grouped into different size scales of (a) 0.05 and (b) 0.1 km^2 between ~1990 (2000) and 2010.

located on the glacier surface exhibited a small mean area increase of 5.3 ± 8.7%.

3.2.3. Mean area changes among glacier-fed and non-glacier-fed lakes

Differences in glacier-fed and non-glacier fed lake changes were examined. Fig. 8a indicates that area change rates were generally higher for glacier-fed lakes than for non-glacier-fed lakes, particularly in the Amu Darya, Tarim, Mekong, Salween, Brahmaputra, and Ganges basins. The difference in area change rates for glacier-fed and non-glacier-fed lakes was small in the Indus basin (Fig. 8a).

Area changes for all lakes within each basin were averaged for glacier-fed and non-glacier-fed lakes. Fig. 8b shows that the average area changes were always greater for glacier-fed lakes than for non-glacier-fed lakes. Differences between the two lake types were most prominent in the Amu Darya, Tarim, Mekong, Salween, and Ganges basins.

Area changes for each glacier-fed and non-glacier-fed lake throughout the entire study area were compared. Fig. 8c clearly shows that area changes were greater in glacier-fed lakes than in non-glacier-fed lakes. Moreover, the mean rate of area change was higher in glacier-fed lakes than in non-glacier-fed lakes (i.e., 33.8 ± 1.8% and 19.1 ± 1.7%, respectively) (Fig. 8d).

3.2.4. Elevation-dependent lake area changes

Area changes among glacial lakes connected to glacier tongues were selected to examine elevation dependencies. Only 40 lakes were identified at elevations lower than 4000 m, and these lakes were combined and grouped into an elevation range of 600 m. Lakes at elevations exceeding 4000 m were aggregated into intervals of 400 m.

Mean area changes from ~1990 (2000) to 2010 exhibited an overall increase from 3400 to 6000 m, with fluctuations in different elevation divisions (Fig. 9). Mean area changes were greater (>40%) among glacial lakes at elevations exceeding 5200 m than among those at elevations of 3400–5200 m from ~1990 (2000) to 2010. The elevation dependence of lake area change further supports a dominant role of glacier melt in most lake expansion. Interestingly, areal change rates were higher during the period ~2000 − 2010 than ~1990 − 2000 at elevations of 4400 to 5600 m, although the reverse was true at lower and higher elevations.

4. Discussion

4.1. Glacial lake changes

Glacial lakes were located primarily in the Brahmaputra, Ganges, Indus, and Amu Darya basins. This finding is in contrast to previously reported data for large lakes (>1 km^2), which were located primarily in the endorheic basin of the Tibetan Plateau and were much fewer in number along the southern plateau (Zhang et al., 2014b).

The Landsat data used in this study were collected primarily from July through November (Fig. 1). Landsat images in other months were also included in this study due to the unavailability of high-quality remote-sensing data. A ± 2-year inter-annual range was used for data

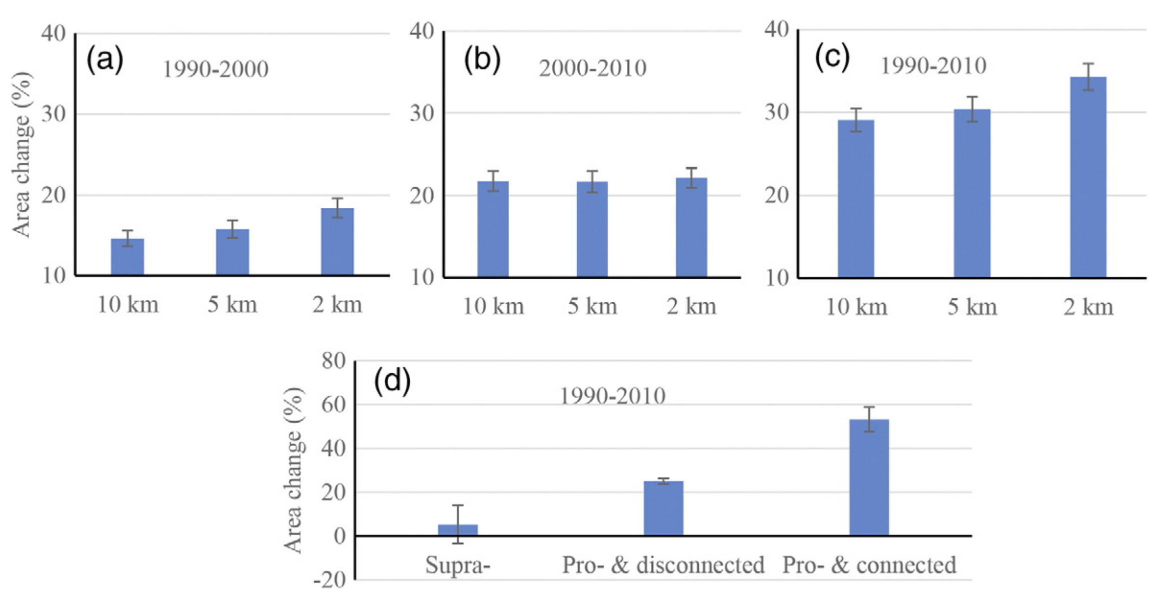

Fig. 7. Average area changes with error bars for glacial lakes located at distances from glaciers of 10, 5, and 2 km for the (a) ~1990 − 2000, (b) ~2000 − 2010, and (c) ~1990 − 2010 and (d) for supra-glacial and pro-glacial lakes in ~1990 − 2010.

selection. In addition to delineation precision errors, seasonal variations may introduce uncertainties in glacial lake area changes (Salerno et al., 2012). However, the data in this study had a consistent spatial resolution of ~30 m and were readily available. We compared area changes over 10-year intervals, i.e., for ~1990 (2000) to 2010. Although seasonal changes could lead to lake area uncertainty over 1- to 2-year periods, these changes were minor compared to the differences that occur during a 10-year period.

Low cloud- and snow-covered Landsat data for the three periods was selected to delineate lake boundaries. For example, the mean cloud coverage of Landsat scenes for ~2010 was 8.2%. However, cloud and seasonal snow coverage were unavoidable. The TP has a mean cloud cover of > 40% per day (Zhang et al., 2012). Cloud and seasonal snow can obscure Landsat imagery, particularly in the southeastern (SE) TP, resulting in a data gap for the second Chinese glacier inventory in this region (Guo et al., 2015). The presence of clouds could cause some glacial lakes to be missed in this inventory. A total of 18 scenes were used for glacial lake examination of the SE TP for each study period. The regions covering three scenes (Landsat PR 134/39, 135/39, 136/39) had the greatest uncertainty due to a high proportion of snow cover. In addition, the glacier boundary offset from the RGI (Pfeffer et al., 2014) could also result in unidentified or misclassified glacial lakes, although the buffer distances of 10, 5, and 2 km used in this study are more significant than glacier boundary displacements.

In contrast to moraine-dammed lakes and supra-glacial lakes, ice-dammed lakes are formed by glacier advancement (Hewitt and Liu,

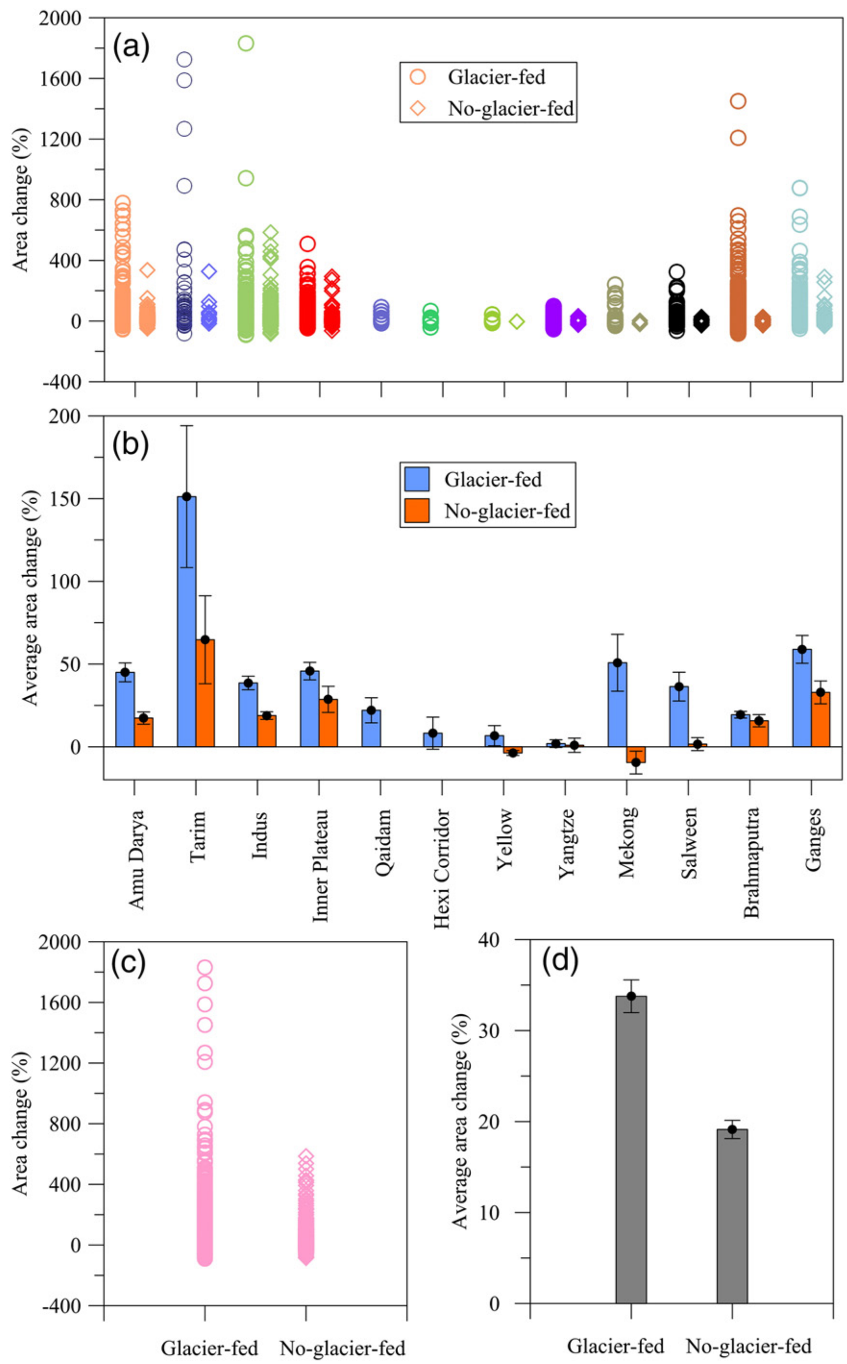

Fig. 8. Area changes in glacial lakes between ~1990 and 2010 for glacier-fed lakes and non-glacier-fed lakes. (a) Signal lakes in the 12 large basins; (b) average area changes with error bars in the 12 large basins; (c) signal lakes for the Third Pole; and (d) average area changes with error bars for the Third Pole.

2010). Published reports of ice dams indicate that 24 GLOFs occurred in the upper Yankand region between 1880 and 2009 and 71 in the upper Indus region between 1533 and 2000 in the Karakoram Himalaya (Hewitt and Liu, 2010). Combining the glacial lakes dataset in ~2010 from this study and Google Earth, 19 ice-dammed lakes were identified in the Karakoram region. Niu et al. (2011) identified and examined the changes in an ice-dammed lake associated with glacier surging in the Yarkant River, Karakoram, in the summer of 2009. These lakes are short-lived, with a duration of only a few months (Hewitt, 2007; Hewitt and Liu, 2010). The short-term fluctuation in ice-dammed lakes could introduce uncertainty in the number and area of glacial lakes identified in this inventory.

4.2. Water sources for glacial lake expansion

Most lakes (>80%) with lake level measurements derived from ICESat altimetry data and area from Landsat data in the TP and surroundings have increased, particularly since 1990 (Phan et al., 2012; Nie et al., 2013; Zhang et al., 2014b). Lake levels exhibited a mean rise of 0.21 m/year from 2003 to 2009 (Zhang et al., 2011), and the lake area expanded by 26% in the Inner Plateau (covering a 66% lake area in the TP) between 1990 and 2010 (Zhang et al., 2014b). The rise in water level and increase in area among large lakes (>1 km^2) and lakes located far from glaciers (>10 km) may be attributable to increased glacier/perennial snow cover melt (Yao et al., 2012a, 2012b), net precipitation (Yang et al., 2014), permafrost degradation (Yang et al., 2010) and groundwater recharge (Wu et al., 2014) to lake basins. The area, length and mass balance of most glaciers have decreased since the 1960s (Bolch et al., 2012; Yao et al., 2012a, 2012b), excluding some regions with balanced budgets over the last decade, such as the Karakoram (Bhambri et al., 2013; Gardner et al., 2013), western Kunlun and central TP (Neckel et al., 2014), and parts of Pamir (Gardelle et al., 2013). Salerno et al. (2012) demonstrated that the areas of disconnected glacial lakes are significantly correlated with the areas of the corresponding drainage basins. However, Salerno et al. (2012) did not differentiate between glacier-fed and non-glacier-fed lakes for disconnected glacial lakes.

Glacier mass balance and air temperature changes may serve as useful parameters for explaining glacial lake evolution. The mean warming rate of annual air temperatures in the TP was 0.04 °C/year from 1960 to 2013 according to 95 China Meteorological Administration (CMA) station records (Fig. 10). The warming in the TP and surroundings was more prominent at higher elevations (<5500 m) than at lower elevations (Liu et al., 2009). This result is consistent with the negative trend in the mean glacier mass budget from the 1960s to 2000s in the Himalayas (Bolch et al., 2012), corresponding spatially with the distribution of the glacial lakes studied. In particular, the glacier mass balance decreased rapidly in the late 1990s, corresponding closely to the abrupt increase in air temperature. In addition, the Xiaodongkemadi glacier in the Tanggula Mountains of the TP, for which long-term field observations exhibited a continuous mass loss between 1989 and 2010 (Yao et al., 2012a, 2012b; Zhang et al., 2013b; Kang et al., 2015). This result suggests that the rapid glacial lake expansion (2000 – 2010) observed in this study was related to the higher mass loss rate since the late 1990s.

Relationships between glacial lake changes and glacial mass balances vary regionally. We examined the correlation between these processes over the Pamir-Karakoram-Himalaya area with the regional boundary from Kääb et al. (2015) due to high lake quantities and considerable spatial correspondence. We utilized the normalized total lake area (NLA) (i.e., total lake area divided by glacier area) used in Gardelle et al. (2011) to compare the regional differences, which suggested that a highly glaciated region is more likely to bear glacial lakes. Our results are consistent with those of Gardelle et al. (2011) that the NLA is higher in eastern regions, such as Everest, Bhutan, and Eastern Nyainqêntanglha, than in western Pamir and Karokaram, excluding the Hindu Kush, which exhibited a high NLA in our study but a low value in Gardelle et al. (2011). A recent study from Kääb et al. (2015) demonstrated that the Hindu Kush has a considerably negative glacier mass balance, which can contribute to glacial lake expansion in this region. In addition, the changes in the characteristics of glacial lakes observed in our study can be correlated to the glacier mass balance. The greater gradient of the negative glacial mass in the eastern Nyainqêntanglha, Bhutan, and Hindu Kush (Kääb et al., 2015) regions corresponds to a higher NLA and lake area changes between ~2000 and 2010 in these regions, and accordingly, the balanced mass balances in the Karakoram and parts of Pamir correspond with the low NLA, particularly in the Karakoram region (Gardelle et al., 2013).

All glacial lakes (located less than 10 km from the nearest glacier) in the study area were examined for three study periods, i.e., ~1990, 2000, and 2010. Glacier-fed lakes exhibited a higher degree of mean areal expansion than non-glacier-fed lakes in the sub-basins and across the entire study area. According to the Global Precipitation Climatology Project, precipitation in the Himalayas followed a decreasing trend from 1970 to 2010 due to weakened Indian monsoons (Yao et al., 2012a, 2012b). Glacial lake changes by type and elevation support the claim that glacier meltwater may serve as the dominant source for most glacial lake expansions; however, precipitation and snowmelt can contribute to water supplies. By contrast, glacial lake expansion can accelerate the retreat of debris-covered glaciers (Benn et al., 2001; Basnett et al., 2013). This phenomenon highlights the need to further examine interactions between glacial lakes and glaciers in the Third Pole.

4.3. Glacial lake outburst floods (GLOFs)

Potentially dangerous glacial lakes and GLOFs in the Himalayas have increased in number since the 1930s (Richardson and Reynolds, 2000; Bolch et al., 2008; Ives et al., 2010; Liu et al., 2013). Historical records

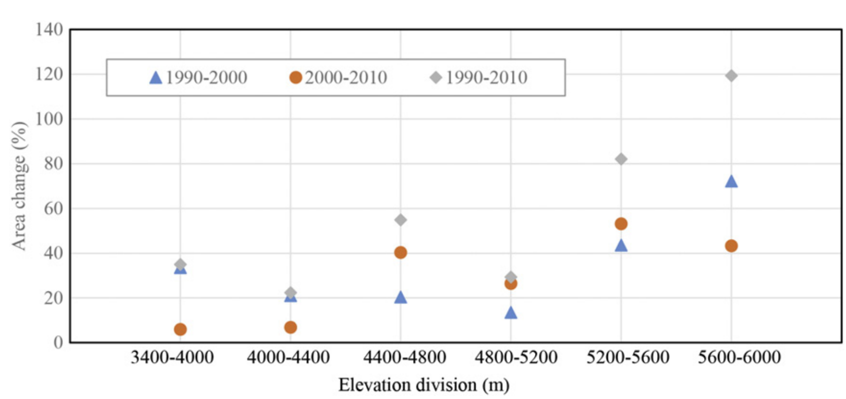

Fig. 9. Average area changes among lakes connected to glaciers for different elevation divisions between ~1990 (2000) and 2010.

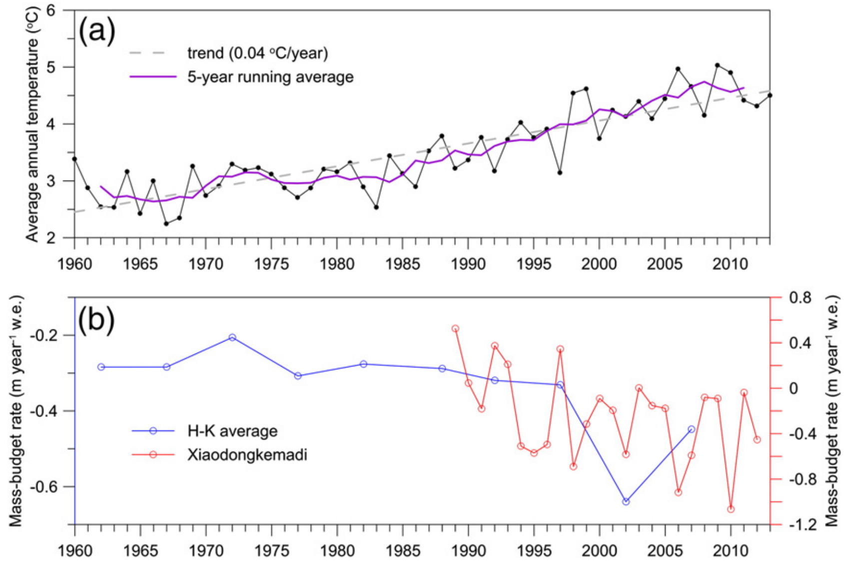

Fig. 10. Average annual air temperatures derived from 95 CMA stations in the TP, mass-budget rate of the Xiaodongkemadi glacier in the Tanggula Mountains of the TP (Yao et al., 2012; Kang et al., 2015; Zhang et al., 2013), and mean mass-budget rate for glaciers in the Himalayan and Karakorum (H-K) regions from Bolch et al. (2012).

indicate that 33 GLOF events occurred in the Himalayas before the year 2000 (Richardson and Reynolds, 2000). The most severe disaster, i.e., the 1981 Cirenmaco GLOF, destroyed the China–Nepal Friendship Bridge and killed 200 people (Wang et al., 2014). Two large-scale debris flows occurred in the Poiqu River basin on May 23, 2002, and June 29, 2002, damaging the China–Nepal Highway and a hydropower station (Chen et al., 2007). Moraine-dammed glacial lakes are expanding due to glacier recession induced by global warming (Thompson et al., 2012). In addition, ice-dammed glacial lakes can form during glacier advancement (Tweed, 2014). The characteristics of outbursts and flood waves differ from those of outburst floods triggered by glacier retreat (Hewitt and Liu, 2010). Hazard assessment of glacial lakes requires an understanding of moraine-/ice-dammed lake formation processes and appropriate field investigations. In this study, 1040 of the 5701 lakes detected in 2010 were glacial lakes connected to glaciers; these are primarily moraine-dammed lakes. This inventory of glacial lakes serves as a basis for further analyses of priority lake and hazard assessments.

5. Conclusions

This study presents a critical database of glacial lakes in the Third Pole (and will be released via the Third Pole Environment Database at http://en.tpedatabase.cn/). In total, 4602, 4981, and 5701 glacial lakes were identified in ~1990, 2000, and 2010, respectively. These lakes cover areas of 553.9 ± 90, 581.2 ± 97, and 682.4 ± 110 km^2, respectively. Small lakes (<0.2 km^2) have undergone more significant area changes, possibly due to global warming. Lake area changes become more prominent as the distance from the lake to a glacier declines, particularly for lakes connected to a glacier terminus. Overall, glacier-fed lakes exhibited more significant area changes than non-glacier-fed lakes. Area changes among lakes connected to glaciers exhibited pronounced elevation dependency; more specifically, lakes at higher elevations exhibited more significant area changes. We conclude that water from processes of accelerated glacial retreat may contribute dominantly to most glacial lake expansions.

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