Recent glacier and glacial lake changes and their interactions in the Bugyai Kangri, southeast Tibet

LIU Qiao,[1] GUO Wanqin,[2] NIE Yong,[1] LIU Shiyin,[2] XU Junli[2]

[1]*Key Laboratory of Mountain Surface Processes and Ecological Regulation, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, China*
[2]*State Key Laboratory of Cryosphere Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China*
Correspondence: Liu Qiao <liuqiao@imde.ac.cn>

ABSTRACT. Glaciers in the Bugyai Kangri are located in a transition zone from southeast Tibet, where monsoonal temperate glaciers dominate, to inner Tibet, where continental glaciers dominate. Here we analyze glacier and glacial lake changes in this region using multi-year inventories based on Landsat images from 1981–2013. Results show that the total area of 141 glaciers in the region decreased by $30.44 \pm 0.89\,km^2$ from $198.35 \pm 9.54\,km^2$ (1980s) to $167.93 \pm 4.52\,km^2$ (2010s). The annual area shrinkage rate ($-0.48\%\,a^{-1}$) is lower than that reported for southeastern Tibet but higher than that of inner Tibet. Both the number and total area of glacial lakes increased between 1981 and 2013. Among all lakes, proglacial lakes contribute most (~81%) to the expansion. The total area of ten proglacial lakes increased by $150.3 \pm 13.17\%$ and of these ten lakes the four that expanded most sharply showed increased calving at their upper margins, resulting in more rapid retreat of lake-terminating glaciers than land-terminating glaciers. Owing to rapid calving, several lakes may undergo further growth in the near future, increasing the potential risk of glacial lake outburst floods.

KEYWORDS: climate change, glacier calving, glacier fluctuations, jökulhlaups (GLOFs), remote sensing

INTRODUCTION

The Tibetan Plateau (TP) has experienced significant warming during past decades compared with other mountain regions around the world (Kang and others, 2010). The presence of many contemporary glaciers and ice caps in the TP and its surroundings is crucial for the availability of water resources downstream (Immerzeel and others, 2010). Glacier changes are altering local or regional hydrological cycles (Lutz and others, 2014; Radić and Hock, 2014) and, in many locations, also posing potential risks of glacial lake outburst floods (GLOFs) (Richardson and Reynolds, 2000) due to the formation and expansion of glacial lakes as glaciers retreat (Komori, 2008; Benn and others, 2012).

The climate in the TP is strongly but heterogeneously influenced by the westerlies and the south and southeast Asian monsoons (Böhner, 2006), inducing spatial differences in glacier mass-balance regimes and their responses to climate change (Fujita and Nuimura, 2011; Yao and others, 2012). Monsoonal temperate glaciers in the southeastern TP are more sensitive to climate warming than continental glaciers in the inner TP (Fujita and Ageta, 2000; Fujita, 2008; Yang and others, 2008; Liu and others, 2010). In the southeastern TP, in agreement with rapid glacier shrinkage, glacier-related hazards (e.g. GLOFs and debris flows) have been widely reported during recent decades (Ding and Liu, 1992; Cheng and others, 2008; Liu and others, 2014). Currently, there are a number of potentially dangerous glacial lakes in this region (Wang and others, 2011; Liu and others, 2014). In this study, we focus on glacier and glacial lake changes in the Bugyai Kangri (BK) massif, a region in the southeastern TP with few previous reports. The study area is located in a transition zone from the monsoonal temperate-type glaciers in the southeastern TP to the continental type in the inner TP. This study aims to: (1) document a detailed inventory of glacier and glacial lake changes in the BK to fill the gaps in our current limited knowledge; (2) determine whether glacier shrinkage rates in this transition region during recent decades are in line with previous conclusions about the gradient of glacier changes from the southeastern to the inner TP (Yao and others, 2012); and (3) discuss the interactions between glacier retreat and lake expansion, since several glacial lakes in this region have formed and expanded considerably in recent years.

STUDY AREA

The BK (31°49′11″ N, 94°42′00″ E), with a maximum elevation of 6328 m a.s.l., is located on the border between Nakchu and Qamdo counties along the Sichuan–Tibet North Highway (G317) (Fig. 1a). It is an independent plateau stretching ~40 km from east to west and ~20 km from north to south, and belonging to the eastern Tanggula range and the north end of Taniantaweng, Hengduan mountains, in the Nujiang (Salween) basin. According to the nearest meteorological observations from the town of Dengqean (31°24′46″ N, 95°35′46″ E; 3860 m a.s.l.) 90 km to the southeast, annual precipitation is ~600–700 mm and mostly falls in June–September. The prevailing wind comes from the northwest, but during the monsoon (precipitation) season it is dominated by southeast and east directions (Li, 1986). Based on field expeditions during the 1980s, the mean equilibrium-line altitude (ELA) in the BK was observed at ~5300–5400 m a.s.l. and the annual mean air temperature at the ELA was estimated to be –6°C to –7°C (Li, 1986).

Climatic and topographic conditions here favour the development of mountain glaciers (Aizen and Helen, 1994). Based on the first Chinese Glacier Inventory (CGI) (~1968) (Shi, 2008), there are 133 glaciers with a total area of

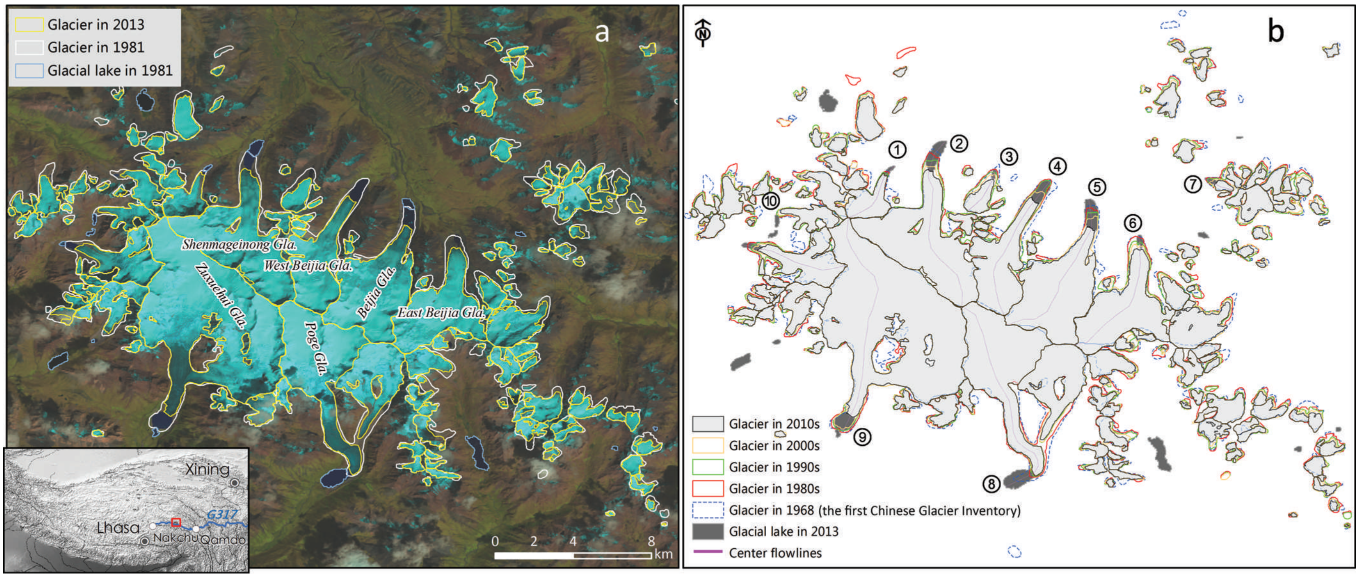

Fig. 1. (a) Glaciers in the BK and their extents in 1981 and 2013. The background is a Landsat 8 image from 28 September 2013. Inset map shows the location of the study area and highway G317. (b) Glacier outlines based on inventories for four periods (1980s, 1990s, 2000s and 2010s) and the first CGI in 1968. Glacial lakes in 1981 (a) and 2013 (b) are also drawn for comparison. The ten proglacial lakes are numbered.

~193.86 km^2 in the BK region. The largest glacier is Zuxuehui located on the south slope of the mountain range, with an area of ~35 km^2 (in 1968). It is also the lowest glacier in this region since its terminus lies at ~4200 m a.s.l. (Li, 1986). Wang and Ding (2002) suggested that up to the time of the first CGI the total area of glaciers in the BK region had decreased by ~24% since the maximum of the Little Ice Age (LIA) in about the 15th century.

DATA AND METHODS

The first CGI of the BK mountain region was based on a topographical map (H-46-10, 1 : 100 000), which was derived from aerial photographs taken in April 1968. In this study, we use Landsat MSS/TM/ETM+ (multispectral scanner/Thematic Mapper/Enhanced TM Plus) images and recently released Landsat 8 OLI (Operational Land Imager) images, archived by the US Geological Survey (USGS), to map the glacier outlines and their changes. Because the data source of the first CGI (scanned topographical map) is different from the remote-sensing-based inventories (Nuimura and others, 2015), our new inventory concerns only four time periods (1980s, 1990s, 2000s and 2010s; Table 1), and direct comparisons of glacier changes between the first CGI and others are for reference only. For each time period, the Landsat scene with the best quality (least contaminated by snow or cloud) was selected as the base image for primary mapping. Several supplementary images were used to eliminate or lessen uncertainties and retrieve glacier boundaries for parts obscured by cloud or snow in the base image.

Band-ratio images with a threshold (Paul and others, 2002) were utilized to delineate the glacier outlines. Although no debris-covered glaciers were found in this region, the raw ice polygons were visually checked for classification errors such as seasonal snow, rock outcrops and moraines. Figure 1a shows the mapped glacier outlines for 1981 and 2013 overlaid on a 2013 Landsat 8 image (band R6,G5,B4), from which outlines were extracted and visually modified for glaciers in the 2010s. Ice coverage on each Landsat image was divided into individual glacier polygons using topographical ridgelines, or ice divides, which were computed using a watershed delineation approach based on the Shuttle Radar Topography Mission (SRTM) (available from http://srtm.csi.cgiar.org/) digital elevation model (DEM) (Jarvis and others, 2008). The SRTM DEM was also used to derive glacial geomorphological parameters (e.g. glacial

Table 1. Landsat images and topographic map data used in the study

Time period	Base image ID	Base image Date yyyy-mm-dd	Base image Resolution m	Supplementary images ID	Supplementary images Date yyyy-mm-dd	Supplementary images Resolution m
First CGI (1970s)	Topographic map H-46-10	1968-04-?? (day unknown)	1 : 100 000	none		
1980s	LM31460381981296AAA03	1981-10-23	60	LM21460381977218AAA03	1977-08-06	60
1990s	LT51360381994219BJC00	1994-08-07	30	LT51360381988283BJC00	1988-10-09	30
2000s	LE71360382002249SGS0	2002-09-06	15	LT51360382000220BJC00	2000-08-07	30
				LE71360382005273PFS00	2005-09-30	15
2010s	LC81360382013271LGN00	2013-09-28	15	LT51360382010119KHC00	2010-04-29	30
				LE71360382012245PFS00	2012-09-01	15

https://doi.org/10.3189/2016AoG71A415 Published online by Cambridge University Press

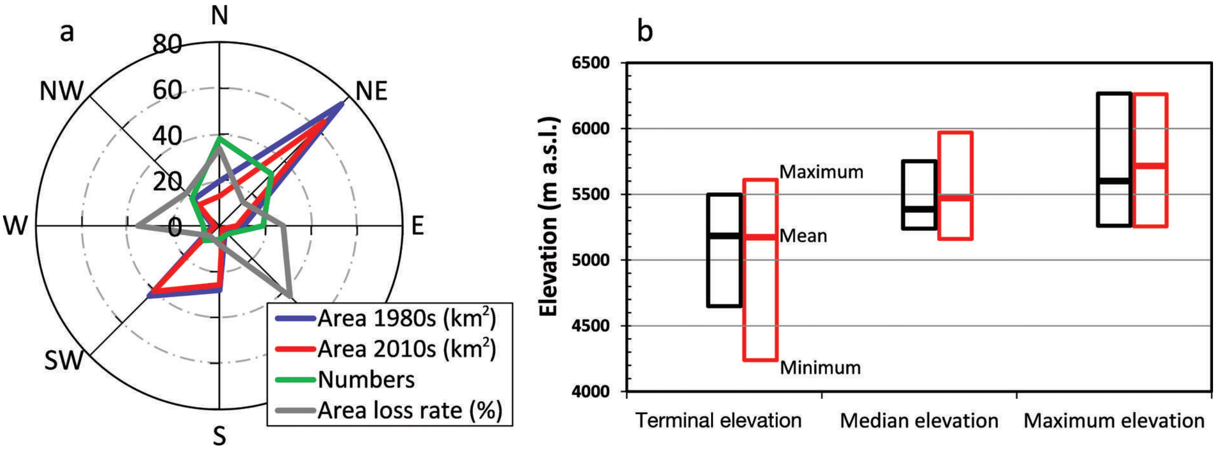

Fig. 2. (a) Glacier distributions with aspect. (b) Terminal, median and maximum elevation distributions (the maximum, mean and minimum values are depicted and indicated) for glaciers with northern (black) and southern (red) aspects.

hypsometry, aspects and surface profiles along the central flowlines) (Fig. 1b). According to the Global Land Ice Measurements from Space (GLIMS) guidelines for the world glacier inventory (Paul and others, 2009), the mean aspect of a glacier is calculated based on the mean sine and mean cosine of all individual cells covered by the glacier. Glacial geomorphological parameters derived in this way for glacier mapping before or after the 2000 date of the SRTM may be biased from the actual values because of changes in ice surface elevation and extent.

Outlines of glacial lakes were extracted using the normalized-difference water index (NDWI) method (Huggel and others, 2002; Fujita and others, 2009). Manual examination and modification were conducted on the automatically extracted results to eliminate or reduce the uncertainties in lake mapping (e.g. for the frozen lakes and lake water areas in terrain shadows).

For each date, ice patches >0.01 km^2 and lakes >0.036 km^2 were mapped. The error analysis for polygon areas and their changes follows Fujita and others (2009) and Bolch and others (2010), in which the uncertainty in the measurement of area was estimated by assuming an error of ±0.5 pixel on the outlines of the shape. For glacier outlines of the first CGI derived from 1 : 100 000-scale topographic maps, line pixel error is estimated to be ±13.5 m (Wei and others, 2014). For mapping results based on Landsat images, line pixel error is the spatial resolution of Landsat scenes (e.g. ±7.5 m for Landsat ETM+ and OLI and ±15 m for Landsat TM).

RESULTS

Contemporary glacier distribution in the BK

Figure 1b presents the mapped boundaries of glaciers and glacial lakes in the BK region for each time period (1968, 1980s, 1990s, 2000s and 2010s) between 1981 and 2013. The latest inventory of the 2010s is based on one base image acquired on 28 September 2013 and two supplementary images from 2010 and 2012. It shows that there are 142 glaciers with a total area of 167.93 km^2 in the BK. Mean glacier area is 1.18 km^2 and the largest glacier, Zuxuehui, has an area of 34.66 km^2. Owing to the northwest–southeast (NW–SW) orientation of the BK, glacier aspects are predominantly to the NE and SW (Fig. 2a), but far more glaciers face NE than SW. Glaciers with NE orientation have the largest total area (64.32 km^2; 38.3%), whereas west-facing glaciers have the smallest (1.9 km^2; 1.1%). Generally, glaciers on the southwestern flank have larger mean area and are fewer than those on the northeastern flank. Poge glacier (Fig. 1a) was the second largest glacier in the BK until it became two separate glaciers as its left tributary became detached from the main ice tongue in 1994. Shenmageinong glacier, located on the northeastern flank and with an area of ~15.19 km^2 in 2013, is currently the second largest glacier although it lost ~1.35 km^2 (~8%) of its area between 1981 and 2013.

Figure 2b shows the different elevation distributions between the north- and south-facing glaciers in the BK region. For the terminal elevations, the mean elevation of north-facing glaciers (5182.6 m a.s.l.) is close to that of south-facing glaciers (5184.6 m a.s.l.), whereas the minimum elevation of the north (4648.6 m a.s.l.) is much higher than the south (4263.6 m a.s.l.). The median elevations (which split the areas of the individual glaciers into equal halves) and maximum elevations of north-facing glaciers are generally slightly lower than those of south-facing glaciers.

Glacier changes between the 1980s and 2010s

Table 2 lists the statistics for each of the five inventories between the first CGI and the 2010s, and their changes during each time period are shown in Table 3. During the past 32 years (1981–2013), total glacier area in the BK has decreased by 30.44 km^2 (15.3% of the total area in 1981), which means an annual glacier area loss rate of –0.48% a^{-1}.

Table 2. Statistical results of five glacier inventories in the BK region between 1968 and 2013

Period (primary time)	Number	Total area km^2	Mean area km^2	Maximum area km^2
First CGI (1968)	133	193.86 ± 8.24	1.46 ± 0.06	36.38 ± 0.70
1980s (1981)	140	198.35 ± 9.54	1.42 ± 0.07	36.28 ± 0.72
1990s (1994)	141	187.44 ± 9.55	1.33 ± 0.07	35.79 ± 0.72
2000s (2002)	141	177.92 ± 4.63	1.26 ± 0.03	35.57 ± 0.37
2010s (2013)	142	167.93 ± 4.52	1.18 ± 0.03	34.66 ± 0.36

https://doi.org/10.3189/2016AoG71A415 Published online by Cambridge University Press

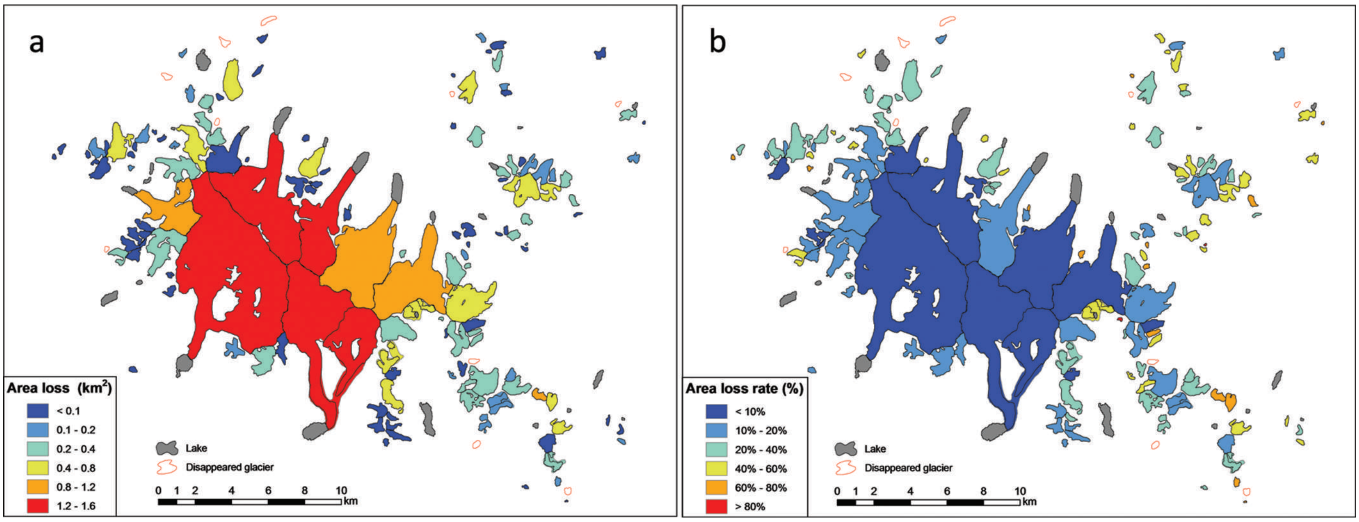

Fig. 3. Individual glacier (a) area loss and (b) area loss rate between 1981 and 2013.

Among the three investigated time intervals, the 1990s–2000s shows the highest annual area loss rate (–0.63% a^{-1}) compared with the other two periods (Table 3). The slight increase in total number of glaciers is a result of the balance between the disappearance of small glaciers and the separation of tributary glaciers. Figure 3 presents the spatial patterns of glacier changes in the BK between 1981 and 2013, plotted as the absolute (Fig. 3a) and relative (Fig. 3b) area loss for each glacier. Six small glaciers, with areas ranging from 0.05 to 0.15 km^2, had disappeared by 2013. Owing to the disintegration of eight glaciers into 16 separate glaciers, the number of glaciers in the BK increased by two between 1981 and 2013. The original area (in 1981) of these separated glaciers ranges from 0.70 to 22.81 km^2.

For separated glaciers, area loss and loss rate are calculated using the area of the previous parent glacier. It is obvious that larger glaciers have lost more area than smaller ones, whereas their area loss rates are relatively lower. Glaciers with an area decrease >0.8 km^2 are concentrated around the central massif of the BK, where glaciers are generally larger (>5 km^2). Figure 3 also shows that some adjacent glaciers with similar size show significant heterogeneous area loss, possibly due to their different topographical or glaciogeomorphological characters. The variation of area loss rate with aspect (Fig. 2a) indicates that glaciers with some specific aspects (SE, N, W and E) have experienced more shrinkage between the 1980s and 2010s. Figure 4 shows the relationship between the area loss rate and glacier size, demonstrating that the shrinkage rate decreases with glacier size. The ten glaciers in contact with proglacial lakes are generally larger (>2.37 km^2) than other glaciers; these glaciers have experienced greater area loss (Fig. 3a), whereas their area loss rates are generally lower than for other glaciers.

Glaciers in the BK ranged in elevation between 4236 and 6328 m a.s.l. in 2013 and the glacierized area reached its maximum at ~5500 m a.s.l. (Fig. 5). Figure 5 also shows the change of glacier area–altitudinal distributions for 1981–2013. The largest area loss (–4.57 km^2) occurred between 5300 and 5400 m a.s.l., whereas absolute changes were smaller (<1 km^2 of total area decrease) above 6000 m a.s.l. and below 4525 m a.s.l.

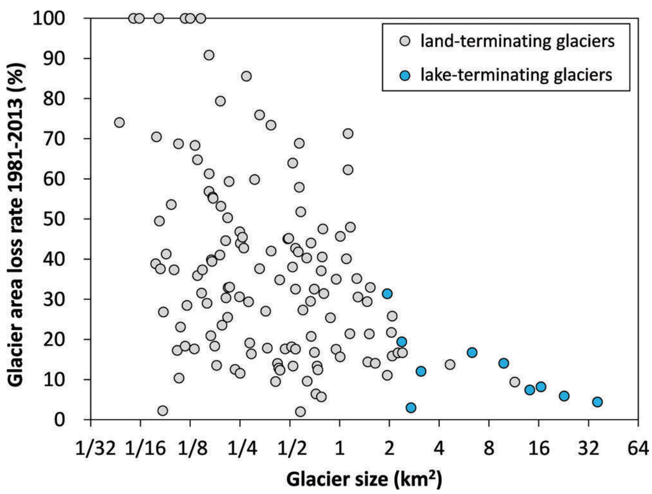

Fig. 4. Glacier area loss rates as a function of glacier size.

Table 3. Glacier changes during four inventories between the 1980s and 2010s

Period	Years	Number	Total area change		Annual area loss rate	Mean area change	Maximum area change
			km^2	%	% a^{-1}	km^2	km^2
1980s–1990s	13	+1	–10.91 ± 0.30	~5.50	~0.42	–0.09 ± 0.03	–0.49 ± 0.05
1990s–2000s	8	0	–9.52 ± 0.29	~5.08	~0.63	–0.07 ± 0.04	–0.22 ± 0.03
2000s–2010s	11	+1	–10.01 ± 0.20	~5.63	~0.51	–0.08 ± 0.02	–0.91 ± 0.06
1980s–2010s	32	+2	–30.44 ± 0.89	~15.3	~0.48	–0.23 ± 0.02	–1.62 ± 0.14

Glacial lakes in the BK region and their changes

A summary of glacial lakes in the BK region is listed in Table 4. Based on the 2013 inventory, there are 26 glacial lakes. Most are moraine-dammed and some others are created by glacial erosion. We assign all glacial lakes to two types: those in contact with glacier termini (TC) and those not (NC). There were ten TC lakes in 2013 at elevations between 4211 and 5269 m a.s.l., mostly fed by glaciers developed around the central BK massif (Fig. 1). The area of TC lakes varies from 0.08 to 0.89 km^2 (mean area of 0.42 km^2), generally larger than most of the 26 NC lakes (0.01–0.75 km^2 with mean area of 0.17 km^2). Comparison of size between a lake and its related glacier (i.e. that directly supplying meltwater to the lake) suggests that, for the TC lakes, larger glaciers tend to have larger proglacial lakes (Fig. 6a).

In 1981 there were only eight TC lakes in the BK, with a total area of 1.67 ± 0.21 km^2. In subsequent years, the number increased and reached 14 in 2002, but four lost contact with their glacier termini by 2013. The ten current TC lakes have a total area of 4.18 ± 0.23 km^2, much larger than that of the 16 NC lakes (2.78 ± 0.25 km^2). In 1981 and 1988, however, the total area of the TC lakes was less than that of the NC lakes. During 1981–2013, the TC lakes showed continuous area expansion, with a total area increase of 2.51 km^2, an expansion rate of ~150.30% (or ~4.7% a^{-1}). Conversely, the total area of the NC lakes increased slightly from 2.19 ± 0.38 km^2 in 1981 to 2.78 ± 0.25 km^2 in 2013, with a smaller range in area variation than for the TC lakes. From 1981 to 2013, the number of NC lakes increased by six, including four that were previously TC. It should be noted that some newly appeared lakes may be seasonally filled lakes. In total, the number of glacial lakes in the BK increased by eight between 1968 and 2013, and their total area expanded by 3.10 ± 0.54 km^2 (~80.31% of the area in 1981, or ~2.51% a^{-1}).

Figure 6b shows the surface profiles of the ten current lake-terminating glaciers along their central flowlines (Fig. 1b), and their lake area changes are illustrated in Figure 6c. The largest TC lake is Poge (lake 8), a moraine-dammed lake currently in contact with the terminus of Poge glacier on the southern slope of the BK. The lake surface is ~4320 m a.s.l. and it is now connected to a steep ice tongue, limiting its further expansion. Poge lake experienced slow expansion from 0.77 ± 0.07 to 0.90 ± 0.04 km^2 during 1981–2002, but in 2013 its area decreased slightly to 0.89 ± 0.04 km^2. There are four TC lakes (lakes 2, 4, 5 and 9) showing considerable area increase over the period of investigation. Lake 2 (fed by Shenmageinong glacier) and lake 5 (fed by Beijia glacier) show continuous expansion from 1981 to 2013, increasing in area by 0.35 km^2 (96.2%) and 0.57 km^2 (~272.7%), respectively. Lake 4 (fed by West Beijia Glacier) is a moraine-dammed lake newly formed after August 1998, since it is not identified in the Landsat images from 1981, 1994 and 1998. At the time of its first mapping in 2002, the area was 0.34 km^2, but the value nearly doubled in 2013. Lake 9 (fed by Zuxuehui glacier) also shows significant expansion during the period of investigation (Fig. 7). It was a small marginal lake dammed by an end moraine and its area was stable (~0.09 km^2) for at least ~20 years before 2002. Viewing lake 9 on the 2005 and 2010 Landsat images indicates that the lower part of the terminus has gradually become inundated by the lake water and was almost detached from the ice tongue in April 2010. By 2013, Zuxuehui glacier had lost a big block from its terminus and the lake had expanded considerably to 0.69 ± 0.04 km^2.

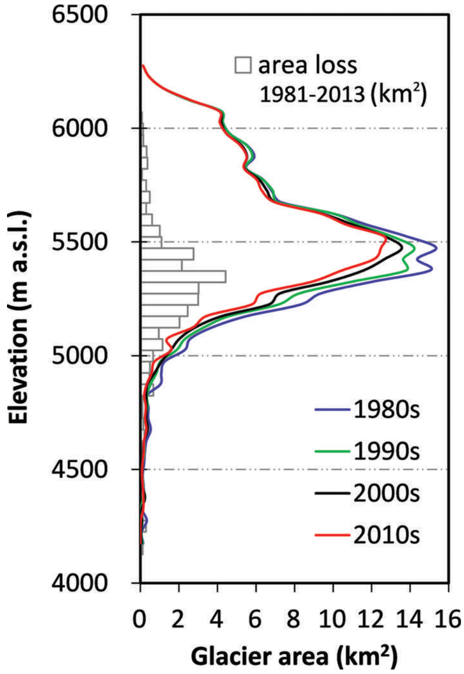

Fig. 5. Glacier hypsometry for each inventory period and the change between 1981 and 2013.

Table 4. Glacial lake inventory in the BK region and lake changes between 1981 and 2013

Time/period	Number	Total lake area	Maximum lake area	TC lakes		NC lakes	
				Number	Area	Number	Area
		km^2	km^2		km^2		km^2
1981	18	3.86 ± 0.59	0.77 ± 0.07	8	1.67 ± 0.21	10	2.19 ± 0.38
1988	22	4.20 ± 0.68	0.82 ± 0.07	10	1.97 ± 0.26	12	2.23 ± 0.42
1994	22	4.56 ± 0.71	0.88 ± 0.07	11	2.33 ± 0.29	11	2.23 ± 0.43
2002	25	5.38 ± 0.41	0.90 ± 0.04	14	3.14 ± 0.20	11	2.24 ± 0.21
2013	26	6.96 ± 0.48	0.89 ± 0.04	10	4.18 ± 0.23	16	2.78 ± 0.25
1981–2013	+8	$+3.10 \pm 0.54$	$+0.12 \pm 0.06$	+2	$+2.51 \pm 0.22$	+6	$+0.59 \pm 0.32$
Lake growth (dA%)	44.44	80.31 ± 13.99	15.58 ± 7.79	25.00	150.30 ± 13.17	60.00	26.94 ± 14.6
Lake growth rate (% a^{-1})	1.39	~2.51	~0.49	0.78	~4.70	1.88	~0.84

https://doi.org/10.3189/2016AoG71A415 Published online by Cambridge University Press

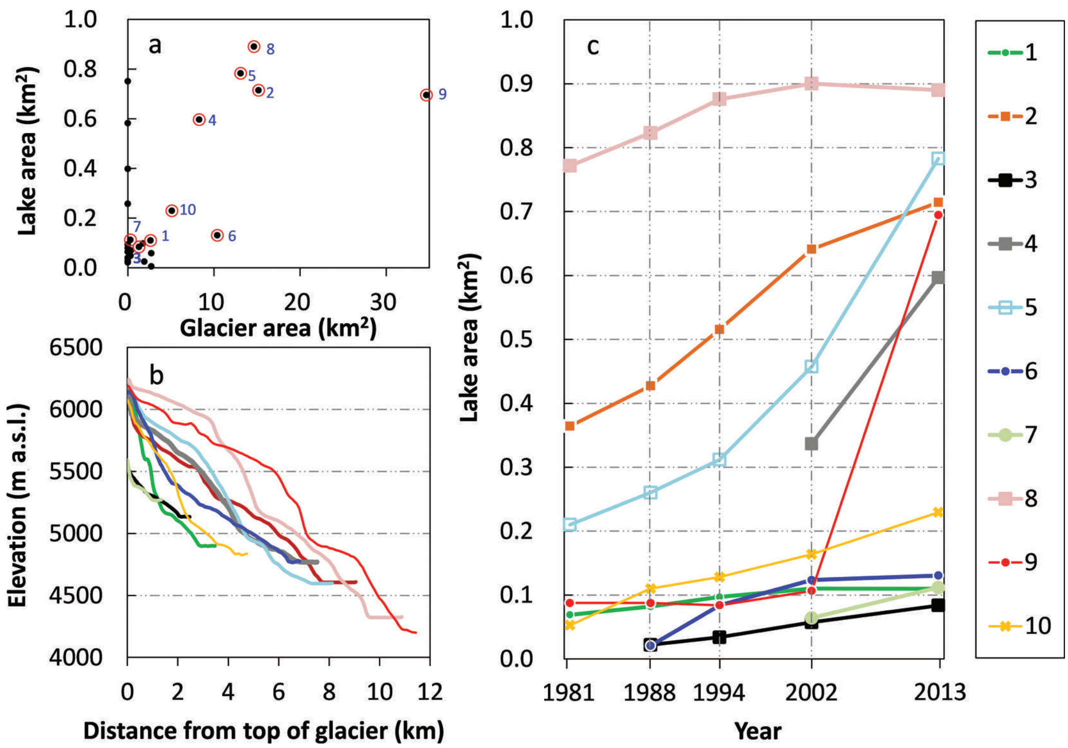

Fig. 6. Investigation of the ten TC lakes: (a) lake areas plotted against their feeding glacier area, with the ten TC lakes numbered and circled in red; (b) surface profiles along the central flowlines (Fig. 1b) of the ten glaciers; (c) area changes.

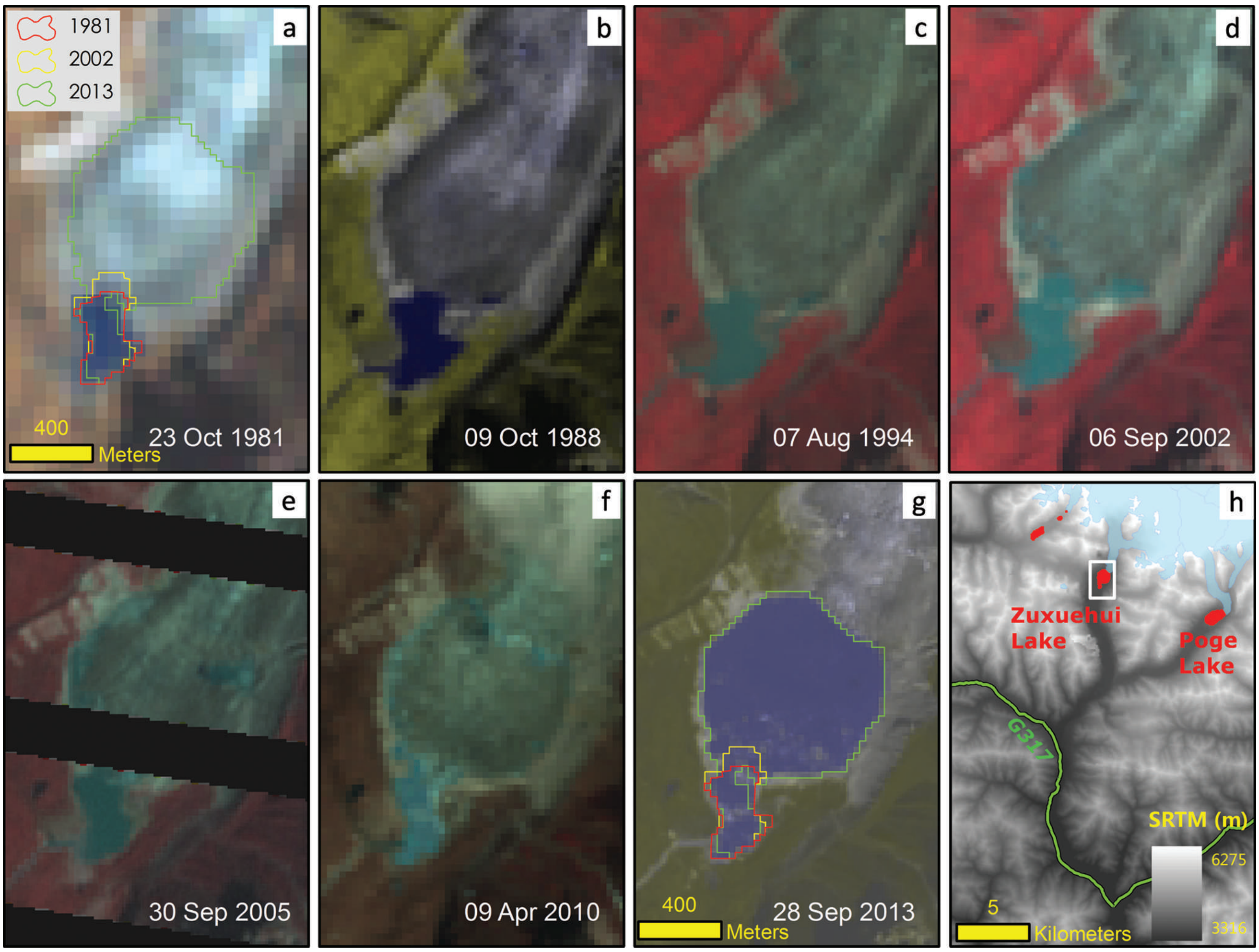

Fig. 7. (a–g) Expansion of Zuxuehui glacial lake between 1981 and 2013; (h) location of Zuexuehui and Poge glacial lakes in the upstream part of a valley crossed by highway G317.

https://doi.org/10.3189/2016AoG71A415 Published online by Cambridge University Press

DISCUSSION

Many studies have reported higher shrinkage rates of glaciers in the southern and eastern TP compared with those in the continental interior: annual glacier area loss rate in the southeastern TP was ~0.90% a^{-1} (129 glaciers, 1980–2001) (Yao and others, 2012), and was $0.27 \pm 0.15\%\,a^{-1}$ (5947 glaciers, 1970–2009) in the inner TP (Wei and others, 2014). The observed area loss of ~140 glaciers in the BK during 1981–2013 is ~0.48% a^{-1}, indicating a moderate glacier shrinkage rate in this transition zone. In the Lancang river basin, located east of the BK, a recent study (Liu and others, 2015) shows a higher glacier area loss rate of 0.75% a^{-1} (423 glaciers, 1970s–2010s). Based on the above regional comparisons and some other studies (e.g. Ding and others, 2006; Liu and others, 2006; Li and others, 2008; Bolch and others, 2012), we can confirm a decreasing gradient of glacier shrinkage rate from the southeastern to the inner TP. This regional gradient of glacier shrinkage rate can be related to changes in the atmospheric circulation patterns above and around the TP during the past few decades, as suggested by many recent studies (Yao and others, 2012; Mölg and others, 2013; Neckel and others, 2014). Glaciers in different precipitation regimes responded differently to changes in climate and shifts in precipitation seasonality (Maussion and others, 2014). Owing to considerable weakening of the summer monsoon (Wu, 2005; Xu and others, 2006) and strengthening of the westerlies (Mölg and others, 2013) during the past few decades, glacier mass balances are showing more negative trends in the southeastern than the inner TP (Neckel and others, 2014).

The spatial gradient of glacier area change rate in the TP is observed not only during recent decades but also since the culmination of the LIA. Su and Shi (2002) reported an overall ~23% area loss for monsoonal temperate glaciers in the southeastern TP between the LIA and the 1970s. In the Qilian mountains in the northeastern TP, glacier area shrinkage was estimated to be ~15% from the LIA to 1990 (Liu and others, 2003). Wang and Ding (2002) also suggested a moderate glacier shrinkage rate in the BK since the LIA, compared with the surrounding area.

However, individual glacier changes for any region show great variation. A trend toward stronger area loss for smaller glaciers has been presented in many previous studies (e.g. Shangguan and others, 2009; Bolch and others, 2010; Scherler and others, 2011) and also in this study (Fig. 5). The formation and expansion of proglacial lakes will also impact on individual glacier retreat rates (Sakai and others, 2009; Basnett and others, 2013), a fact that can be evidenced by the observed higher expansion rates of proglacial lakes compared with other lakes (Gardelle and others, 2011; Nie and others, 2013; Wang and others, 2013). Owing to the difference in the time period and the total number and area of lakes investigated, it is difficult to compare our results for changes of TC lakes with other regions in the Himalaya or the TP. However, for individual TC lakes, expansion rates in the BK (0.001–0.019 $km^2\,a^{-1}$ between 1981 and 2013) are generally lower than those in the Hindu Kush Himalaya (0.0001–0.0404 $km^2\,a^{-1}$ between 1990 and 2009) and the Bhutan Himalaya (0–0.037 $km^2\,a^{-1}$ between the 1960s and 2001) (Gardelle and others, 2011).

Considerable expansion of glacial lakes in the BK occurs together with glacier shrinkage. Recent formation and expansion of TC lakes in the BK may also have accelerated the retreat of lake-terminating glaciers. TC lakes in the BK show higher expansion rates than other lakes (Table 4), indicating that calving loss at the termini of their mother glaciers is a significant contribution to lake expansion. Some newly formed or previously small marginal lakes have expanded rapidly, resulting in striking retreat of their related glaciers. This glacier–lake positive feedback due to calving has been widely reported for lake-terminating glaciers in Patagonia (Venteris, 1999; Warren and Aniya, 1999) and the Southern Alps (Kirkbride and Warren, 1999; Warren and Kirkbride, 2003), and also for debris-covered glaciers in the Himalaya (Sakai and others, 2009; Sakai and Fujita, 2010; Benn and others, 2012). Of the ten lake-terminating glaciers in the BK, only four show continuous terminal retreat as well as lake expansion during our investigation period. The other six glacier–lake systems show relative stability as the potential for further growth of the lake is limited by the steep terrain (Fig. 6b). In some other cases, lake growth may be balanced by terminal advance. Confirming the latter case requires surveys at high temporal resolution, documenting the terminus positions and ice velocities (McNabb and others, 2015). This is beyond the scope of the present study, but is meaningful for further investigations since the terminal calving may account for non-negligible mass loss.

An important issue related to glacial lake expansion in the BK region is the potential risk of GLOFs. Generally, a GLOF hazard may arise when downstream human activities are exposed to the flood risk, which mainly depends on the downstream topography (Wang and others, 2012) and the potential outburst volume of the lake (Fujita and others, 2013). Historic GLOFs in the BK region were the outbursts of Poge lake (Liu and others, 2014) on 23 July 1972 (triggered by an ice avalanche) and in 1974 (date and triggers unknown). The outburst in 1972 destroyed a bridge on highway G371 (Lu and others, 1999). These two failures happened in the period of rapid lake expansion. Currently, Poge lake (lake 8) is relatively stable in size and is the largest lake in the southern BK. However, considering its 1968 glacier outline (Fig. 1b), the lake area expanded notably after 1968. Zuxuehui glacial lake (lake 9) is another recently expanded glacial lake not far upstream from highway G317. Since these two large lakes are both ~13 km from the highway (Fig. 7h), their evolution should be given more attention in future investigations. However, to assess their outburst probabilities (Richardson and Reynolds, 2000; Fujita and others, 2013; Wang and others, 2013) more detailed in situ surveys (Fujita and others, 2009) combined with remote sensing and modelling (Huggel and others, 2002; Westob and others, 2014) are necessary.

CONCLUSION

We have presented changes during the past three decades in glaciers and glacial lakes in the BK massif in a transition zone between the southeast and inner TP. A glacier shrinkage rate of ~0.48% a^{-1} averaged between the 1980s and the 2010s is in good agreement with the previously suggested spatial gradient of glacier area loss rate in the southeast TP. Glacial lakes in the BK experienced considerable expansion during the past few decades, but most of this was contributed by several proglacial lakes, which showed more rapid area increase than other lakes. Glaciers terminating in the TC lakes also show rapid area loss, indicating the interactions between lake growth and glacier retreat. Several rapidly expanding lakes show high risk of GLOFs, since iceberg calving may cause moraine dams to fail by wave erosion. Therefore close and intense monitoring is suggested for outburst flood risk assessments in this region.

AUTHOR CONTRIBUTION STATEMENT

Liu Qiao wrote most of the paper; Liu Shiyin, Xu Junli and Guo Wanqin compiled the first CGI data; Liu Qiao and Nie Yong collected Landsat images and mapped the glacier and lake boundaries for the four periods; Guo Wanqin extracted the attributes; Nie Yong, Liu Shiyin and Guo Wanqin helped in writing the paper.

ACKNOWLEDGEMENTS

This work was funded by the National Natural Science Foundation of China (41371094) and the National Science and Technology Support Program of Chinese MOST (2012BAC19B07 and 2013BAC10B01). The partial datasets used in the study were a result of an immediate past project from the MOST (2006FY110200). Satellite images were from the USGS and NASA. We thank K. Fujita, J.G. Cogley, W.C. Wang and an anonymous reviewer for constructive comments on the manuscript.

REFERENCES

Aizen VB and Helen L (1994) The existing conditions of the southeastern Tibet glacier. In Xie Z and Kotlyakov VM eds, *Glaciers and environment in the Qinghai–Xizang (Tibet) Plateau – The Gongga Mountain*. China Science Press, Beijing

Basnett S, Kulkarni AV and Bolch T (2013) The influence of debris cover and glacial lakes on the recession of glaciers in Sikkim Himalaya, India. *J. Glaciol.*, **59**(218), 1035–1046 (doi: 10.3189/2013JoG12J184)

Benn D and 9 others (2012) Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards. *Earth-Sci. Rev.*, **114**, 156–174 (doi: 10.1016/j.earscirev.2012.03.008)

Böhner J (2006) General climatic controls and topoclimatic variations in Central and High Asia. *Boreas*, **35**, 279–295 (doi: 10.1111/j.1502–3885.2006.tb01158.x)

Bolch T, Menounos B and Wheate R (2010) Landsat-based inventory of glaciers in western Canada, 1985–2005. *Remote Sens. Environ*, **114**(1), 127–137 (doi: 10.1016/j.rse.2009.08.015)

Bolch T and 11 others (2012) The state and fate of Himalayan glaciers. *Science*, **336**, 310–314 (doi: 10.1126/science.1215828)

Cheng Z, Zhu P, Dang C and Liu J (2008) Hazards of debris flow duo to glacier-lake outburst in southeastern Tibet. *J. Glaciol. Geocryol.*, **30**(6), 954–959 [in Chinese with English summary]

Ding Y and Liu J (1992) Glacier lake outburst flood disasters in China. *Ann. Glaciol.,* **16**, 180–184

Ding Y, Liu S, Li J and Shangguan D (2006) The retreat of glaciers in response to recent climate warming in western China. *Ann. Glaciol.*, **40**, 97–105 (doi: 10.3189/172756406781812005)

Fujita K (2008) Effect of precipitation seasonality on climatic sensitivity of glacier mass balance. *Earth Planet. Sci. Lett.*, **276**(1–2), 14–19 (doi: 10.1016/j.epsl.2008.08.028)

Fujita K and Ageta Y (2000) Effect of summer accumulation on glacier mass balance on the Tibetan Plateau revealed by mass-balance model. *J. Glaciol.*, **46**(153), 244–252 (doi: 10.3189/172756500781832945)

Fujita K and Nuimura T (2011) Spatially heterogeneous wastage of Himalayan glaciers. *Proc. Natl Acad. Sci.*, **108**(34), 14 011–14 014 (doi: 10.1073/pnas.1106242108)

Fujita K, Sakai A, Nuimura T, Yamaguchi S and Sharma RR (2009) Recent changes in Imja Glacial Lake and its damming moraine in the Nepal Himalaya revealed by in situ surveys and multi-temporal ASTER imagery. *Environ. Res. Lett.*, **4**(4), 045205 (doi: 10.1088/1748-9326/4/4/045205)

Fujita K and 6 others (2013) Potential flood volume of Himalayan glacial lakes. *Natur. Hazards Earth Syst. Sci.*, **13**(7), 1827–1839 (doi: 10.5194/nhess-13-1827-2013)

Gardelle J, Arnaud Y and Berthier E (2011) Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. *Global Planet. Change*, **75**, 47–55 (doi: 10.1016/j.gloplacha.2010.10.003)

Huggel C, Kaab A, Haeberli W, Teysseire P and Paul F (2002) Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. *Can. Geotech. J.*, **39**(2), 316–330 (doi: 10.1139/t01-0099)

Immerzeel WW, Van Beek LPH and Bierkens MFP (2010) Climate change will affect the Asian water towers. *Science*, **328**(5984), 1382–1385 (doi: 10.1126/science.1183188)

Jarvis A, Reuter HI, Nelson A and Guevara E (2008) *Hole-filled seamless SRTM data V4* International Centre for Tropical Agriculture (CIAT) http://srtm.csi.cgiar.org

Kang S, Xu Y, You Q, Flugel WA, Pepin N and Yao T (2010) Review of climate and cryospheric change in the Tibetan Plateau. *Environ. Res. Lett.*, **5**(1), 015101 (doi: 10.1088/1748-9326/5/1/015101)

Kirkbride MP and Warren CR (1999) Tasman Glacier, New Zealand: 20th-century thinning and predicted calving retreat. *Global Planet. Change*, **22**(1–4), 11–28

Komori J (2008) Recent expansions of glacial lakes in the Bhutan Himalayas. *Quat. Int.*, **184**, 177–186 (doi: 10.1016/j.quaint.2007.09.012)

Li J (1986) *The glaciers in Tibet*. Science Press, Beijing [in Chinese]

Li X and 9 others (2008) Cryospheric change in China. *Global Planet. Change*, **62**(3–4), 210–218 (doi: 10.1016/j.gloplacha.2008.02.001)

Liu J, Cheng Z and Su P (2014) The relationship between air temperature fluctuation and glacial lake. *Quat. Int.*, **321**, 78–87 (doi: 10.1016/j.quaint.2013.11.023)

Liu Q and 6 others (2010) Recent shrinkage and hydrological response of Hailuogou glacier, a monsoon temperate glacier on the east slope of Mount Gongga, China. *J. Glaciol.*, **56**(196), 215–224 (doi: 10.3189/002214310791968520)

Liu Q, Liu S and Guo W (2015) Glacier changes in the upper reaches of Lancang River Basin, China, between 1960–1970s and 2005–2010. *Arct. Antarct. Alp. Res.*, **47**(2), 95–104 (doi: 10.1657/AAAR0013-104)

Liu S, Sun W, Shen Y and Li G (2003) Glacier changes since the Little Ice Age maximum in the western Qilian Shan, northwest China, and consequences of glacier runoff for water supply. *J. Glaciol.*, **49**(164), 117–124 (doi: 10.3189/172756503781830926)

Liu S and 8 others (2006) Glacier changes during the past century in the Gangrigabu mountains, southeast Qinghai–Xizang (Tibetan) Plateau, China. *Ann. Glaciol.*, **43**, 187–193 (doi: 10.3189/172756406781812348)

Lu R, Tang D and Zhu P (1999) *Debris flows and environment in Tibet*. Chengdu Science and Technology University Press, Chengdu [in Chinese]

Lutz AF, Immerzeel WW, Shrestha AB and Bierkens MFP (2014) Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, **4**, 587–592 (doi: 10.1038/NCLIMATE2237)

Maussion F, Scherer D, Mölg T, Collier E, Curio J and Finkelnburg R (2014) Precipitation seasonality and variability over the Tibetan Plateau as resolved by the High Asia Reanalysis. *J. Climate*, **27**(5), 1910–1927 (doi: 10.1175/JCLI-D-13-00282.1)

McNabb RW, Hock R and Huss M (2015) Variations in Alaska tidewater glacier frontal ablation, 1985–2013. *J. Geophys. Res. Earth Surf.*, **120**(1), 120–136 (doi: 10.1002/2014jf003276)

Mölg T, Maussion F and Scherer D (2013) Mid-latitude westerlies as a driver of glacier variability in monsoonal High Asia. *Nature Climate Change*, **4**, 68–73 (doi: 10.1038/NCLIMATE2055)

Neckel N, Kropácek J, Bolch T and Hochschild V (2014) Glacier mass changes on the Tibetan Plateau 2003–2009 derived from ICESat laser altimetry measurements. *Environ. Res. Lett.*, **9**, 014009 (doi: 10.1088/1748-9326/9/1/014009)

Nie Y, Liu Q and Liu S (2013) Glacial lake expansion in the Central Himalayas by Landsat images, 1990–2010. *PLoS One,* **8**, e83973 (doi: 10.1371/journal.pone.0083973)

Nuimura T and 12 others (2015) The GAMDAM Glacier Inventory: a quality controlled inventory of Asian glaciers. *Cryosphere*, **9**, 849–864 (doi: 10.5194/tc-9-849-2015)

Paul F, Kääb A, Maisch M, Kellenberger T and Haeberli W (2002) The new remote-sensing-derived Swiss glacier inventory: I. Methods. *Ann. Glaciol,* **34**, 355–361 (doi: 10.3189/172756402781817941)

Paul F and 9 others (2009) Recommendations for the compilation of glacier inventory data from digital sources. *Ann. Glaciol.*, **50**(53), 119–126 (doi: 10.3189/172756410790595778)

Radić V and Hock R (2014) Glaciers in the Earth's hydrological cycle: assessments of glacier mass and runoff changes on global and regional scales. *Surv. Geophys.*, **35**, 813–837 (doi: 10.1007/s10712-013-9262-y)

Richardson SD and Reynolds JM (2000) An overview of glacial hazards in the Himalayas. *Quat. Int.*, **65–66**, 31–47 (doi: 10.1016/S1040-6182(99)00035-X)

Sakai A and Fujita K (2010) Formation conditions of supraglacial lakes on debris-covered glaciers in the Himalayas. *J. Glaciol.*, **56**(195), 177–181 (doi:10.3189/002214310791190785)

Sakai A, Nishimura K, Kadota T and Takeuchi N (2009) Onset of calving at supraglacial lakes on debris-covered glaciers of the Nepal Himalaya. *J. Glaciol.*, **55**(193), 909–917 (doi: 10.3189/002214309790152555)

Scherler D, Bookhagen B and Strecker MR (2011) Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geosci.*, **4**, 156–159 (doi: 10.1038/ngeo1068, 2011)

Shangguan D, Liu S, Ding Y, Ding L, Xu J and Jing L (2009) Glacier changes during the last forty years in the Tarim Interior River basin, northwest China. *Progr. Natur. Sci.*, **19**(6), 727–732 (doi: 10.1016/j.pnsc.2008.11.002)

Shi Y (2008) *Concise glacier inventory of China*. Shanghai Popular Science Press, Shanghai

Su Z and Shi Y (2002) Response of monsoonal temperate glaciers to global warming since the Little Ice Age. *Quat. Int.*, **97–98**, 123–131 (doi: 10.1016/S1040-6182(02)00057-5)

Venteris ER (1999) Rapid tidewater glacier retreat: a comparison between Columbia Glacier, Alaska and Patagonian calving glaciers. *Global Planet. Change*, **22**(1–4), 131–138

Wang N and Ding L (2002) Study on the glacier variation in Bujiagangri section of the east Tanggula Range since the Little Ice Age. *J. Glaciol. Geocryol.*, **24**(3), 234–244 [in Chinese with English summary]

Wang W, Yao T and Yang X (2011) Variations of glacial lakes and glaciers in the Boshula mountain range, southeast Tibet, from the 1970s to 2009. *Ann. Glaciol.*, **52**(58), 9–17 (doi: 10.3189/172756411797252347)

Wang W, Yang X and Yao T (2012) Evaluation of ASTER GDEM and SRTM and their suitability in hydraulic modelling of a glacial lake outburst flood in southeast Tibet. *Hydrol. Process.*, **26**, 213–225 (doi: 10.1002/hyp.8127)

Wang and 6 others (2013) Changes of glacial lakes and implications in Tian Shan, central Asia, based on remote sensing data from 1990 to 2010. *Environ. Res. Lett.*, **8**, 044052 (doi: 10.1088/1748-9326/8/4/044052)

Warren C and Aniya M (1999) The calving glaciers of southern South America. *Global Planet. Change*, **22**, 59–77 (doi: 10.1016/S0921-8181(99)00026-0)

Warren CR and Kirkbride MP (2003) Calving speed and climatic sensitivity of New Zealand lake-calving glaciers. *Ann. Glaciol.*, **36**, 173–178 (doi: 10.3189/172756403781816446)

Wei J and 6 others (2014) Surface-area changes of glaciers in the Tibetan Plateau interior area since the 1970s using recent Landsat images and historical maps. *Ann. Glaciol.*, **55**(66), 213–222 (doi: 10.3189/2014AoG66A038)

Westob MJ, Glasser NF, Brasington J, Hambrey MJ, Quincey DJ and Reynolds JM (2014) Modelling outburst floods from moraine-dammed glacial lakes. *Earth-Sci. Rev.*, **134**, 137–158 (doi: 10.1016/j.earscirev.2014.03.009)

Wu B (2005) Weakening of Indian summer monsoon in recent decades. *Adv. Atmos. Sci.*, **22**(1), 21–29 (doi: 10.1007/BF02930866)

Xu M and 6 others (2006) Steady decline of east Asian monsoon winds, 1969–2000: evidence from direct ground measurements of wind speed. *J. Geophys. Res.*, **111**, D24111 (doi: 10.1029/2006JD007337)

Yang W, Yao T, Xu B, Wu G, Ma L and Xin X (2008) Quick ice mass loss and abrupt retreat of the maritime glaciers in the Kangri Karpo Mountains, southeast Tibetan Plateau. *Chinese Sci. Bull.,* **53**(16), 2547–2551 (doi: 10.1007/s11434-008-0288-3)

Yao T and 14 others (2012) Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change*, **2**, 663–667 (doi: 10.1038/NCLIMATE1580)