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Estimation of lakes water storage and their changes on the northwestern Tibetan Plateau based on bathymetric and Landsat data and driving force analyses

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Lake water storage changes in four lakes were analyzed based on in situ bathymetric survey data and Landsat images in the extremely dry and cold northwestern Tibetan Plateau region. The results indicated that Bangdag Co and Aksai Chin Lake, which are glacier-fed and closed lakes, showed decreasing trends from 1976 to 1996, then increasing trend from 1996 to 2015, during which period water storage increased by 1.24 km^3 and 1.37 km^3, respectively, and 65% of the water storage increase in Aksai Chin Lake during this period occurring in 2006 and 2013. Longmu Co, which is a non-glacier-fed lake, exhibited little variation from 1976 to 1996 and a slight increase of 0.1 km^3 from 1996 to 2015. The precipitation, temperature and potential evaporation (Ep) trends indicated that lake shrinkage from 1976 to 1996 was attributed to less precipitation and less meltwater at lower surface air temperatures. Decreased Ep (15.5 mm/y) contributed approximately 2% and 4% to the lake expansion of Aksai Chin Lake and Bangdag Co from 2000 to 2009. Based on the assumption of equal precipitation-evaporation for the study area, glacial meltwater contributed 76.6% to the lake expansion of Bangdag Co from 2000 to 2015. Because change in lakes' water storage showed a large difference between glacier-fed lakes and non-glacier-fed lakes from 1996 to 2015 under relatively high precipitation conditions, it is suggested that glacial meltwater exerted more influence on increasing lake water storage associated with rising temperatures.

1. Introduction

The Tibetan Plateau (TP) is known as the “Asian water tower” because many major rivers in Asia originate there (Immerzeel et al., 2010), e.g. the Yellow River, Yangtze River, and Brahmaputra River, which nourish hundreds of millions of people in Asia. There are a large number of glaciers and lakes that have considerable influence on surface runoff on the TP under warming climate. Lake water and glacial meltwater, which is located in exorheic basin, can be transmitted to fluvial systems and outflow from the TP, but for endorheic basins, glacial meltwater can directly contribute to lakes, and lake water is only removed by surface water evaporation and a portion likely becomes groundwater. On the one hand, increased glacial meltwater with rising temperatures maybe lead to glacial lake outburst floods on the southern TP, which threaten life and property as well as critical road infrastructure (Song et al., 2016). Lake expansion also floods pasture and causes a large economic loss to local herdsman. On the other hand, the changes in area and water storage of inland lakes may have significant influences on regional water and energy cycles (Yang et al., 2014). Therefore, it is important to elucidate the causes of lake changes on the TP.

Many studies have focused on the area and water level changes in TP lakes over the past decades, and inland lake area expansion has been observed via large-scale remote sensing investigations (Li

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et al., 2014b; Phan et al., 2012; Wang et al., 2013; Song et al., 2014a, 2014b; Zhang et al., 2011b, 2014). In contrast, most lakes on the southern TP shrank slightly (Lei et al., 2014; Song et al., 2013; Wang et al., 2013; Zhang et al., 2011b). Precipitation is generally considered as the main reason for lake expansion (Lei et al., 2013; Song et al., 2014b; Zhou et al., 2015) because it has increased considerably over the past decades, especially on the central TP (Xu et al., 2008). The decreased lake evaporation is also beneficial to rapid water level increases (Ma et al., 2016, e.g. at Nam Co) due to near-surface wind speed declines (McVicar et al., 2010, 2012). However, most glaciers have experienced serious shrinkage on the TP, especially in the Himalayas (Yao et al., 2012). For example, mass balance of Dongkemadi glacier was −421.2 mm/y based on ICESat data (Ice, Cloud and Land Elevation Satellite) (Ke et al., 2015a). Increasing glacial meltwater under rising temperature conditions could make an important contribution to lake expansion (Li et al., 2014a; Meng et al., 2011; Zhang et al., 2011b, 2015; Zhu et al., 2010). For example, Zhu et al. (2010) quantified the proportions of different factors that affected the water balance of Nam Co and indicated that although precipitation played a dominant role in maintaining the water balance, the increase in glacial meltwater accounted for 50.6% of the water storage change. A comparison of the difference between changes in glacier-fed glaciers and non-glacier-fed lakes in the Tanggula Mountains indicated that glacial meltwater made a contribution to lake expansion that was equivalent to that of precipitation-evaporation (Song and Sheng, 2016). Because most lakes expansion has occurred in the inland area of the TP where permafrost is widely distributed and glaciers are less retreated, Li et al. (2014b) speculated that the main reason for inland TP lake expansion was permafrost degradation. The results of Zhou et al. (2013) indicated that the large water imbalance was explained by water seepage in Nam Co based on hydrological observations. Therefore, the reasons for lake changes on the TP are still fraught with uncertainty and need further study.

Although the changes in lake area (Wan et al., 2014; Zhang et al., 2014, 2015) and lake level (Phan et al., 2012; Song et al., 2014a; Zhang et al., 2011b) on the TP have been widely studied, researches on lake water storage change (Lei et al., 2013; Song et al., 2013, 2014a; Yang et al., 2017; Zhang et al., 2013) are still insufficient, let along the study on the absolute lake water storage (Zhang et al., 2011a). The heat storage of the water body is depended upon the water storage, because the variation of lake heat storage is an important component to estimate evaporation for a deep lake (McMahon et al., 2013), understanding of lake water storage and its variation are very important in the analysis of water balance. However, due to the lack of bathymetric data to estimate water storage, water storage of most lakes on the TP is unknown. In Table 1, we have summarized lake change researches of TP over the past decades, and found that the studies of lake water storage are still insufficient due to the lack of bathymetric data.

The variations in lake water storage are essential responses of lakes to climatic changes, which is better response than lake area change due to different topographic conditions. For example, a lake with steep basin slopes may experience less area change than a lake in a gently sloping basin, even though the former receives more water inflow. In addition, the particle of the lake sediments is also an important factor influencing the change in lakes' levels, and a lake would increase less in a lake with coarse coast, which would allow the water to inflow into groundwater, than in lake with finer particles, given that both receive equal water inflow. Satellite radar altimetry data can be effectively used to estimate lake level changes and calculate lake water storage changes. Although some types of satellite data (e.g., Jason-1, ERS-1/2, TOPEX and ENVISAT) cover long timescales from 1991 to present, the accuracies of altitudinal data are limited due to their large footprints of several kilometers. Therefore, these data can only be used for large lakes (e.g., Nam Co, Siling Co and Qinghai Lake). ICESat has been widely used to study lake level changes (Li et al., 2014b; Phan et al., 2012; Song et al., 2013; Wang et al., 2013; Zhang et al., 2011b). Although the footprint of ICESat data is as small as 70 m, the time sequence only covers a short period (2003–2009); thus, it is difficult to accurately detect changes in water level and water storage over long timescales. However, if the bathymetric distribution and topography of a lake basin are known, it is possible to estimate the water storages under different lake area (corresponding with certain lake level altitude) conditions and construct the relationships between lake area and water storage changes. Therefore, the long-term changes in lake water storage can be estimated because the lake areas can be extracted from long-term Landsat satellite images.

The southern slope of the west Kunlun Mountains and eastern slope of the east Karakorum Mountains, which are situated in the northwestern part of the TP, contain a number of endorheic lake basins and polar-type glaciers. Despite most glaciers on the TP have experienced obviously serious decreases trend in area in recent decades (Bolch et al., 2010; Kääb et al., 2012; Wei et al., 2014; Yao et al., 2012), the mass balance of glaciers in the Pamir and Karakoram regions showed a slight mass gain (Gardelle et al., 2013), which is called the “Pamir-Karakoram anomaly”. Because precipitation in this region is generally the lowest on the TP (Zheng, 1998) and has exhibited increasing trends due to the strengthened westerlies (Yao et al., 2012), it is important to determine if the glacial meltwater in this region makes much more important contribution to fluvial system than precipitation. This is helpful for understanding the responses of lakes to recent climatic change.

In this paper, we study four lakes with bathymetric data (Gozha Co, Aksai Chin Lake, Bangdag Co and Longmu Co) on the northwestern TP as a case study to estimate water storage in 2015, and we combine these data with multi-temporal Landsat images to estimate water storage changes from 1976 to 2015. The purposes of this study are, based upon the analyses of the underwater topographic characteristics and water storage estimations, (1) to reconstruct the lake water storage and water level changes from 1976 to 2015; (2) to estimate the contribution of glacial meltwater to lake expansion; and (3) to analyze the possible linkage between lake changes and climate factors.

2. Study area

The study area is located on the northwestern TP, which is on the southern slope of the western Kunlun Mountains (WKM). There is a dense distribution of polar-type glaciers over the WKM (Huang, 1990) that are mainly affected by mid-latitude westerlies (Bolch et al., 2012). The region consists of 537 glaciers (>0.02 km^2), with a total area of 3137 km^2 in 2013. The well-known Guliya Ice Cap (over 370 km^2), which is the largest ice cap in the Kunlun Mountain ranges, is located in the eastern of the region (Ke et al., 2015b). Previous results indicated that the total glacier area of WKM decreased by 16.83 km^2 (1.53 km^2/y) from 1990 to 2011, but some individual glaciers showed advancing trends in the region (Li et al., 2013). However, according to the ICESat elevation data, glaciers in the WKM showed mass gain, with a mean rate of increase in surface elevation of 0.17 ± 0.15 m/a (Gardner et al., 2013). This rate ranged from −0.4 ± 0.2 m/y to 0.7 ± 24 m/y from 2003 to 2008, the glaciers in the northern slope of WKM showed a thickening trend, but several glaciers in the southern of WKM, which supplied Aksai Chin and Gozha Co, showed a thinning trend (Ke et al., 2015b). Lei et al. (2014) theorized that lakes expansion was not significantly associated with glacial meltwater in this region based on the results of Neckel et al. (2014) which the glaciers of WKM showed a slightly positive mass balance.

Table 1
Summary of relevant researches about lake change on the Tibetan Plateau. "Key results" includes four components: 1, calculating lake area; 2, calculating lake level; 3, calculating lake water storage change; 4, calculating lake water storage. N/A represents "not dealt" in this research.

Study	Data	location	Key results
1.Wan et al. (2014)	Landsat/CBERS CCD	Tibetan Plateau	1, total area of 1055 lakes (>1 km^2) was 41,831.72 km^2 in 2005–2006 2, N/A 3, N/A 4, N/A
2.Zhang et al. (2014)	Landsat	Tibetan Plateau	1, 32,843 lakes (>0.001 km^2) with a total area of 43,151.08 km^2, which makes up 1.4% of the total area of the Tibetan Plateau 2, N/A 3, N/A 4, N/A
3.Zhang et al. (2015)	Landsat	Tibetan Plateau	1, 5701 glacial lakes (>0.003 km^2) covered 682.4 km^2 in 2010 2, N/A 3, N/A 4, N/A
4.Phan et al. (2012)	ICESat	Tibetan Plateau	1, N/A 2, average increase in lake level of 0.2 m/year 3, N/A 4, N/A
5.Song et al. (2014a)	ICESat	Tibetan Plateau	1, N/A 2, most lakes showed large water-level increases in warm seasons, declines or minor fluctuations in cold seasons 3, N/A 4, N/A
6.Song et al. (2013)	Landsat/ICESat	Tibetan Plateau	1, most lakes experienced shrinkage during 1970–1990, but most lakes experienced expansion 2, most lakes showed significant upward tendency (0.2–0.6 m/y) 3, lake water storage increased by 92.43 km^3 between the early 1970s and 2011 based on an empirical model 4, N/A
7.Zhang et al. (2011b)	ICESat	Tibetan Plateau	1, N/A 2, the mean lake water level increase rate is 0.23 m/y for the 56 salt lakes 3, N/A 4, N/A
8.Zhang et al. (2013)	Landsat/ICESat	Ten largest lakes in China	1, lake area of Selin Co increased by 32.59 km^2/y during 2003–2009 2, lake level of Bositeng Lake decreased by 0.43 m/y during 2003–2009 3, water storage of Selin Co, Nam Co, Qinghai Lake increased by 9.08 km^3, 4.07 km^3 and 2.88 km^3 during 2003–2009 4, N/A
8.Lei et al. (2013)	Landsat/bathymetric data	Six closed lakes on the central Tibetan Plateau	1, total area of six lakes expanded by 20.2% during 1976–2010 2, average lake level increase of six lakes was 8.7 m during 1976–2010 3, total water storage increased by 37.7 km^3 during 1976–2010 4, N/A
9.Zhang et al. (2011a)	Landsat/CBERS-CCD/HJ-CCD/bathymetric data	Nam Co	1, lake expansion from 1927 km^2 to 2015 km^2 during 1976–2009 2, N/A 3, lake water storage expansion with a tendency value of 0.267 km^3/y during 1976–2009 4, lake water storage was 87 km^3 in 2009
10.Yang et al. (2017)	Landsat/bathymetric	113 lakes with area great than 50 km^2 in the Tibetan Plateau	1, for calculating variations of lake water storage 2, N/A 3, total water storage increased 102.64 km^3 during 1976–2013 with an average annual rate of 2.77 km^3/y. 4, N/A.
11.This study	Landsat/bathymetric	Four lakes in the northwestern of Tibetan Plateau	1, lake area of Bangdag Co and Aksai Chin increased by 2.2 km^2/y and 5.2 km^2/y from 1996 to 2015, respectively 2, lake level of Bangdag Co and Aksai Chin increased by 11.2 m and 6.2 m from 1996 to 2015, respectively 3, lake water storage of Bangdag Co and Aksai Chin increased by 1.24 km^3 and 1.372 km^2 from 1996 to 2015 from 1996 to 2015, respectively. 4, Lake water storage of Gozha Co, Longmu Co, Bangdag Co and Aksai Chin was 14.3 km^3, 2.78 km^3, 2.6 km^3 and 2.57 km^3 in 2015, respectively.

For the four lakes we studied, three of them (Aksai Chin Lake, Longmu Co and Bangdag Co) are closed lakes, and Gozha Co is an upstream lake of Aksai Chin Lake which supplies Aksai Chin Lake through a large river (Fig. 1). As shown in Fig. 1, several large rivers originate from glaciers in the southern of WKM, which supply Aksai Chin Lake and Gozha Co. Two large rivers originate from glaciers that are located in the southern of Woerbajiu Co, Woerbajiu Co is a large upstream lake that supplies Bangdag Co through a large river. There are nearly no permanent residents in this area, and the Shiquanhe town, with approximately 20,000 people, is located approximately 200 km away. Therefore, these lakes are less influenced by human activities, and lake variations are only caused by climate change. Long-term meteorological records are extremely scarce in this climatic zone, which has only two weather stations. According to the China Meteorological Forcing Dataset (CMFD), the mean annual precipitation and annual mean temperature were 90 mm and −12.9 °C from 1979 to 2013, respectively which indicated extremely dry and cold conditions.

There are large amount glaciers providing glacial meltwater to input Aksai Chin, Gozha Co and Bangdag Co. From the Landsat

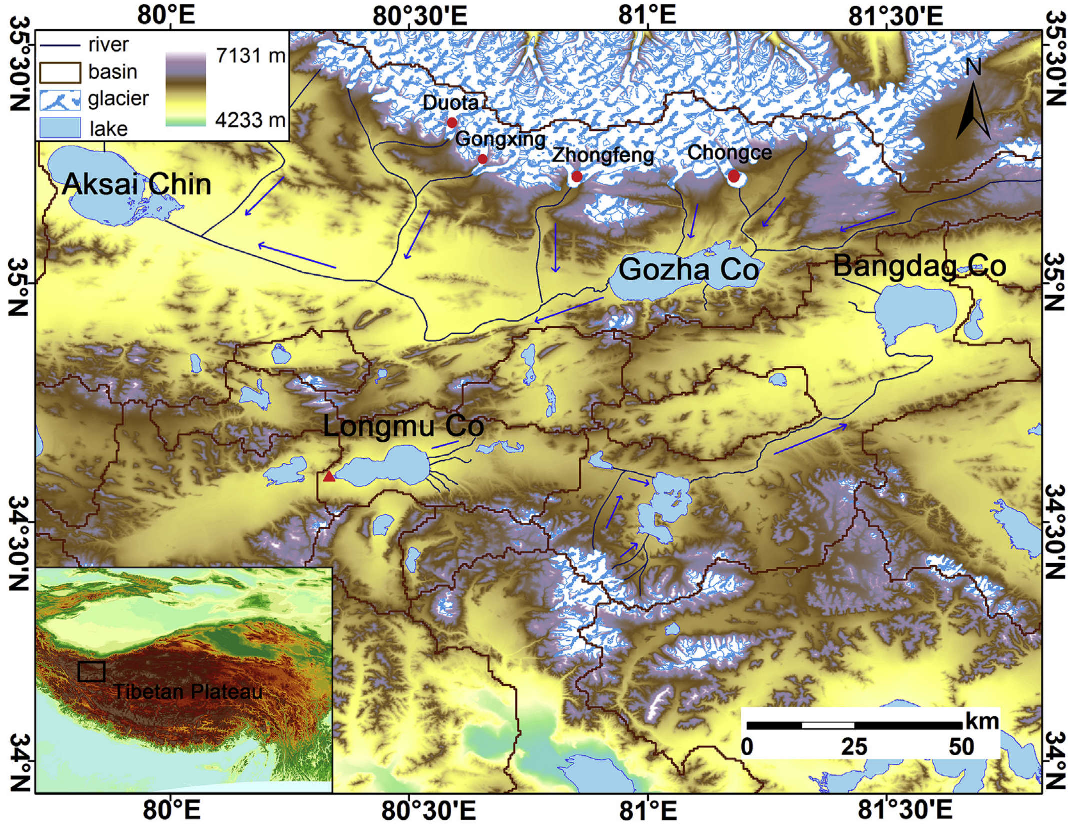

Fig. 1. Location of study area and the spatial distribution of lakes and glaciers. The blue arrow is the water flow direction. The solid red circles and red triangle represent the location of glaciers and springs, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

images of 2015, the glacier area of Aksai Chin basin and Bangdag Co basin were 1228.7 km^2 and 99.3 km^2 while their drainage basin areas are 10,718 km^2 and 3613 km^2. Glacial meltwater maybe make an important influence on these lakes with rising temperature. However, glacier area of Longmu Co was only 11.1 km^2 in its 957 km^2 drainage basin area, we consider Longmu Co as non-glacier-fed lakes.

3. Data and methods

3.1. Multi-temporal Landsat images for lake and glacier area extraction

Landsat Multispectral Scanner (MSS)/Thematic Mapper (TM)/ Enhanced Thematic Mapper Plus (ETM+)/Operational Land Image (OLI) images were used to extract lake areas for 1976, 1991, 1994, 1996 and 2000 to 2015, and all images were downloaded from the U.S. Geological Survey (USGS) (http://glovis.usgs.gov) and the Geospatial Data Cloud, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn). The results of Song et al. (2014a) showed that the water level of most lakes on the TP had a large increase in warm seasons (March–October) and had declines or minor fluctuations in cold seasons (November–February), but that some lake levels also rose in the cold season due to snow meltwater. To compare the inter-annual changes and reduce the influence of seasonal variations, only the images obtained between September and November were selected, during which period most lake levels are at their highest level, and even though glacier-fed lakes also exhibit increased water levels at the end of cold seasons (Song et al., 2014a), we can compare the lake area change of a lake for the past decades. The highest quality images with fewer clouds and snow were prioritized, and the detailed information about the images used is shown in Supplement 1. The Normalized Difference Water Index (NDWI) is used to extract lake area (Mcfeeters, 1996), we used the equation NDWI=(Green-NIR)/(Green + NIR), Green and NIR are the green band and near infrared band (Band 2 and Band 4 for TM/ETM+, Band 3 and Band 5 for OLI), respectively. We used the TM3/TM5 band ratio method for the TM/ETM + instruments (Band 4/Band6 for OLI) with a threshold of 2 to extract glacier outlines, this method is most appropriate for mapping glacier outlines for large regions (Bolch et al., 2010, 2012; Paul et al., 2009; Xiang et al., 2014). We calculated glaciers area changes and analyzed glacier area changes in 1976, 1991, 1996, and from 1999 to 2015. All these data were projected in the Albers Conical Equal Area coordinate system.

3.2. Bathymetric data for estimating water storage

Bathymetric data from four lakes were surveyed in situ in September 2015. The bathymetric device was a Lowrance HDS5, which has a vertical accuracy of 0.01 m, and bathymetric data was recorded once per second. The measured route on the four lakes is shown in Fig. 2. The underwater lake topography was established with grid units of 56 m × 56 m using the spatial analyst tools (Topo to Raster) in ArcGIS 9.3 based on the bathymetric data from a total of 0.38 million measurement points in the four lakes. Topo to Raster is an interpolation method designed for the creation of hydrological correct digital elevation model (DEM). The tool was developed by Hutchinson, (1988, 1989) and uses an iterative finite difference interpolation technique. For testing the accuracy of the interpolation, we used a large proportion of bathymetric data in Bangdag Co to establish the underwater lake topography, and the remaining

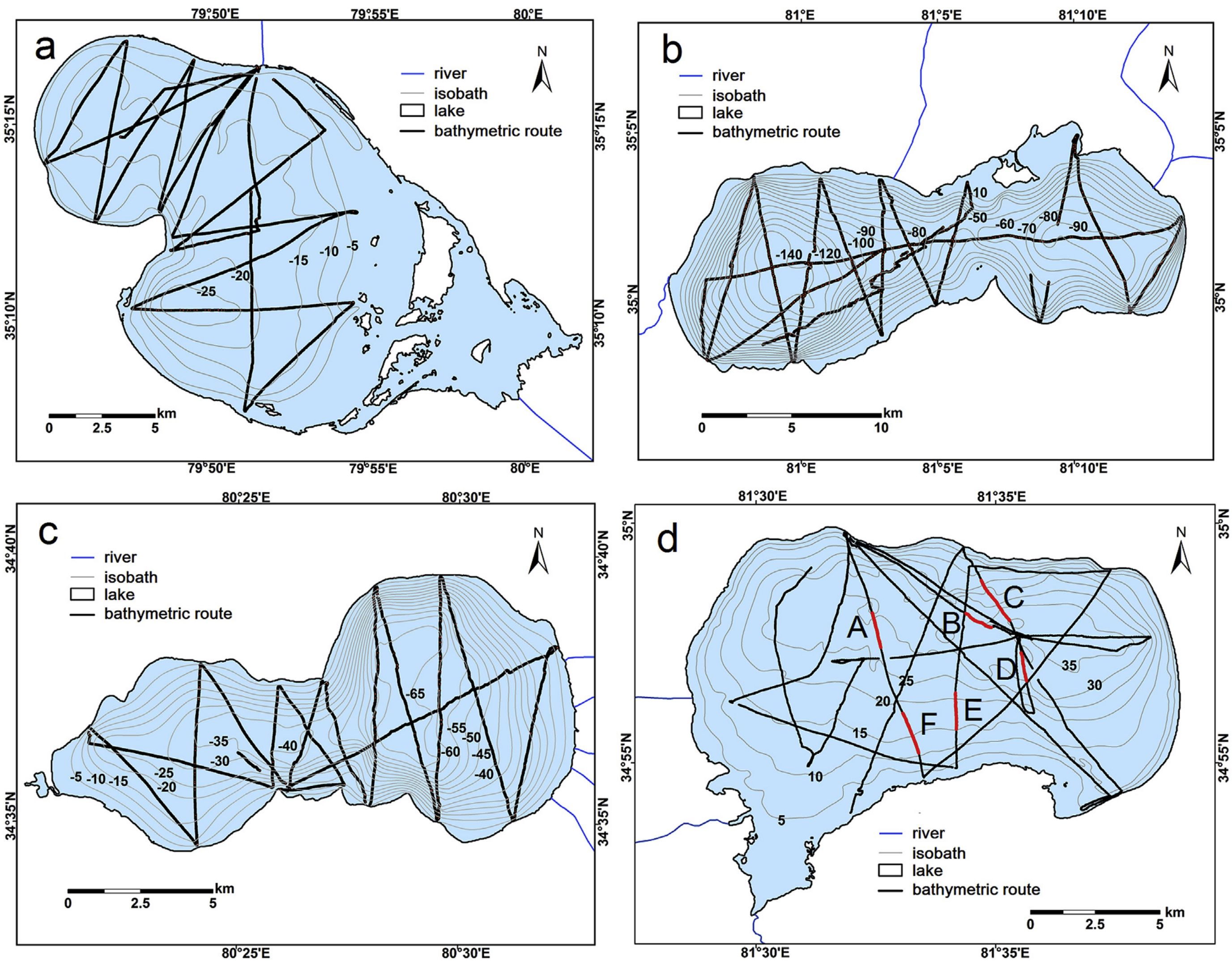

Fig. 2. The bathymetric survey routes (black thick line) and isobaths (gray thin line) of the four lakes. a, Aksai Chin Lake; b, Gozha Co; c, Longmu Co; d, Bangdag Co. The red line represents the removed portion in Bangdag Co and remaining data is used to establish the underwater lake topography. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

bathymetric data to test the accuracy. For example, as shown Fig. 2d, we have made 6 times interpolation to construct bathymetric map, and each time the data of one of the red lines was not involved to be interpolated but for accuracy testing, respectively. Table 2 listed the difference of the 6 times interpolation results, and indicated that the interpolation method was suitable for use in this filed with an average difference less than 1.6 m.

The detailed information about the bathymetric characteristics and related results for the four lakes are shown in Table 3. By using the underwater topography, the water storage and lake areas can be estimated based on given lake's depth by using the “Area and Volume” tool in 3D Analyst in ArcGIS 9.3. Using this method, lake water storage and lake depth data were obtained based on the known lake areas.

Table 2
Comparison of the difference of six portions between the result s of interpolation by removing a portion of data and in-situ bathymetry data.

	Max difference (m)			Min difference (m)			Average depth of in-situ (m)	Average difference (m)
	In-situ	Interp.	Diff.	In-situ	Interp.	Diff.		
A	24.82	28.7	3.88	29.56	29.56	0	29.16	0.78
B	24.86	29.75	4.89	26.16	26.17	0.01	27.76	1.6
C	28.16	33.91	4.25	34.19	34.19	0	33.58	1.05
D	31.39	34.37	2.98	30.35	30.35	0	31.86	1.22
E	16.87	18.4	1.53	15.7	15.7	0	17.78	0.75
F	12.43	14.1	1.68	16.89	16.89	0	15.04	0.28

“Interp.” represents “Interpolation”, “Diff.” represents “Difference”.

Table 3
Bathymetric characteristics and related results of four lakes in 2015.

	Gozha Co	Longmu Co	Bangdag Co	Aksai Chin
Maximum depth (m)	149.53	69.87	48.52	29.06
Average depth (m)	58.58	25.99	23.8	8.97
Water storage (km^3)	14.30	2.78	2.60	2.57
Area (km^2)	248.44	106.48	145.57	264.98
Bathymetric points (million)	7.44	4.93	16.83	9.07

3.3. The meteorological data used to analyze the causes of lake variation

Temperature and precipitation data during the study period are from the CMFD. This dataset, covering 1979–2012, was developed by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (He and Yang, 2011) based on meteorological data from 740 stations operated by the China Meteorological Administration (CMA), Princeton meteorological forcing data (Sheffield et al., 2006) and the Tropical Rainfall Measuring Mission (TRMM) 3B42 precipitation products (Huffman et al., 2007). The dataset includes near-surface temperature, pressure, wind speed and specific humidity with temporal and spatial resolutions of 3 h and 0.1°, respectively.

The Penman equation (Penmen, 1948) has been widely and successfully used for estimating open-water evaporation (McMahon et al., 2013). Because actual evaporation is difficult to acquire on the TP, we use the Penman equation to estimate the potential evaporation (Ep) of lake surface water based on data from 56 meteorological stations on the TP and estimate their spatial distribution using the Kriging interpolation method in ArcGIS 9.3. The daily maximum and minimum temperatures, relative humidity, sunshine duration and wind velocity at each meteorological station were used to calculate Ep from 1976 to 2013:

$$Ep = \frac{\Delta}{\Delta + \gamma}\frac{Rn}{\lambda} + \frac{\gamma}{\Delta + \gamma}\frac{6430(1 + 0.536u2)D}{\lambda} \quad (1)$$

where Rn is daily net radiation (mm/d); $\triangle$ is the slope of the saturation vapour pressure curve (KPa/°C); γ is the psychrometric constant (KPa/°C); D is the vapour pressure deficit (Pa); u_2 is daily average wind speed at a height of 2 m (m/s), and λ is the latent heat of vaporization of water (2.45×10^6 J/kg).

Due to low temperature in the winter of this region, sublimation from the lake surface ice can be considered negligible (Ma et al., 2016). The duration of ice cover and complete ice cover was 209 and 149 days in the northwestern region of the TP and 126 and 72 days, respectively, in the southern region of the TP from 2001 to 2010 based on MODIS data (Kropáček et al., 2013). The complete ice cover of the lakes in the Hoh Xil region was completed in the middle of October to the early December, and the complete melt was completed in early May to the middle of June (Yao et al., 2015). Therefore, we assume the Ep value from December to April to be 0 and the Ep value of other months represents the annual Ep.

4. Results

4.1. The underwater topography and water storage values of the four lakes

The bathymetric survey routes and isobaths of the four lakes are shown in Fig. 2. According to the bathymetric data from 2015, Gozha Co was the deepest of the four lakes, with a maximum depth of 149.53 m. The lake could be divided into two portions (east portion and west portion), and the deepest region was located in western Gozha Co. The deepest depth in the east portion was only 95.21 m. A continuous underwater divide was approximately 50 m deep in the middle of the two portions of Gozha Co based on the underwater topography, which can divide Gozha Co into two lakes when the lake level falls approximately 50 m. Longmu Co exhibited a maximum depth of 69.9 m in the eastern portion of the lake. However, Aksai Chin Lake and Bangdag Co were much shallower than Gozha Co and Longmu Co, with maximum depths of 29.1 m and 48.5 m, respectively. The average water depths were calculated as approximately 57.6 m, 26.1 m, 17.8 m and 9.7 m in Gozha Co, Longmu Co, Bangdag Co and Aksai Chin Lake when their areas were 248.44 km^2, 106.74 km^2, 145.57 km^2 and 264.98 km^2, respectively. The corresponding water storages were approximately 14.299 km^3, 2.775 km^3, 2.598 km^3 and 2.568 km^3. Based on the underwater topography, a water level-storage curve was established for each lake (Fig. 3).

4.2. Water storage and water level variations from 1976 to 2015

As shown in Fig. 4, all four lakes showed little variation from 1976 to 2000, and Aksai Chin Lake and Bangdag Co showed slight expansion from 2000 to 2015, with the area of increase for Bangdag Co mainly concentrated in the eastern portion of the lake, and the area of increase for Bangdag Co mainly concentrated in the southern protion of the lake. Longmu Co had small expansion from 2000 to 2015, which was mainly in the eastern region of the lake. Gozha Co only increased in area slightly during these periods, mainly in the eastern region of the lake. The lake areas and water storages of the four lakes are shown in Fig. 5. The area and water storage of Gozha Co remained relatively stable, with slight decreasing trends from 251.73 km^2 to 14.313 km^3 in 1976 to 248.44 km^2 and 14.299 km^3 in 2015, respectively. Longmu Co showed a small expansion from 1976 (98.36 km^2, 2.65 km^3) to 1991 (100.28 km^2, 2.692 km^3) and decreased in 1996 (99.59 km^2, 2.676 km^3), followed by continuous expansion at an average rate of 0.005 km^3/y from 1996 to 2015 (106.48 km^2, 2.775 km^3). However, Aksai Chin Lake and Bangdag Co showed slight decreasing trends from 1976 to 1996 and then rapidly expanded from 1996 to 2015. From 1996 to 2015, the lake areas of Aksai Chin Lake and Bangdag Co ranged from 166.1 km^2 to 264.98 km^2 (5.2 km^2/y) and 109.43 km^2 to 145.57 km^2 (2.2 km^2/y), while the water storages increased from 1.328 km^3 to 2.568 km^3 (0.065 km^3/y) and 1.226 km^3 to 2.598 km^3 (0.072 km^3/y), respectively. The water storage increases in Aksai Chin Lake were mainly concentrated in 2006 (0.338 km^3) and 2013 (0.473 km^3), accounting for 27.2% and 38.1%, respectively, of the total water storage change (1.24 km^3) from 1996 to 2015, and the water level rose by approximately 1.76 m in 2006 and 2 m in 2013, accounting for 28.4% and 32.2% of the total increase in water level (6.2 m) from 1996 to 2015.

As shown in Fig. 5b and d, the lake levels of the four lakes showed the same trends as their areas and water storages. The lake levels in 2000 were calculated based on the Shuttle Radar Topography Mission (SRTM, 90 m resolution) data, which was used to produce a global DEM in 2000. The lake levels were then calculated in other periods relative to 2000. The lake level of Longmu Co only

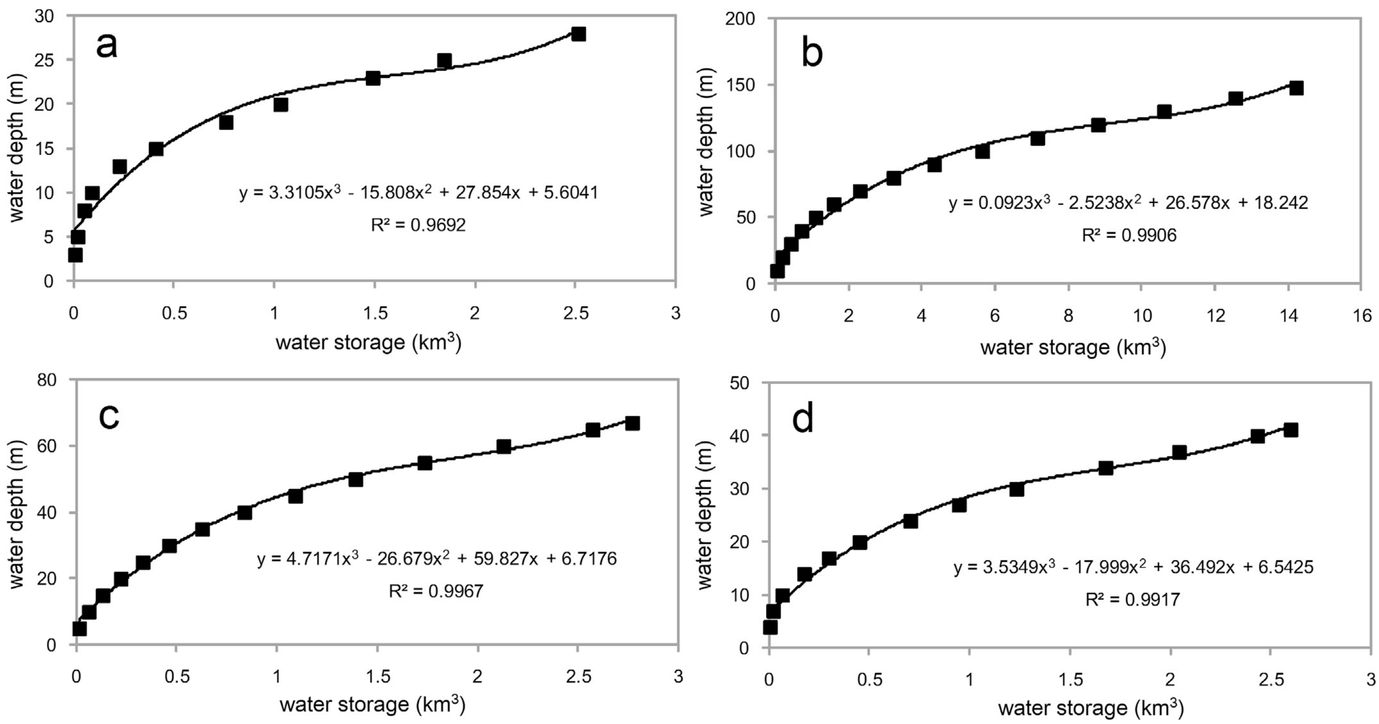

Fig. 3. Water level-storage curve of four lakes. a, Aksai Chin Lake; b, Gozha Co; c, Longmu Co; d, Bangdag Co.

showed a slight increase of 1.5 m from 1976 to 2015. The fluctuation in Gozha Co lake level was less than 0.1 m over the same period. The lake levels of Bangdag Co and Aksai Chin Lake had slight decreasing trends with a decrease of 0.66 m and 0.89 m from 1976 to 1996, but they quickly increased by 11.2 m (Bangdag Co) and 6.2 m (Aksai Chin Lake) from 1996 to 2015, respectively. The rate of increase of the Aksai Chin Lake level was 0.44 m/y from 2003 to 2008, which was close to the result (0.5 m/y) reported by Phan et al. (2012) based on ICESat data.

4.3. Inter-annual variations in meteorological factors

Because the change trends for precipitation, Ep and temperature in the three basins are basically consistent (Fig. 6), we only analyzed the variations of the average values for these meteorological elements in the three basins. As shown in Fig. 6a, the mean annual precipitation of the three basins in the study area was very low and showed little variation from 1979 to 1996, with an average of 37.9 mm. This value increased to 163.3 mm in 2000 and remained high from 2000 to 2013. The mean annual precipitation from 1997 to 2013 (151.7 mm) was approximately four times that from 1979 to 1996. Ep showed a significant increasing trend with an average rate of increase of 4.4 mm/y from 1976 to 2000, then decreased significantly with an average rate of decrease of 15.5 mm/y until 2009 (Fig. 6b). The average Ep was 1369 mm in the three basins for 1976–2000, 1358 mm for 2000–2009 and 1361 mm for 2010–2013. The mean annual temperature showed a significant increasing trend from 1979 to 2013, except in 2009 and 2010 (Fig. 6c). After 1996, the rate of increase was much more rapid (0.08 °C/y) than that from 1979 to 1996 (0.03 °C/y). There was a significant temperature decrease in 2009 and 2010, which was colder than other years, but the temperature increased quickly in 2011–2013 which was hotter than other years. Because the temperature in the warm seasons has more influence on glacier melting, we also calculated the temperature from June–September, which showed a more apparent increasing trend from 1979 to 1996 with a mean temperature of −2.85 °C than the period from 1997 to 2013, which had a mean temperature of −1.16 °C.

5. Discussions

5.1. The hydrological conditions of the four lakes

Generally, the water balance of a lake is dominated by precipitation, runoff and evaporation, and glacial meltwater is an additional important supply to glacier-fed lakes, around which there are a lot of glaciers distribution. Previous studies showed that lake variations in the central regions of the TP depended on precipitation (Lei et al., 2013, 2014; Song et al., 2014a), glacial meltwater (Phan et al., 2013) and degraded permafrost (Li et al., 2014b). However, there are large differences in climatic conditions in different regions on the TP (Zhang et al., 2007; Tong et al., 2014); for example, the annual precipitation is much greater in the eastern TP than in the western TP, but the annual average temperature is much higher. These factors may exert different effects on lake variation processes, an in the study area in particular, which has low precipitation and has extremely dry and cold climatic conditions, glacial meltwater might make an important contribution to lake expansion with rising temperatures. The hydrological conditions of closed lakes are the most important basis for understanding lake variations, inflow water could be from precipitation on the lake surface, surface runoff or glacial meltwater, but lake water can only be removed by surface water evaporation. There are many glaciers distributed in the Bangdag Co and Aksai Chin basin, but fewer in Longmu Co basin (Fig. 1). However, we found that several springs flow into the lake in the western portion of the Longmu Co basin, representing important contributions to this salt lake. Gozha Co is an upstream lake of Aksai Chin Lake and is connected to Aksai Chin Lake through a river channel, so the lake water will overflow when the water level is higher than the riverbed that supplies the Aksai

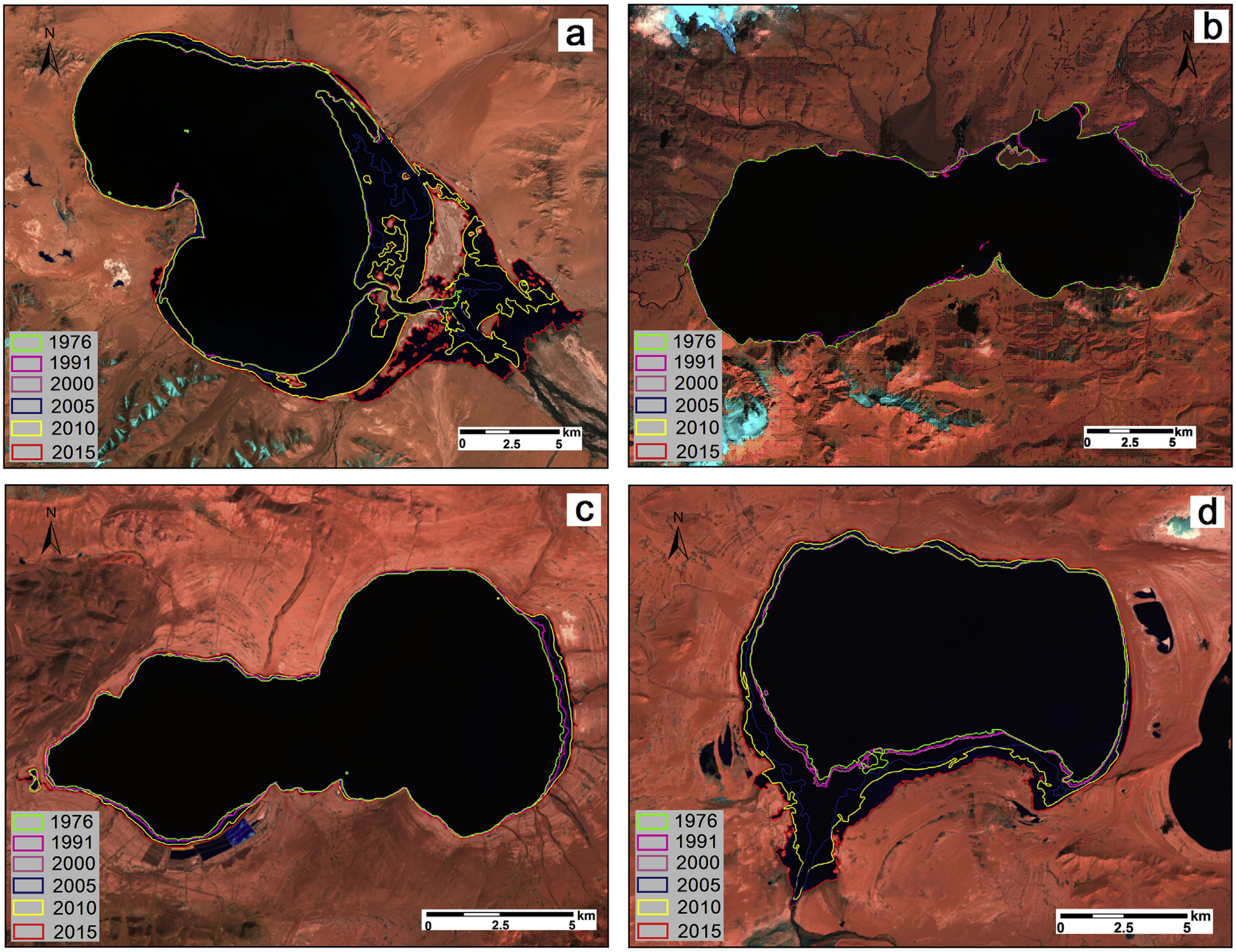

Fig. 4. Lake change in lake shoreline in six different periods (1976, 1991, 2000, 2005, 2010, 2015) for four lakes (band 6, 5, 4 of Landsat OLI images for R, G, B). a, Aksai Chin Lake; b, Gozha Co; c, Longmu Co; d, Bangdag Co.

Chin watershed. Thus, Aksai Chin watershed, includes the Gozha Co watershed, is the largest watershed with largest glacial meltwater contribution in this study region. In conclusion, precipitation, glacial meltwater and evaporation have different effects on the variations in these lakes due to different topography and hydrological conditions.

5.2. The relationships between lake variations and meteorological factors

The lake area and water storage of Bangdag Co and Aksai Chin Lake decreased with low precipitation during 1976–1996, but they increased with high precipitation during 1996–2015, so it is easy to assume that precipitation is the dominant factor of lake water storage because the variation trends in lake water storage and lake level mirror those of precipitation from 1976 to 2015. However, due to the low precipitation and high evaporation in Aksai Chin Lake and Bangdag Co and large number glaciers distributed in these basins, especially for Aksai Chin Lake which glacier area is 1232.1 km^2, glacial meltwater likely makes a more important contribution to these lakes than precipitation. The lake water storage and lake level of Longmu Co exhibited only small increases under the same precipitation conditions from 1996 to 2015 in comparison with Aksai Chin Lake and Bangdag Co. For the four lakes, the lower precipitation and less meltwater at lower temperatures could not offset the water loss via lake surface evaporation during 1976–1996, and the increased Ep during this period would cause much more water loss. This likely led to the lake water storage decrease observed in Aksai Chin Lake and Bangdag Co, and the increased Ep with average rate of increase of 4.4 mm/y would make an approximately 13% and 10% contribution to the shrinkage of Aksai Chin Lake and Bangdag Co, respectively; however, the lake water storage of Longmu Co had less variation which might be due to spring supplies. The lake water storage and lake level of Bangdag Co and Aksai Chin Lake increased from 1996 to 2015, perhaps because there was decreased Ep, increased meltwater under higher temperature conditions and increased precipitation. However, the lake water storage and lake level of Longmu Co exhibited no large changes with increasing precipitation, perhaps because there was high evaporation with a high salinity. Therefore, the increased precipitation exerted different influences on lakes water storage changes in glacier-fed lakes and non-glacier-fed lake from 1996 to 2015. We suggest that precipitation likely is not the main reason for lake expansion, but rather that glacial meltwater exerted more

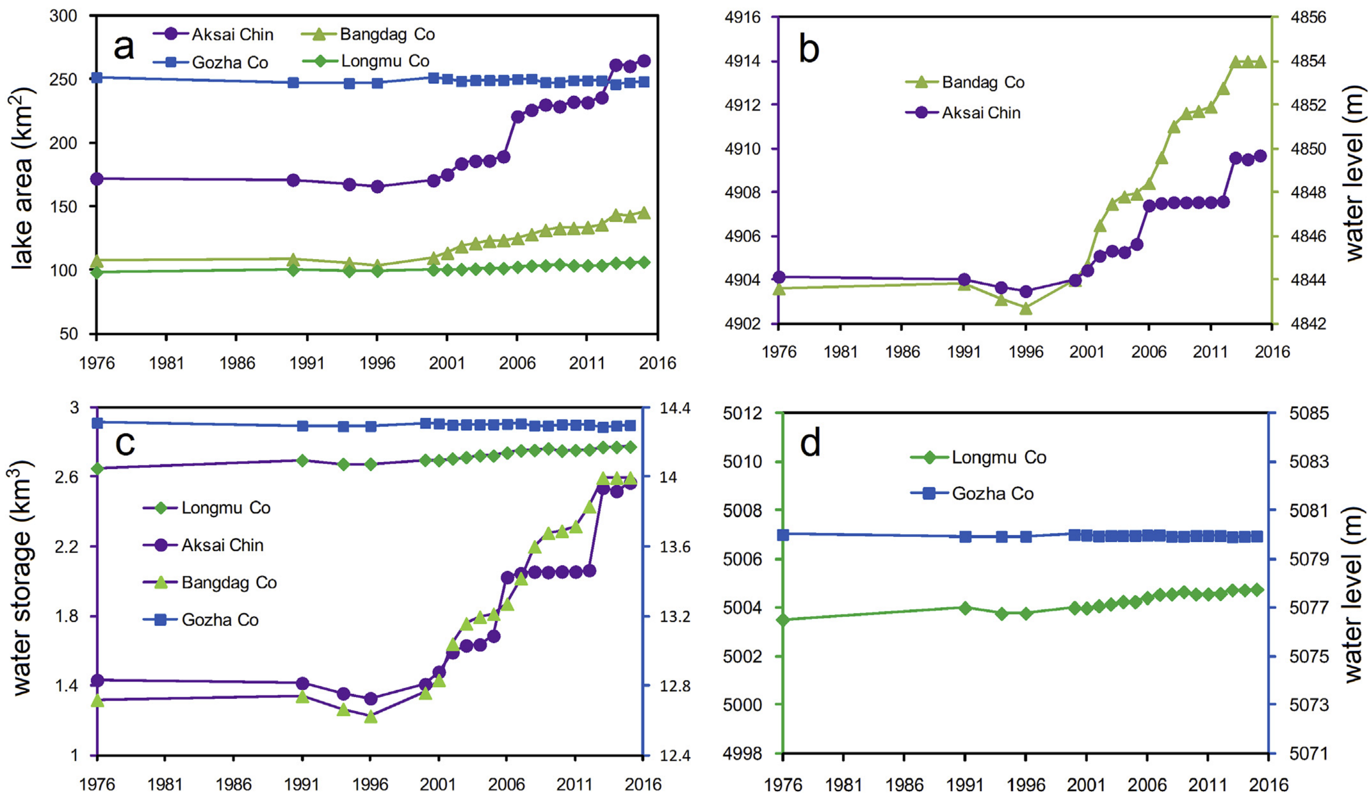

Fig. 5. The variations of lake area, water storage and lake level during 1976–2015 (the color of coordinate axis represents the lake which line color is consistent with coordinate axis). (a), The lake area change; b. Lake level change of Bangdag Co (green line) and Aksai Chin Lake (violet line); (c) the water storage change (the violet coordinate axis is for Longmu Co, Aksai Chin and Bangdag Co, the blue coordinate axis is for Gozha Co); d, lake level change of Gozha Co (blue line) and Longmu Co (dark green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

influence on increasing lake water levels associated with rising temperatures. Decreasing Ep with average rate of 15.5 mm/y from 2000 to 2009 made approximately 21%, 2% and 4% contributions to the lake expansion of Longmu Co, Aksai Chin Lake and Bangdag Co, respectively.

Both the lake area and water storage of Gozha Co were stable. The lake level remained nearly invariant during the study period, indicating that the lake level of Gozha Co had not fallen below the riverbed that connects to Aksai Chin Lake and that the water supply was much larger than the water lost via evaporation. Although the stable lake levels of Gozha Co from 1976 to 1996 implied that there was still water flowing into Aksai Chin Lake, this supply was not enough to diminish the water loss observed at Aksai Chin Lake. Because the area of both Bangdag Co and Aksai Chin Lake exhibited decrease under lower precipitation conditions and Longmu Co remained stable due to extra water supplied from springs, the stable lake level of Gozha Co might be attributed to more meltwater contributions compared with the other three lakes.

5.3. The linkage between variations of glaciers and lakes

All glaciers areas of three basins were calculated for 1976, 1991, 1996, and from 1999 to 2015 using the same images to extract lake area. The results showed that total glacier area of Bangdag Co basin and Longmu Co basin remained stable, but the total glacier area of the Aksai Chin basin had an increasing trend from 1976 (1225.1 km^2) to 2004 (1231.5 km^2), and had a decreasing trend until 2015 (1288.7 km^2). We selected four large glaciers, occupying 43% of the total glacier area in the Aksai Chin basin, to analyze the glacier area change. As shown in Fig. 7, the glacier areas showed heterogeneous changes. The Zhongfeng glacier, Duota glacier and Gongxing glacier directly supply Aksai Chin Lake, and Chongce glacier supplies Gozha Co. Zhongfeng glacier showed a decreasing trend from 1976 to 2003 but increased by 2.4 km^2 from 22 July 2003 to 11 November 2003 over four months, and had a small increase in 2004, then remained in a stable state until 2015. The Duota glacier increased by 0.55 km^2 from 1976 to 1991, and then had a small decrease until 2015. The Gongxing glacier continuously decreased from 1976 to 2015. The Chongce glacier decreased by 2.46 km^2 from 1976 to 1991, and then increased by 7.81 km^2 from 1991 to 2002, then decreased until 2015. Previous studies reported that the rate of advancement of the Zhongfeng glacier was 661 m/y from 2002 to 2004, and that of the Chongce glacier was 200 m/y from 1991 to 1998 (Li et al., 2013). As shown in Fig. 8, there were two times glacier surging from 1991 to 1996 and 1996 to 1999 at the Chongce glacier, with an average rate of increase of 0.98 km^2/y (Fig. 8a, 8b, 8c), and from July to November in 2003 at the Zhongfeng glacier (Fig. 8d, 8e, 8f). Although the reduced areas of the Gongxing and Zhongfeng glacier from 1976 to 1996 suggested that meltwater continued to supply Aksai Chin Lake, the meltwater amount did not compensate for the water loss. The area of the Chongce glacier decreased during 1976–1999, and the glacier surging of the Chongce glacier from 1991 to 1999 perhaps brought much more meltwater than before because much of the glacier area was located in high temperature above the melt point, which glacial meltwater supplied Gozha Co. Gozha Co remained stable from 1976 to 1999, perhaps reason was that the great amount of meltwater could compensate for water loss by lake surface evaporation. Because the thinning of the Zhongfeng and Gongxing glaciers was monitored from 2003 to 2009 based on their surface elevation changes

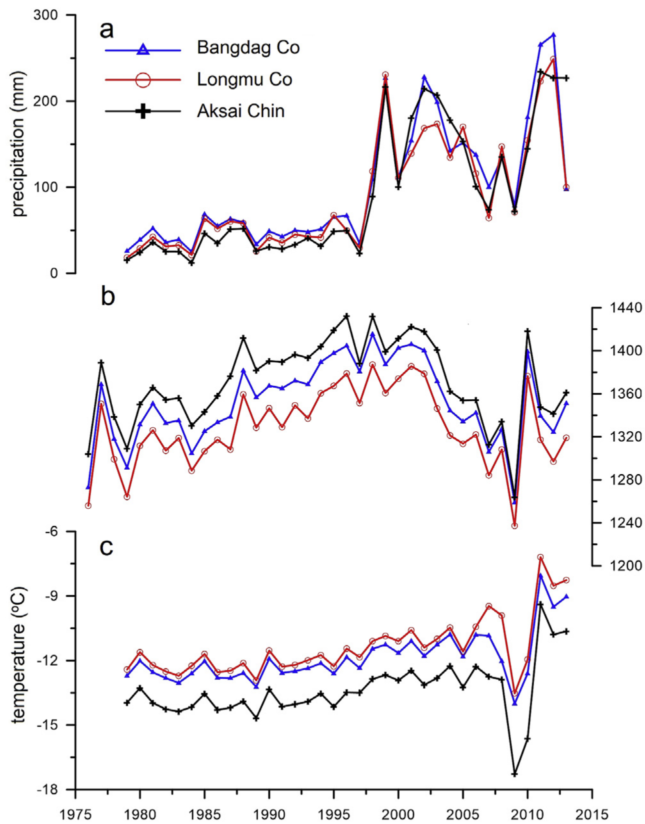

Fig. 6. The variation of meteorological elements from 1976 to 2013 for three basins. a, annual precipitation; b, annual Ep; c, annual mean temperature.

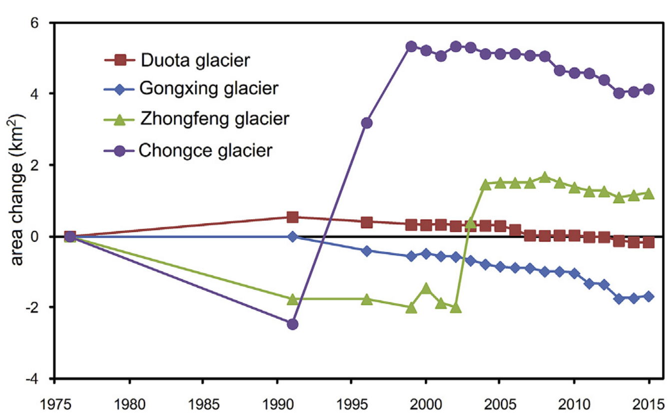

Fig. 7. Area change of four large glaciers in Aksai Chin basin from 1976 to 2015.

(Ke et al., 2015b), it is believed that the meltwater amount increased much more to supply Aksai Chin Lake after 2000, although the glacier areas did not exhibit larger changes than in earlier periods. Because Bangdag Co expanded from 1996 to 2015 when precipitation increased, and although the glacier area of the Bangdag basin remained stable, the rate of increase of water storage was much faster than that of Aksai Chin Lake and Longmu Co; thus, meltwater may have made an important contribution to the expansion of Bangdag Co.

Our assumption is that Longmu Co is mainly controlled by precipitation and evaporation, and that Aksai Chin Lake and Bangdag Co have an equal precipitation and evaporation (Song and Sheng, 2016). According to this assumption, water storage of Longmu Co increased by 0.077 km^3 which was from precipitation-evaporation from 2000 to 2015. Thus, 0.86 km^3 and 0.29 km^3 water storage of Aksai Chin Lake and Bangdag Co was from precipitation-evaporation which occupied 74.1% and 23.4% of the total increased water storage, respectively. Glacial meltwater made 25.9% and 76.6% contributions to the lake expansion of Aksai Chin and Bangdag Co, respectively. However, because the basin area of Aksai Chin (10,718.6 km^2) is much greaster than those of Longmu Co (957.1 km^2) and Bangdag Co (3613.5 km^2), and Ep of Aksai Chin basin is much higher than in Longmu and Bangdag basins (Fig. 6b), it is likely that the water loss due to land evaporation under high evaporation conditions in Aksai Chin basin is much greater than that in Bangdag Co and Longmu Co basin (Fig. 6b). Thus, this assumption is more suitable for Longmu Co and Bangdag Co but not for Aksai Chin Lake, and the glacier area in the Aksai Chin basin is approximately 12 times greater than that in Bangdag Co, so glacial meltwater perhaps made much more important contribution (>76.6%) to the lake expansion than Bangdag Co. We believe that lakes would still expand, and would do so more quickly with rising temperature.

During the expansion process of Aksai Chin Lake, there were two jumps in lake water storage that occurred in 2000, 2006 and 2013. As shown in Fig. 6a, precipitation increased quickly from 1997 to 1999, so perhaps the reason for the quick expansion in this period was the quick increase in precipitation. Fig. 9 shows the seasonal water storage variations in Aksai Chin Lake based on 34 phases of Landsat images obtained from 2005 to 2007 and from 2012 to 2014. The detailed area and water storage results for each phase are shown in Supplement 2. The water storage of Aksai Chin Lake had no significant seasonal variations except in 2006 and 2013. The lake water storage increased by 0.041 km^3 from April 2005 (1.626 km^3) to August 2005 (1.667 km^3), with a 0.23 m increase in lake level. The lake water storage decreased by 0.06 km^3 from October 2013 (2.538 km^3) to June 2014 (2.478 km^3), with a lake level decline of 0.33 m. Therefore, the two jumps are not the result of seasonal variation. However, precipitation and Ep exhibited insignificant changes around those jumps. These abrupt changes in lake water storage were likely associated with glacier surging and quickly increasing temperature. Glacier surging causes more glaciers to be located in regions with melt-point temperatures, so perhaps much more meltwater would be produced than before the glacier surging (e.g. Zhongfeng glacier). The temperature increased until 2006, and decreased until 2008, and the lowest temperature was in 2009 (Fig. 6c), but the temperatures from 2011 to 2013 were the highest in the study period. The two jumps of Aksai Chin Lake in 2006 and 2013 were likely related to the glacier surging with increased temperatures.

6. Conclusions

Based on the in-situ bathymetric survey data from the studied lakes combined with multi-temporal Landsat images of the northwestern Tibetan Plateau, we have established underwater lake topographies and constructed the relationships between lake water storage and maximum lake depths. This allowed us to obtain the lake water storage and changes that realistically reflect the water balances of the lakes.

The reconstructed results of water storage and water levels from 1976 to 2015 showed that the water storage of two closed and glacier-fed lakes (Aksai Chin Lake and Bangdag Co) decreased from 1976 to 1996, and increased quickly with water storage increases of 1.24 km^3 and 1.37 km^3 from 1996 to 2015, respectively. Gozha Co, an upstream lake, exhibited relatively stable water storage. Longmu Co, which is a closed and non-glacier-fed lake, exhibited a water storage increase of 0.1 km^3 at a slowly increasing rate from 1996 to

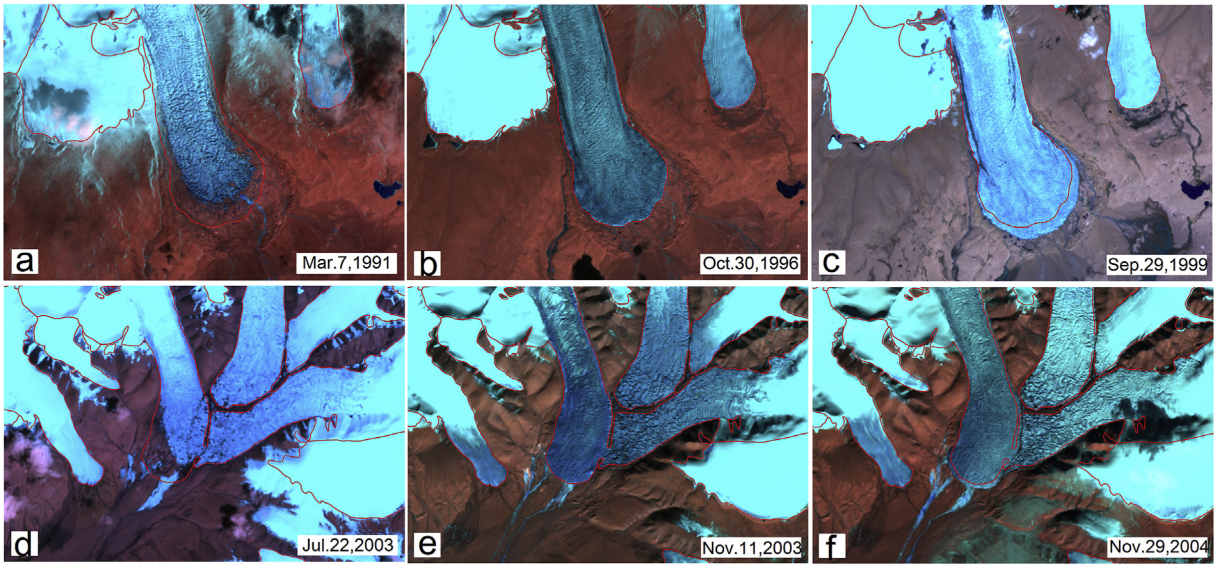

Fig. 8. Glacier surging of Chongce and Zhongfeng glacier based on Landsat image (band 5, 4, 3 of Landsat TM and ETM + images for R, G, B). a, b, c, Chongce glacier, red line is the glacier boundary of October 30, 1996; d, e, f, Zhongfeng glacier, red line is the glacier boundary of November 11, 2003. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

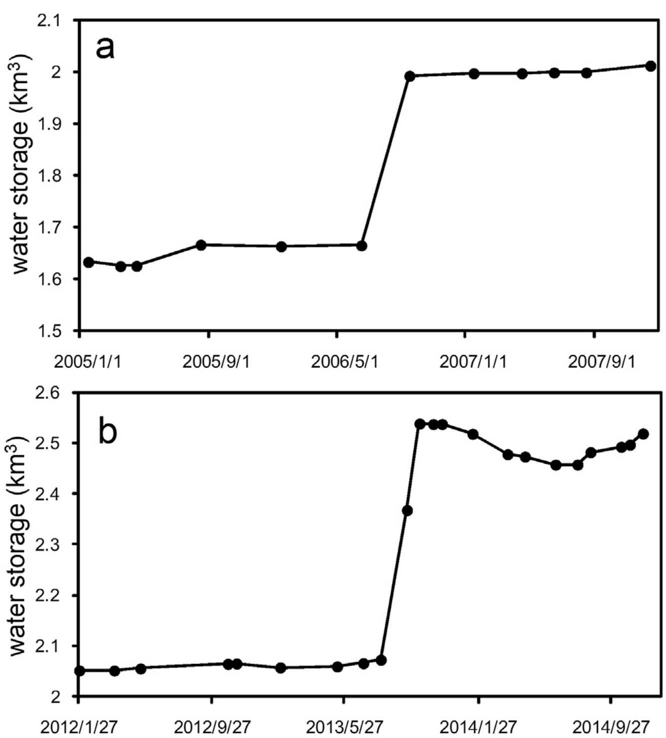

Fig. 9. The seasonal water storage change of Aksai Chin Lake. a, 2005–2007; b, 2012–2014.

2015.

Analyzing the trends in precipitation, temperature and Ep, we found that the main reasons for lake shrinkage were less precipitation and less meltwater under lower temperature conditions from 1976 to 1996, increased Ep (4.4 mm/y) only contributed approximately 13% and 10% contribution to shrinkage of Aksai Chin Lake and Bangdag Co, respectively. Because the lake water storage of Longmu Co (non-glacier-fed lake) showed a small increase with increased precipitation, but Aksai Chin Lake and Bangdag Co (glacier-fed lakes) showed apparent increases in lake water storage from 1997 to 2015, and decreased Ep (15.5 mm/y) from 2000 to 2009 made approximately 21%, 2% and 4% of the contribution to the lake expansion of Longmu Co, Aksai Chin Lake and Bangdag Co, respectively. Water storage change showed a large difference between glacier-fed lakes and non-glacier-fed lake under increased precipitation, so glacial meltwater likely had more influence on the lake water increases due to rising temperatures. Glacial meltwater made approximately 76.6% of the contribution to lake expansion of Bangdag Co from 2000 to 2015 based on the assumption of equal precipitation-evaporation in Longmu Co and Bangdag Co basin.

During the process of water level increase in Aksai Chin Lake, there were two jumps, which occurred in 2006 (increased by 0.338 km^3) and 2013 (0.473 km^3). These jumps accounted for 65% of the total water storage increase (1.24 km^3). The abrupt increases in lake water storage were likely attributed to glacier surging and quickly increasing temperatures.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2017.08.005.

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