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Contrasting evolution patterns between glacier-fed and non-glacier-fed lakes in the Tanggula Mountains and climate cause analysis

Chunqiao Song[1] · **Yongwei Sheng**[1]

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Abstract High-altitude lakes in the Tibetan Plateau (TP) showed strong spatio-temporal variability during past decades. The lake dynamics could be associated with several important factors including lake type, supply of glacial meltwater, local climate variations. It is important to differentiate these factors when analyzing the driving forces of lakes dynamics. With a focus on lakes over the Tanggula Mountains of the central TP, this study investigates the temporal evolution patterns of lake area and water level of different types: glacier-fed closed lake, non-glacier-fed closed lake and upstream lake (draining into closed lakes). We collected all available Landsat archive data and quantified the inter-annual variability of lake extents. Results reveal accelerated expansions of both glacier-fed and non-glacier-fed lakes during 1970s–2013, and different temporal patterns of the two types of lakes: the non-glacier-fed lakes displayed a batch-wise growth pattern, with obvious growth in 2002, 2005 and 2011 and slight changes in other years, while glacier-fed lakes showed steady expanding tendency. The contrasting patterns are confirmed by distinct lake level changes between the two groups derived from satellite altimetry during 2003–2013. The upstream lakes remained basically stable due to natural drainage regulation. The intermittent expansions for non-glacier-fed lakes are found to be related to excessive precipitation events and positive "precipitation–evaporation". In contrast, glacier-fed lake changes showed weak correlations with precipitation variations, which implies a joint contribution from glacial meltwater to water budgets. Our study suggests that glacial meltwater supply may have an equivalent influence on lake growth with precipitation/evaporation in the study area.

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✉ Yongwei Sheng
ysheng@geog.ucla.edu

[1] Department of Geography, University of California, Los Angeles, 1255 Bunche Hall, Los Angeles, CA 90095, USA

1 Introduction

The Tibetan Plateau (TP), known as the “Asian Water Tower” (Immerzeel and Bierkens 2010). holds many glaciers and lakes, which play an important role in maintaining regional water balance and are considered as sensitive indicators of climate change and variability. During the past several decades, Tibetan lakes showed strong spatio-temporal variability in response to rising temperatures and changing precipitation and evaporation (Lei et al. 2014; Liao et al. 2012; Song et al. 2013; Wan et al. 2014; Zhang et al. 2011).

Many previous studies have addressed the spatio-temporal heterogeneity of lake changes in the TP (Lei et al. 2014; Liao et al. 2012; Phan et al. 2012; Song et al. 2013, 2015a; Zhang et al. 2011). However, the driving mechanism of lake dynamics is still under debate. Numerous researchers focused on typical large glacier-fed lakes and attempted to explore the role of increasing glacial meltwater on lake expansion (Krause et al. 2010; Lei et al. 2012; Li et al. 2014b; Wu and Zhu 2008; Ye et al. 2008). No doubt, increasing glacial meltwater induced by rapidly rising temperature could be an important contributor to lake growths. However, quantitative estimate of glacier mass balances is largely limited by the rather insufficient field observations and large uncertainty of satellite measurements. Thus it is still difficult to quantify the percentage of glacial meltwater contribution to Tibetan lake expansion across different regions. Moreover, a large number of lakes in the TP, which are supplied by no or limited glacial meltwater, were also experiencing obvious expansions (Phan et al. 2013; Song et al. 2014b). Lei et al. (2014) investigated the spatio-temporal variations of Tibetan lakes since the 1970s by dividing these lakes into several different sub-zones, and attributed the coherent lake growth in the interior TP to increasing precipitation since the late-1990s. Based on time-series of lake levels derived from multiple satellite altimeters, the lake evolutions (including inter-annual and abrupt changes) are believed to be highly related to changing precipitation and evaporation (Song et al. 2014a, 2015a). The major contributions from precipitation variations to lake water budgets were also revealed in other recent studies based on modelling methods (Biskop et al. 2015; Li et al. 2014a; Zhou et al. 2015; Zhu et al. 2010). Besides, Li et al. (2014b) speculated that the Tibetan lake expansions were mainly driven by warming-triggered permafrost degradation. Although there seems to be a good agreement between the spatial patterns of permafrost degradation and lake evolution (transition of shrinking, to stable, to rapidly expanding trends from southwest to northeast), direct evidences of permafrost changes and their impact on hydrologic cycles in the TP are lacking and require more investigation.

The above-mentioned debate largely lies in the lack of continuous measurements of lake dynamics. In this study, we select high-altitude lakes in the Tanggula Mountains in the inner TP and separate them into different groups: glacier-fed closed lakes, non-glacier-fed closed lakes and upstream lakes. Based on all available Landsat images and combined ICESat (Ice, Cloud and land Elevation Satellite) and CryoSat-2 altimetry data over this area, the temporal patterns of lake extent and water level changes are examined and compared for different lake groups. To better understand the mechanism of Tibetan lake dynamics, we explored the relationship between these different lake evolution patterns and the changes of key factors in the hydrological process such as precipitation and glacier meltwater supply. Our assumption is that if lake growths are dominated by changing precipitation, the lake evolution (areal expansion or water level rise) would show a batch-wise pattern in phase of specific precipitation events; otherwise, lakes tend to show relatively steady expansions as the continued glacier melt or permafrost thawing provide increasing meltwater supply with significant warming tendency over the plateau. Based on satellite products, the relationships between lake changes and precipitation/evaporation variability are further analyzed to confirm the direct climate contributions.

2 Study area and data

2.1 Study area

The study area is located in the Tanggula Mountains of the central Tibetan Plateau where mountain glaciers are extensively distributed (Fig. 1). The selected lakes are between two high mountains of Purog Kangri and Gêladaindong, which are closed catchments. In recent years, the glaciers over this area were experiencing rapid retreating and negative mass balances (Gardner et al. 2013; Pu et al. 2008; Yao et al. 2012). There are 21 lakes larger than 1 km^2 (calculated from Landsat images acquired in 2013). According to the dependence of lake water budget on glacial meltwater and drainage system of lakes (Phan et al. 2013). the types of examined lakes are differentiated. Among these lakes, there are seven lakes that drain into other catchments (called upstream lake); for the rest, five lakes are fed by glacial meltwater from surrounding mountains. The details (e.g., geographic locations, lake sizes, water supply types, glacier areas within lake drainage basins and their ratios relative to corresponding lakes) can be referenced in Table 1. As there are seven unnamed lakes, we use Lake IDs to differentiate them (as shown in Fig. 1 and Table 1). Chibzhang Co and Dorsoidong Co are the two largest lakes, accounting for ~60 % of the total lake area. The two lakes became interlinked due to the recent rapid water-level rises after the mid-2000s (as analyzed below). The climate belongs to the cold and semi-arid type. Over 85 % precipitation falls in wet season (May to October) (based on TRMM precipitation estimates during 2000–2013). Under the semi-arid continental climate, the glaciers developed in this region are of semi-continental type with annual mass balance mostly dominated by accumulation and ablation in summer (Ke et al. 2015). Thus, lakes grow mostly during the wet season and get to the maximum of annual cycle in September/October.

2.2 Data and processing

2.2.1 Landsat images for lake extraction

The variations of lake extent were investigated based on time series of Landsat images since the mid-1970s (downloaded from http://glovis.usgs.gov). These images have already been radiometrically corrected and projected in the UTM coordinate system. To make lake extent comparable at inter-annual timescale, we selected images with acquisition dates mostly between August and November, the end of wet season when lake water budget remains at a relatively stable stage. More than 85 % images are completely cloud-free over lakes. For annual lake mapping, one images of the highest quality were chosen as the base image. Given that a few lakes are "contaminated" partially by cloud or seasonal snow cover, the occluded lake boundaries were reconstructed by referring to auxiliary images acquired in neighboring months. Details of selected base/auxiliary images and lake extent mapping are available in Table S-1.

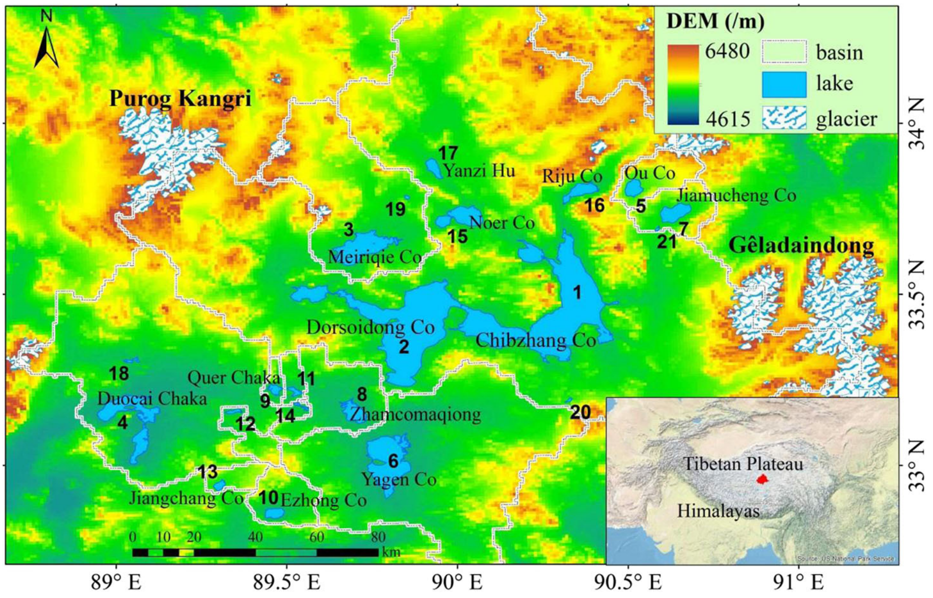

Fig. 1 Map of study area showing the spatial distribution of lakes and glaciers, and surrounding topography in the central Tibetan Plateau

In this study, a two-step NDWI (Normalized Difference Water Index) threshold segmentation method was applied to extract the lake inundation areas (Li and Sheng 2012; Wang et al. 2014). In the first step, all potential waterbody pixels are filtered by a loose initial threshold segmentation based on calculated NDWI maps of selected multiple spectral images (as shown in Fig. 2b); the second step is locally iterative segmentation for each potential lake entity, and the iteration goal is to obtain relatively more stable lake boundary within consecutive segmentations until the mapping lake extent variance less than 2 % (see Fig. 2c). The NDWI map is generated by the normalized water index between the green (ρ_{green}) and near infrared (ρ_{NIR}) spectral bands, which was developed by McFeeters (1996).

The two-step threshold segmentation method can efficiently improve the accuracy of waterbody extent delineation, compared to single-threshold segmentation method which uses a fixed threshold to delineate outlines of different lakes although they have obviously distinctive spectral features due to different water depths and turbidity levels. For instance, as shown in Fig. 2, Lake 9 and Lake 11 show different spectral features and NDWI value ranges, this method can delineate lake extents by iterative segmentation of their NDWI histograms respectively. The final NDWI segmentation thresholds are set around 0.22 and 0.00, respectively. To facilitate the editing of missing lakes, an interactive lake mapping tool was used to reconstruct lake boundaries from alternative images (Wang et al. 2014).

2.2.2 ICESat and CryoSat-2 altimetry data for measuring lake levels

In this study, both ICESat and CryoSat-2 altimetry data were used to detect inter-annual changes of glacial lake levels during 2003–2013. The ICESat altimeter provides surface elevations within a diameter of 70 m footprint spaced at 172 m along-track. Elevation data were collected during the period from February 2003 to November 2009. The accuracy of

Table 1 Detailed information on all of studied lakes

Lake ID	Lake name	Latitude (°)	Longitude (°)	Lake area	Water level	Type	Supply coefficient	Glacier area/ratio to lake
1	Chibzhang Co	33.4559	90.2682	563.05	4935	glacier-fed	11.58	348.27/ 0.33
2	Dorsoidong Co	33.4100	89.8375	489.38	4929	glacier-fed		
3	Meiriqie Co	33.6368	89.7197	95.90	4947	glacier-fed	15.04	18.26/ 0.19
4	Duocai Chaka	33.1352	89.0459	103.64	4843	glacier-fed	28.57	15.77/ 0.15
5	Ou Co	33.8104	90.5160	19.25	5062	glacier-fed	13.26	7.52/ 0.39
6	Yagen Co	33.0124	89.7971	148.67	4872	non-glacier-fed	18.92	/
7	Jiamucheng Co	33.7385	90.6367	33.79	5000	non-glacier-fed	7.51	/
8	Zhamcomaqiong	33.1546	89.6971	30.37	4892	non-glacier-fed	17.44	/
9	Quer Chaka	33.2215	89.4650	7.95	4923	non-glacier-fed	7.09	/
10	Ezhong Co	32.8598	89.4638	13.95	4915	non-glacier-fed	19.63	/
11	/	33.2158	89.5239	5.10	4929	non-glacier-fed	17.11	/
12	/	33.1570	89.3446	3.62	4934	non-glacier-fed	43.16	/
13	Jiangchang Co	32.9411	89.3029	6.59	5043	non-glacier-fed	17.43	/
14	/	33.1730	89.5415	2.28	4943	non-glacier-fed	17.15	/
15	Noer Co	33.7261	90.0126	55.24	4954	upstream lake-32	/	/
16	Riju Co	33.8027	90.3610	27.00	4956	upstream lake-32	/	/
17	Yanzi Hu	33.8696	89.9306	14.71	4973	upstream lake-32	/	/
18	/	33.3065	89.0466	2.84	4931	upstream lake-26	/	/
19	/	33.7842	89.8525	1.22	5000	upstream lake- 4	/	/
20	/	33.1903	90.3270	1.14	5040	upstream lake-32	/	/
21	/	33.6910	90.5858	1.09	5003	upstream lake-10	/	/

The latitude and longitude of lakes represent the geographic location of lakes' geometric center; the lake area (km^2) and water level (m) is referenced to the information derived from Landsat-8 image acquired on July 31, 2013 and elevations from the Shuttle Radar Topography Mission (SRTM) DEM; the supply coefficient is defined as the ratio of basin area to lake area; the glacier area (km^2) within each catchment for glacier-fed lakes and the ratio to lake area is obtained from the latest Chinese Glacier Inventor v-2 data (Guo et al. 2015)

elevation measurements of ICESat were reported on the order of several or ten more centimeters (Urban et al. 2008; Zwally et al. 2002).

The good performances of ICESat altimetry measurements on detecting Tibetan lake level changes have been evaluated in many earlier studies through comparison with gauge-based observations and other satellite data (Kropáček et al. 2012; Song et al. 2015a; Zhang et al. 2011). This study used Release-33 ICESat level-2 product (GLA14) provided by the National Snow and Ice Data Center (NSIDC). On the pre-processing stage, the latitude, longitude and elevation data of footprints were extracted by the GLAS Visualizer and NSIDC GLAS Altimetry elevation extractor Tool (NGAT). In the study area, six large lakes are covered repeatedly by ICESat tracks, including Chibzhang Co (ID: 1), Dorsoidong Co (ID: 2), Meiriqie Co (ID: 3), Duocai Chaka (ID: 4), Yaggain Co (ID: 6) and Jiamucheng Co (ID: 7).

The ESA satellite CryoSat-2, launched in 2010, carries a radar altimeter named Synthetic aperture Interferometric Radar ALtimeter (SIRAL) (Kleinherenbrink et al. 2014). Its resolution in the along-track direction is about 300 m. CryoSat-2 operates in a 369-day repeat cycle, which is built of shifting subcycles of 30 days (Labroue et al. 2012). Thus, the density of

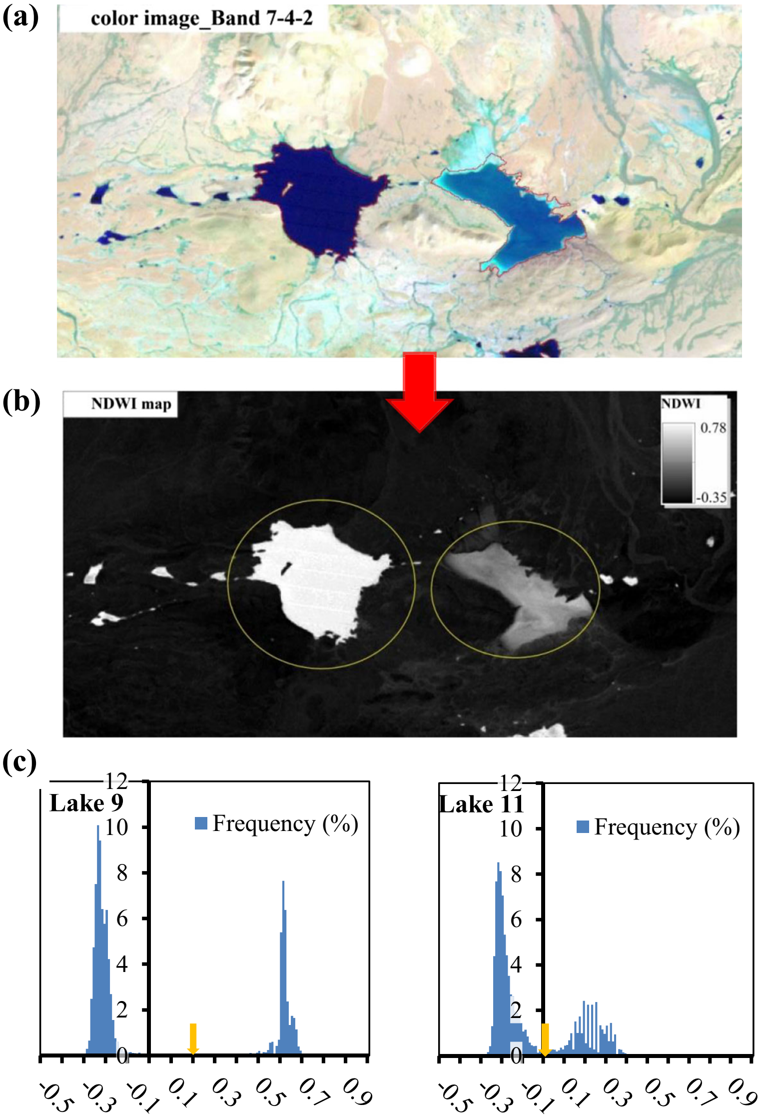

Fig. 2 Case study for presenting the method of two-step (global-to-local) threshold segmentation of NDWI map to delineate lake extents. The color image is based on RGB composition of Band 7, 4 and 2

CryoSat ground tracks is high (7–8 km spacing at the Equator) and opens larger possibilities with respect to monitoring small lakes in the Tibetan Plateau. We used Level-2 SIRAL SARIn mode data over the same six lakes observed by ICESat (https://earth.esa.int/web/guest/-/products-overview-6975#_101_INSTANCE_VeF6_matmp), which cover the period July 2010 to December 2013. As the two satellite altimetry measurements are referenced to different ellipsoids and height datums (Song et al. 2015b, c). we converted ICESat height data to the reference system of CryoSat-2 data (WGS84 and EGM96). The detailed procedures of altimetry data preprocessing and noise removal can be referenced in Song et al. (2015b). By comparing with gauge-based water level data of Namco and Yamzhog Yumco, CryoSat-2 data shows good performance, with small bias of order 0.1 m (Song et al. 2015c). The error may cause a biased estimate in change rate of lake level within 0.03 m/year, which is negligible relative to the water level changes for these examined lakes.

2.2.3 Other auxiliary data

As there is no meteorological station in the Tanggula Mountains, we analyzed precipitation change based on the version-7 Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis 3B42 data between 2000 and 2013 (daily sampling and 0.25×0.25° gridded). The product algorithm aims to produce TRMM- and rain gauge-adjusted multi-satellite precipitation rate and root-mean-square (RMS) precipitation-error estimates. It combines multiple independent precipitation estimates, including the TRMM Microwave Image (TMI), Advanced Microwave Scanning Radiometer for Earth Observing Systems (AMSR-E), Special Sensor Microwave Imager (SSMI), etc. All input microwave data are inter-calibrated to TRMM Combined Instrument (TCI) precipitation estimates (TRMM product 3B31) (Huffman et al. 2007). The comparative analysis of multiple precipitation products have been conducted in many prior studies (Tong et al. 2014a, b; Yin et al. 2008; You et al. 2015). These results all suggest the satellite retrievals have much better performance than reanalysis precipitation on the Tibetan Plateau. Among the high-resolution gridded precipitation data, Tong et al. (2014a) indicates that the TRMM 3B42 performs better than the 3B42RT data at both plateau and basin scales and has comparable performance to the station-based data in streamflow simulations due to the merge with gauge rainfall data. Over the study area, the inter-comparison of annual precipitation anomaly between TRMM 3B42 and GPCP data also indicate the reliability in depicting the inter-annual variation of precipitation during 2000–2013 (shown in Figure S-1).

The 8-day-composite and 1 km-resolution evapotranspiration (ET) product (MOD16A2) over the same 13-year span was used in this study (Mu et al. 2011). This product contains estimates of actual ET and potential ET. The estimation algorithm involves the quality-control procedure using the quality assurance information. Although the MODIS ET data cannot be validated directly by gauge-based data over the study area, the performance of MODIS-derived evaporative fraction was evaluated based on the "ground truth" measurements of neighbouring meteorological stations during 2003–2007 (Ma et al. 2014). The results indicate the satellite retrievals match the ground measurements well and the absolute percentage difference is within 10.0 %. In arid and sub-arid climate zones of the TP, actual ET is mainly determined by soil water availability and surface conditions. Thus, the actual ET was used to indicate climate conditions and soil water content that might affect water budgets of lake catchments.

3 Result and discussions

3.1 Analysis on lake areal variations at decadal and inter-annual timescales

This study investigates areal variations of 21 lakes larger than 1 km^2 in the Tanggula Mountains, including 14 closed lakes (5 glacier-fed lakes and 9 non-glacier-fed lakes) and 7 upstream lakes (Table 1 and Fig. 3). The total lake area showed an overall ascending tendency but increases at different rates, which vary with different decades and lake types. The total lake area had slight changes from the mid-1970s (1262.1 km^2) to 1989 (1264.1 km^2). In the 1990s, both glacier-fed and non-glacier-fed lakes showed obvious increases in area by 53.1 and 17.9 km^2, respectively. In the 2000s, the lake area increased by 235.2 km^2, which showed much more rapid expansion rate than the first two phases. Specifically, the glacier-fed lake group contributed the major proportion (187.9 km^2, 79.9 %) to the total area increase in the 2000s. During the study period, the seven upstream lakes remained at basically unchanged extents.

Figure 3b shows the annual lake areas of glacier-fed and non-glacier-fed lake groups between 2000 and 2013 (2012 excluded due to the lack of high-quality images). It illustrates that two groups of lakes experienced rapid expansions in surface extent: 17.1 km^2/year for glacier-fed lakes and 5.2 km^2/year for non-glacier-fed lakes. However, both time series of annual lake area displayed contrasting temporal patterns. The area time series of non-glacier-fed lake group shows a batch-wise ascending pattern, with obvious increases in 2002, 2005 and 2011. The areal increment in the 3 years (65.9 km^2) accounts for about 97 % of the total increase. By contrast, glacier-fed lakes show relatively steady expansions despite at different inter-annual magnitudes. The time series of annual area variation for each lake (glacier-fed and

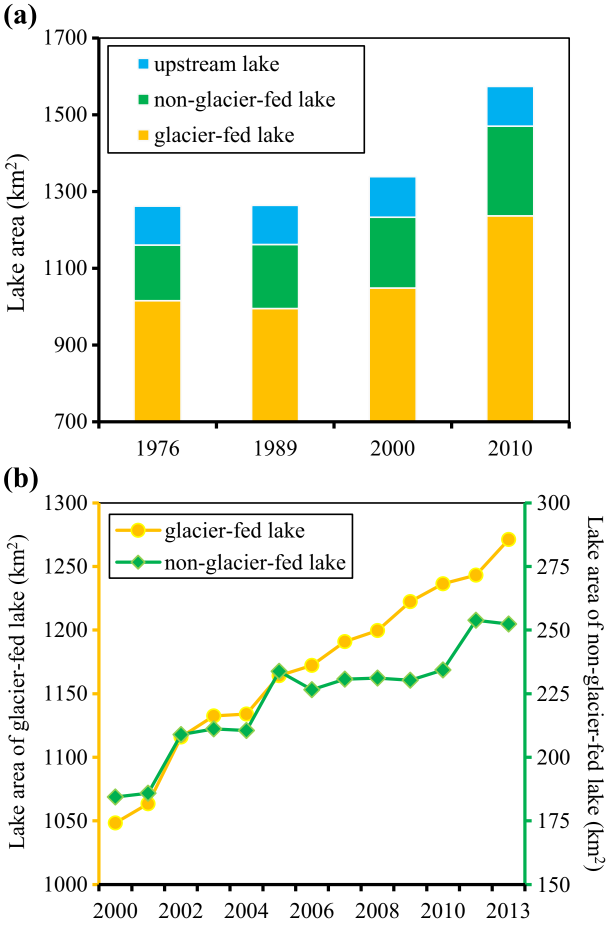

Fig. 3 Statistics of lake areal variations from the mid-1970s to 2013. (**a**) Comparison of decadal area variations for glacier-fed lake, non-glacier-fed lake and upstream lake groups in the four phases: 1976, 1989, 2000 and 2010; (**b**) time series of annual lake area for glacier-fed lake and non-glacier-fed lake groups between 2000 and 2013 (2012 excluded)

non-glacier-fed) are presented in Figure S-2. From the figure, it is clear to observe the area time series for Lake 1–5 show approximately linear ascending patterns, while time series for most non-glacier-fed lakes have upward shifts only in 2002, 2005 and 2011 and stagnate or slightly go down in other years.

3.2 Analysis on time series of lake level

The combined ICESat and CryoSat-2 altimetry provides the measurements of water level for six large lakes in the study area during 2003–2013. The examined lakes account for about 88.2 % of the total lake area. As shown in Fig. 4, six lakes all displayed rapid water level increases during 2003–2013, with the rising rate ranging from 0.159 to 0.621 m/year. In comparison, four glacier-fed lakes (0.421±0.018 m/year) showed higher growth rates than two non-glacier-fed lakes (0.171±0.036 m/year). The above analyzed contrasting patterns of temporal evolutions between glacier-fed lakes and non-glacier-fed lakes can also be revealed by water level measurements: the former group showed lasting upward tendency during 2003–2013, while the latter two lakes showed obvious upward shifts of water level mostly in 2005 and 2011, and then remained basically unchanged or declines in other years. It is worth mentioning that the two largest lakes Chibzhang Co and Dorsoidong Co reached the approximate water level and got completely interlinked around 2005. The drainage from Chibzhang Co (at higher water level) into Dorsoidong Co may explain why Dorsoidong Co had a larger increase (1.29 m) than Chibzhang Co (0.54 m) in 2005.

3.3 The climate causes of lake dynamics

The lake area/level variation reflects changes in hydrological water balance, which is controlled by combined water inputs (e.g., precipitation and glacial meltwater) and outputs (evaporation or groundwater discharge). Commonly precipitation and evaporation are two fundamental factors that have significant influence on the water budget of lakes in the endorheic basins of the plateau. This study analyzes the relationship between precipitation/evaporation and lake area variations during the period of 2001–2013. As shown in Fig. 5, time series of annual area variations of different lake types are plotted against the annual precipitation and evaporation (calculated according to the hydrological year November to October). The time series plot reveals positive correlation between precipitation and evaporation changes during the study period except for in 2001 (with a correlation coefficient of 0.8), which indicates that evaporation is largely limited by water availability in the sub-arid climate zone, as indicated in previous studies (Xu et al. 2006; Yang et al. 2014).

For the non-glacier-fed lake group, the total lake area showed close relationship with precipitation and "precipitation evaporation" variability, with correlation coefficients of 0.81 and 0.79 ($p<0.01$), respectively (as shown Fig. 5). The total lake area in 2003/04, 2007–2010 and 2013 remained largely unchanged, indicating relatively balanced water budgets associated with normal precipitation and evaporation amount in these years. In contrast, in the 3 years of 2002, 2005 and 2011, the higher precipitation and larger "precipitation evaporation" resulted in positive water budgets and lake extent enlargements (19.5 23.3 km^2). The obvious lake shrinkages mostly occurred in 2006 (−7.3 km^2), which could be largely attributed to the rather low precipitation and negative "precipitation evaporation". We further examined daily precipitation over the study area and found there were heavy rainfall events during the three wet years, as illustrated in Fig. 6. The date of heavy

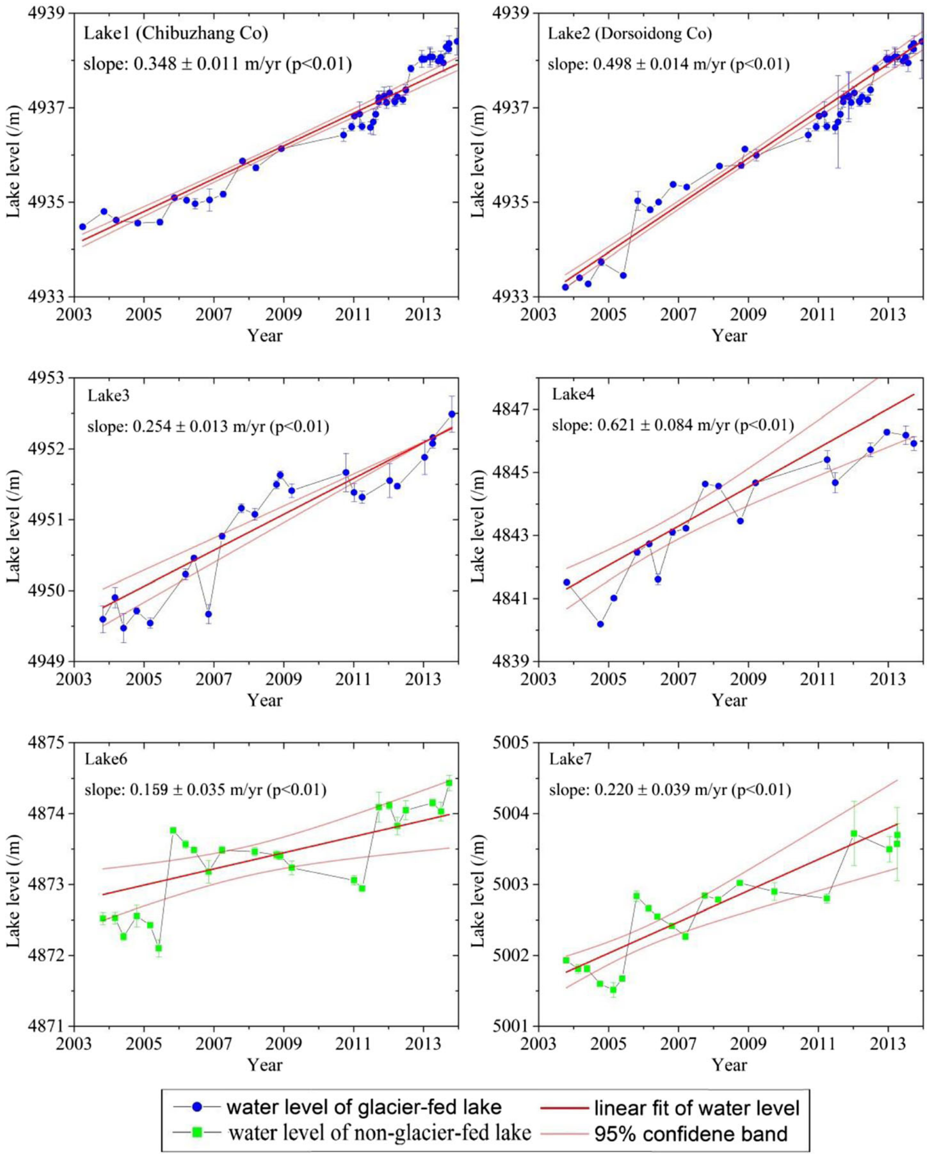

Fig. 4 Time series of lake level (Y-axis: m) derived from the ICESat (2003–2009) and CryoSat-2 (2010–2013) altimetry measurements during 2003–2013 for four glacier-fed lakes (in *blue*) and two non-glacier-fed lakes (in *green*). The *red lines* indicate the linear fit and 95 % confidence band of lake levels during the whole study period

precipitation events varied within different years. For example, more than half of annual precipitation (131.6 mm) fell during the late-July and early-August of 2005 while the consecutive heavy rainfalls in 2002 and 2011 respectively occurred in early-September and mid-June.

Compared with non-glacier-fed lakes, glacier-fed lake group was less sensitive to changes in precipitation/evaporation. The area variations of glacier fed lakes were weakly correlated with precipitation (“precipitation evaporation”) amount, with the low correlation coefficient

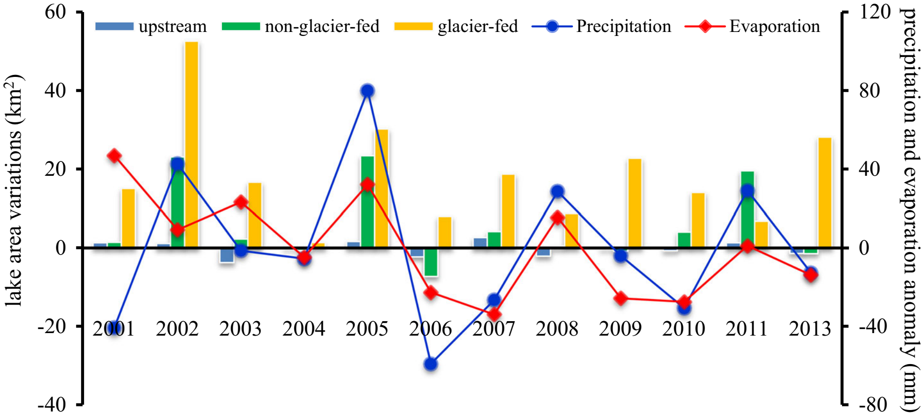

Fig. 5 Comparison of annual lake areal variations of three lake-type groups (upstream lake, non-glacier-fed lake and glacier fed lake) and annual precipitation/evaporation anomaly time series

of 0.44 (0.50). As shown in Fig. 5, glacier-fed lakes showed larger enlargements in the wet years of 2002 and 2005. However, in other relatively dry years (except in 2004), these lakes still showed obvious expansions. The relatively weaker dependence on precipitation/evaporation implies that there are other important factors controlling annual water budgets for the glacier-fed lakes. As the climatic and geomorphological conditions (e.g., lake supply coefficient that is defined as the ratio of lake catchment area to lake area, altitudes, as shown in Table 1) are basically similar between glacier-fed and non-glacier-fed lake groups, the steady growth for glacier-fed lakes could be tightly associated with the supply of glacial meltwater. Many recent studies revealed the rapid retreat and thinning of mountain glaciers on the Tibetan Plateau in the context of warming climate (Gardner et al. 2013; Ke et al. 2015; Yao et al. 2012). As there is no weather station over the study area, we used temperature observation data from the neighboring stations Tuotuohe and Anduo (shown in Figure S-3) to examine the regional warming. The two temperature time series indicate rapid temperature rising tendency between the mid-1970s and 2013, especially in the recent decade (Tuotuohe: 0.79 °C/decade, Anduo: 0.65 °C/decade, during 2000–2013). Therefore, with the rising temperature once exceeding the melt point of glaciers during ablation seasons, these lakes receive continued

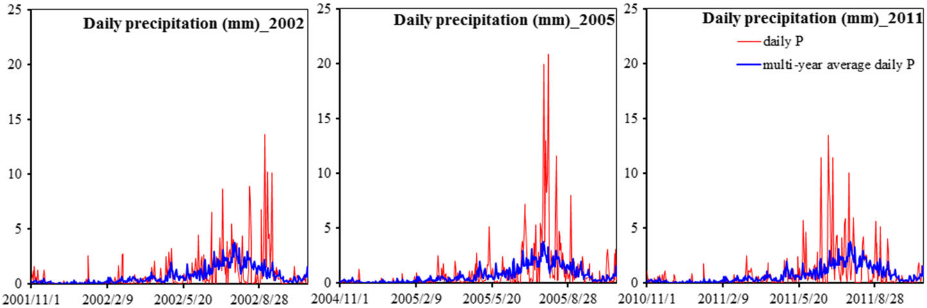

Fig. 6 Time series of daily precipitation (y-axis: mm) over the lake basins (32.5°–34.5° N, 88.5°–91.5°E) from TRMM 3B42 v7 dataset in the three wet years 2002, 2005 and 2011 (in *red*) comparing with multi-year average daily precipitation (in *blue*)

glacial meltwater supply and modulate annual water budgets more steadily compared to the influence from specific precipitation events.

3.4 The contributions of glacial meltwater and other factors to lake water budget

Based on lake level data between 2003 and 2013 for the six examined lakes, the net lake water storage variation can be roughly estimated. By area-weighted averaging the change rates of water level for four glacier-fed lakes and two non-glacier-fed lakes, the mean change rates for the two groups were approximately 0.421±0.018 m/year and 0.171±0.036 m/year, respectively. The multi-year (2003–2013) averaged areas of glacier-fed and non-glacier-fed lake groups were 1196.65 and 231.46 km^2. Thus, we estimate a net water budget of 0.544± 0.030 Gt/year (km^3/yr, assuming the lake water density to be 10^3 kg/m^3) for all of studied lakes, including 0.504±0.022 Gt/year from glacier-fed lakes and 0.040±0.008 Gt/year from non-glacier-fed lakes. Assuming that climatic factors (precipitation/evaporation) exerted comparable influences on the water budgets of glacier-fed lake group to non-glacier-fed lake group (0.171±0.036 m/year), it can be estimated that approximately half (~55.12 %) of the water level rise for glacier-fed lakes was contributed from glacial meltwater. For all lakes examined in this study, the net water storage increase from precipitation/evaporation and glacial meltwater supply were 0.244±0.015 and 0.300±0.032 Gt/year, respectively. The estimates imply that the glacial meltwater and precipitation/evaporation variation contributed equivalently to the water budget of glacier-fed lakes in the Tanggula Mountain region.

It should be noted that the glacier meltwater that contributes directly to lake water balances, is not exactly equivalent to the glacier mass balances. The meltwater amount is determined by the intensity of ice melting, mostly concentrating in ablation seasons, but not always reflect the overall mass balances of glaciers which are not only determined by the thinning rates but also the accumulation (e.g., snowfalls) over the high-altitude glaciered area. Thus, even though the Puruogangri ice field was in slightly negative mass balance probably due to increasing snowfalls (Neckel et al. 2013). it does not mean that the amount of glacier meltwater did not increase largely during that period. Previous studies (Kääb et al. 2012) also indicate that the turnover of glacier mass (the difference between glacier accumulation and ablation) increased over some areas of the TP, probably associated with the warming and wetting climate. Due to insufficient observations, we cannot directly quantify the meltwater amount released from glaciers, but our results do indicate it increased during 2000–2013. In addition, other than Puruogangri ice field, these lakes also received meltwater from glaciers in the middle and eastern Tanggula Mountains where glaciers could had experienced more negative mass balances (Gardner et al. 2013; Yao et al. 2012).

4 Summary

Based on Landsat image series and combined ICESat and CryoSat-2 altimetry data, we investigated the temporal evolution of inland lakes in the Tanggula Mountains of the central TP. Landsat-derived lake area time series indicate that these lakes experienced a considerable expansion by 28.9 % since the mid-1970s. The lake growth became obviously more rapid after about 2000. We separated these lakes into glacier-fed closed lake, non-glacier-fed closed lake and upstream lake groups, to understand the detailed evolution processes of different lake types. The results show that the non-glacier-fed lakes displayed a batch-wise growth pattern, with obvious expansions in 2002, 2005 and 2011 but stagnation or slight shrinkage in other years, while glacier-fed lakes showed steady expanding tendency. In addition, the upstream lakes remained unchanged by self-regulation of seasonal drainage. The inconsistent changing patterns between non-glacier-fed lake and glacier fed lake are also confirmed by lake level changes derived from satellite altimetry during 2003–2013. Two non-glacier-fed lakes had large water-level rises only in 2005 and 2011, and showed slight declines or stagnation in other years. In contrast, four glacier-fed lakes showed obvious water-level rises in other years besides the noticeable growth in the 2 years. The large expansions of non-glacier-fed lakes in specific years were strongly related to higher precipitation and larger "precipitation–evaporation" differences, with high correlation coefficients of 0.81 and 0.79. For glacier-fed lakes, area variations showed weak correlations with precipitation (or "precipitation–evaporation") variability, which could be attributed to annual glacial meltwater modulation.

By combining the lake area and water level measurements, we estimated the net water budget of 0.544±0.030 Gt/year for all examined lakes. Assuming the similar precipitation/evaporation conditions for both non-glacier-fed and glacier-fed lake groups, it can be concluded that glacial meltwater supply contributed approximately half of water level rise for glacier-fed lakes, while for the whole lakes, the increased lake water storage from the glacial meltwater supply (0.300±0.032 Gt/year) slightly overweighed precipitation/evaporation influence (0.244±0.015 Gt/year). This study characterized distinct inter-annual variation patterns of different lake groups (glacier-fed and non-glacier-fed) in the central Tanggula Mountains, and provided remote sensing based quantitative estimates of contributions from glacial meltwater and precipitation/evaporation to lake growth of different types since 2000. This study is helpful to better understanding of spatial and temporal variability of area and water level for Tibetan lakes, and evaluation of different contributors, and can be extended to other areas of the plateau where field observations are lacking currently.

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