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ORIGINAL ARTICLE

Lake dynamics and its relationship to climate change on the Tibetan Plateau over the last four decades

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Abstract The high sensitivity of the Tibetan Plateau (TP) to global warming is ascribed not only to its high altitude and low temperature but also to the change in the components of water cycling, such as glaciers' retreat, permafrost degradation, and lakes' shrinkage or expansion. Among the components, change in lakes attracts more attention as lakes are crucial for local water management and are easier to monitor. But, how water cycling components respond to global change remains unclear, although they are crucial in understanding the regional environmental change. Lakes, glaciers, and permafrost data derived from meteorological records and remote sensing images were used to detect the change of the water environment on the TP from 1971 to 2013. The climate on TP changed toward a warm-humid condition in the last four decades. Three-quarters of the lakes were significantly expanded over the TP, and the summed area of all the lakes increased by 6061 km^2 from 1975 to 2010. Panel regression showed that annual average air temperature (T), annual precipitation (P), and reference crop evapotranspiration (ET_o) regulate the change in lake surface area (LSA) on the entire TP. The change in LSA is more related to the change in P than in the other two factors, even in the catchment where lakes are recharged by water from glacier melting and permafrost degradation, especially in extremely arid and arid climate zones. Elevation and size affected the sensitivity of lakes to climate change with lakes in a high-elevation area more sensitive to T and small lakes more sensitive to T, P, and ET_o. Warming-induced glacier's retreat led to the significant lake expansion, while permafrost degradation might be responsible for the lake shrinkage in the seasonally frozen ground area due to the related cryogenic waterproof layer downward. Our results about the responses of lakes to climate change in different catchments were in accordance with the findings of previous studies about several typical lakes, which implied that overall response of all the lakes to climate change could be obtained by examining several typical lakes in the catchment level.

Keywords Anusplin interpolation · Climate change · Lake change · Panel regression model · Remote sensing · Tibetan Plateau

Introduction

The water environment greatly impacts both human activities and natural ecosystem functions and services (Ge 2005; Immerzeel et al. 2010). Global warming and the associated change in water cycling have aroused extensive public awareness since the mid-twentieth century (IPCC 2014). Climate change can affect the water environment; for instance, continental regions show a net increase in permanent water due to reservoir filling and climate change (Pekel et al. 2016). Meanwhile, the water environment can feedback to the global change due to the energy balance through the transportation and phase change of water. The Tibetan Plateau (TP), the highest plateau worldwide with an average elevation

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exceeding 4000 m a.s.l., has an area about 2.57×10^6 km^2 (Zhang et al. 2002). TP, called as the “Asian Water Tower,” is the origin of several major rivers in South and Southeast Asia, which ensures the water security to more than one billion people in China and other downstream countries (Immerzeel et al. 2010). Lakes and glaciers are dominant components for the TP water sources, and their status quo and future are strongly impacted by climate change. Climate warming on the TP is earlier and with a higher magnitude than other regions in the same latitude (Duan et al. 2008). Moreover, rising precipitation (You et al. 2012; Yue et al. 2013), decreasing wind speed (Jiang et al. 2010; Yang et al. 2011), glaciers retreat (Pu et al. 2008; Yang et al. 2008), permafrost degradation (Hinzman et al. 2005; Li et al. 2012), and snow cover reduction have been widely observed, which might accelerate the hydrological dynamic, thus change the local and continental water balance (Kang et al. 2010; Palazzi et al. 2013).

Lakes, one of the primary water sources on the TP, are crucial for local water management and in the understanding of the response of the natural ecosystem to climate change. Due to the prominent role of lakes, changes in the lake area and its relationship with climatic factors has attracted much attention. The satellite data have been extensively used to investigate the lake resource (Song et al. 2013; Zhang et al. 2013), to monitor the lake surface level (Kleinherenbrink et al. 2015; Phan et al. 2012), and to study the seasonal (Song et al. 2014a) and long-term (Lei et al. 2013; Song et al. 2014b) patterns of lake dynamics to climate change (Liao et al. 2013; Liu et al. 2009). Responses of lakes to climate change show temporal and spatial variation because of heterogeneous climate backgrounds and morphologies across biomes (Song et al. 2014a). Site-specific or catchment-level studies have shown the quick lake expansion in the middle part of the TP (Meng et al. 2012; Wang et al. 2013), a contrast to the sharp lake decline in the southern TP (Nie et al. 2013). These contrary changes in individual lakes were attributed to climate warming, glacier melting, precipitation, and evapotranspiration change (Lei et al. 2013; Yang et al. 2014). Lake area varies dramatically within a year, but it shows minor seasonal variation from September to December (Li et al. 2011). The feature of the seasonal dynamic (seasonal change less than 2%) during this period provides the potential use of lake area to study the lake area change in the period.

The investigation of individual lakes provides us a view of the lake area and its response to climate change. But most of the studies about individual lakes and its relationship with climate have been confined in several basins rather than in the whole TP due to the disparate distributions of lakes and the meteorological stations (e.g., Liu and Chen 2000; Song et al. 2014b; Wan et al. 2014; Wang et al. 2014), as different natural conditions have different water features and might result in various responses of lakes to climate change. Whether the conclusions of the response of individual lake to climate change in previous studies are representative of all lakes in the whole TP remain uncertain. Therefore, the objectives of this study were to investigate the lake area change over the whole TP, and to examine the response of all lakes as a whole to climate change by taking full advantage of the easily accessible and widely used data.

The meteorological data, Landsat images, topographic maps, SRTM DEM data, division maps of catchments and climate zones, as well as distribution maps of glaciers and permafrost across the TP were used in this study. A Lake Expansion Index was defined to indicate the LSA change. The Anusplin Interpolation method was used to obtain the spatial variations of climate variables throughout the entire TP. Panel regression model was applied to investigate the influences of climate change and related water environmental factors change on TP lakes.

Materials and methods

Data collection

The monthly maximum, minimum, and mean air temperature ($T_{\max}$, $T_{\min}$, T_{mean}), precipitation (P), mean relative humidity (RH), sunshine hours (n), and wind speed at 10 m height (U_{10}) were collected from 241 standard meteorological stations in the years 1971–2013. The meteorological stations include 79 on the TP (Fig. S1, Table S1) and 162 of them in the surrounding area of the TP. The records of all the meteorological stations have complete observation datasets. Climate values from 79 weather stations on the TP were used for climate change analysis, and values from all 241 weather stations were used for interpolation of climatic variables over the entire TP.

Small lakes are unstable because P variation can change lake size in a very short time. The dramatic emergence and disappearance of small lakes may result in an unbalanced model and high estimation errors (Jeffrey 2009). Therefore, lakes with an area smaller than 10 km^2 were excluded in this study.

Landsat MSS, TM/ETM images (103) from September to December 1975, 1990, 2000, and 2010 were collected for interpreting lake areas over the TP, according to the characteristic of TP climate condition (Supplement 1). In addition, a few topographic maps of 1:100,000 scales were used when RS images were absent in the 1970s. Albers Equal Area Projection based on the WGS-84 Coordinate System was used for all of the images and maps above.

Elevation data of the TP come from Shuttle Radar Topography Mission Digital Elevation Models (SRTM DEMs). The distribution of identified lakes and 79 meteorological stations, as well as catchment regionalization (modified by National Administration of Surveying, Mapping and Geoinformation), were displayed in Fig. S1. The distribution of climate patterns (modified by SinoMaps Press 1990), glaciers (Wu and Li 2003), and frozen ground (Li and Cheng 1996) across the TP was shown in Fig. S2.

Lakes characteristics

Based on the environmental data above, lakes on the TP were classified into different groups by the following attributes: (1) regional catchment basins, (2) climate zone, (3) lake size, (4) elevation, (5) distance to glaciers, and (6) frozen ground type. More details about lake classification were shown in Supplement 2 and Fig. S3.

Calculation

The estimation of evapotranspiration

The reference crop evapotranspiration (ET_o) is quite an important component of the hydrological cycle which represents the evaporative power of the atmosphere. The estimation of ET_o follows the Penman-Monteith model, proposed by the Food and Agriculture Organization of the United Nations (Allen et al. 1998, Supplement 3).

Aridity index and lake expansion index

Aridity index is an indicator of climate aridity based on the balance between precipitation and evapotranspiration: $I_A = P/ET_o$ (UNESCO 1979).

According to the results of Li et al. (2011), 2% of the lake area change rate is considered to be the threshold for the changing trend of lakes. Thus, lakes with relative change larger than 2% were designated as expanded lakes, and lakes with relative change smaller than −2% were designated as shrank lakes. The lake expansion index (I_E = increased area/decreased area) was used to indicate the overall change of lakes across the TP. The I_E was calculated for each specific catchment, climate zone, lake size, elevation, frozen ground, and close to or far from glaciers (Fig. S3) during each period. The value of I_E higher than 1 means a general lake expansion tendency while I_E smaller than 1 means a general lake shrinkage tendency. A higher absolute value of I_E represents a more dramatic lake surface area (LSA) change. Different from relative change rate, which is used for representing the change of a specific lake, I_E is used for identifying the general change of a group of lakes. According to classifications in Fig. S3, I_E of each kind of lakes in each period was calculated, respectively.

Anusplin interpolation

Anusplin interpolation is a spatial interpolation technique for weather station data to determine climate variables throughout the entire study region. Annual T, P, and estimated ET_o in 241 meteorological stations were interpolated by the Anusplin software (version 4.3, The Australian National University, Supplement 3) to obtain these climatic factors in a spatial resolution of 1 km in 1975, 1990, 2000, and 2010.

Statistics

Trend test

The Mann-Kendall non-parametric trend test (M-K test) is a rank-based method that has been identified as one of the most robust techniques available to uncover and estimate linear trends in environmental data (Mann 1945; Kendall 1975; Zhang et al. 2011). The test was employed to investigate the changing trend of meteorological-related variables. The changing trend was significant at the 1%, 5%, and 10% level when the absolute value of the statistic Z was greater than 2.575, 1.960, and 1.645.

Panel regression model

The panel regression model including both a cross-sectional and a time series dimension dataset (Jeffrey 2009) was used to investigate the effects of T, P, and ET_o on lake change. The LSA and climatic factors in each time point developed a cross-sectional dimension, and the four-time points (1975, 1990, 2000 and 2010) developed a time series dimension. The LSA and climate data in the four-time points then were analyzed simultaneously in the panel regression model (Supplement 3).

Results

Climate changes on the Tibetan Plateau

Observed climate change on the Tibetan Plateau

The T and P both demonstrated an increasing trend in the last 43 years with the increasing rate of 0.35 °C and 7.41 mm per decade, respectively (Fig. 1a–b). While ET_o showed a decreasing trend with a rate of 8.64 mm per decade (Fig. 1c). The I_A across the TP showed an increasing tendency (Fig. 1d), representing a more humid climate across the TP.

The TP experienced a relatively cold climate during 1971–1997 and then a relatively warm climate during 1997–2013

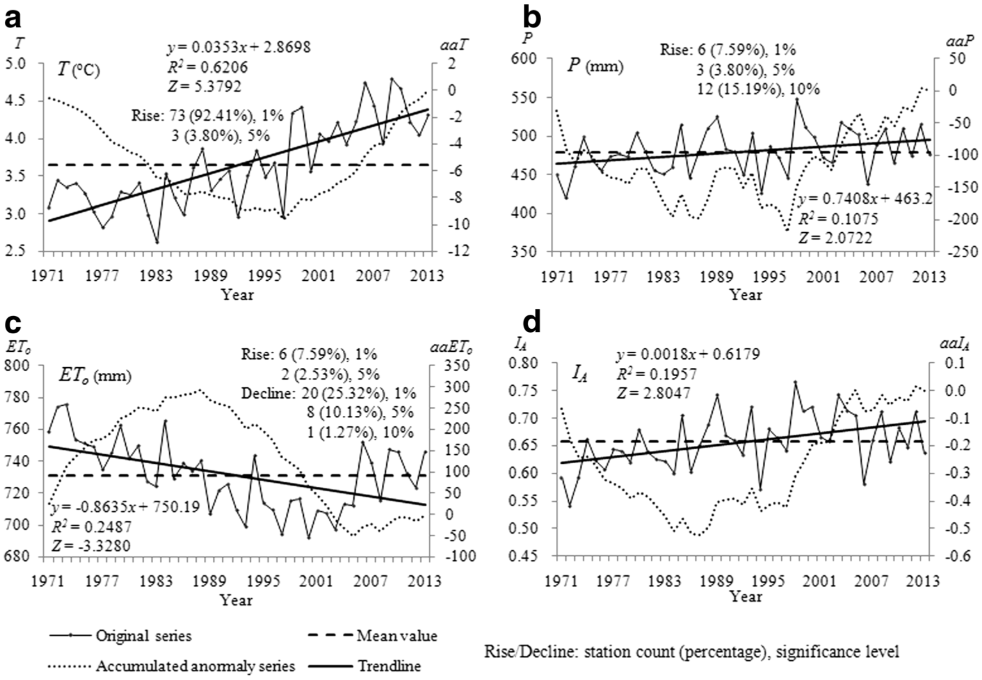

Fig. 1 Observed T, P, ET_o, and I_A changes on the Tibetan Plateau during 1971–2013

(Fig. 1a). High variation in P induced frequent dry-wet cycles (dry periods: 1971–1987, 1990–1997; wet periods: 1987–1990, 1997–2013; Fig. 1b). ET_o was higher in 1971–1988 and 2005–2013 than in 1988–2005 all over the TP (Fig. 1c). The TP was relatively arid in 1971–1987 and then turned to a relatively humid period (Fig. 1d).

Interpolated climate changes on the Tibetan Plateau

By using the Anusplin software, the interpolated T, P, ET_o and I_A (I_A = interpolated P/interpolated ET_o) in 1975, 1990, 2000, and 2010 were obtained. The mean Pearson correlations between interpolated and observed T, P, and ET_o data from 79 weather stations is 0.917 (ranges from 0.814 to 0.996) with $p = 0.000$, which means that the interpolated values are reliable in further analysis. Then, the annual change rate of each climatic factor during each period (1975–1990, 1990–2000, 2000–2010, and 1975–2010) was displayed in Fig. 2. The T over the whole TP increased dramatically, especially in the last decade. The P over the whole TP showed an increasing trend, but the P change varied spatially in different parts of the TP, with a contrast tendency in the northern and southern TP. P generally decreased on the northern TP while increased notably on the southern TP during the period of 1975–1990. By contrast, P increased clearly on the northern TP while decreased significantly on the southern TP during the period of 2000–2010. Although the ET_o increased in the last decade, the dramatic decrease in earlier years resulted in a decreasing trend in the last four decades. The variation in change tendency of I_A was similar to P.

Lake surface area changes on the Tibetan Plateau

There are 314 lakes with a surface area above 10 km^2 (Fig. S1) on the TP. The total LSA expanded by 199.25 km^2 from 1975 to 1990, 523.57 km^2 from 1990 to 2000, and 5338.19 km^2 from 2000 to 2010 (Fig. 3).

Both the number of expanding lakes and the expanding rate kept increasing in the last four decades. The I_E of all TP lakes was 1.19 in 1975–1990, increased to 1.92 in 1990–2000, and increased by about 20 times in 2000–2010 (Fig. 4).

The I_E in the Chiangtang Plateau and River Source Region increased in the last four decades, from 1.19 and 0.83 in the first period to 94.7 and 11.77 in the last decade, respectively. I_E in the northeastern basin decreased from 1.3 to 0.10 (from 1975 - 1990 to 1990–2000) firstly and then increased to 50.29 (2000–2010). Contrast change was found in the southern TP, with an I_E increased from 0.96 to 52.04 in the first two periods, and then decreased to 0.01 in the last decade. Most of the I_E values in each climate zone were greater than 1, except those in the extremely arid region during 1990–2000 (0.03) and in the semi-humid region in the first two periods (0.49 and 0.87). I_E was much greater in the extremely arid and arid region (443.08) than in the semi-arid and semi-humid region (15.05 and 4.74). I_E was higher than 1 in almost all-sized lakes, especially in the last decade, except those in small- and super-sized during 1975–1990 (0.64 and 0.49) and large-sized during 1990–2000 (0.77). In almost all elevation regions, I_E was greater than 1 except those in the low-elevation region during 1990–2000 (0.11) and in the high-elevation region in the first period (0.48). The I_E

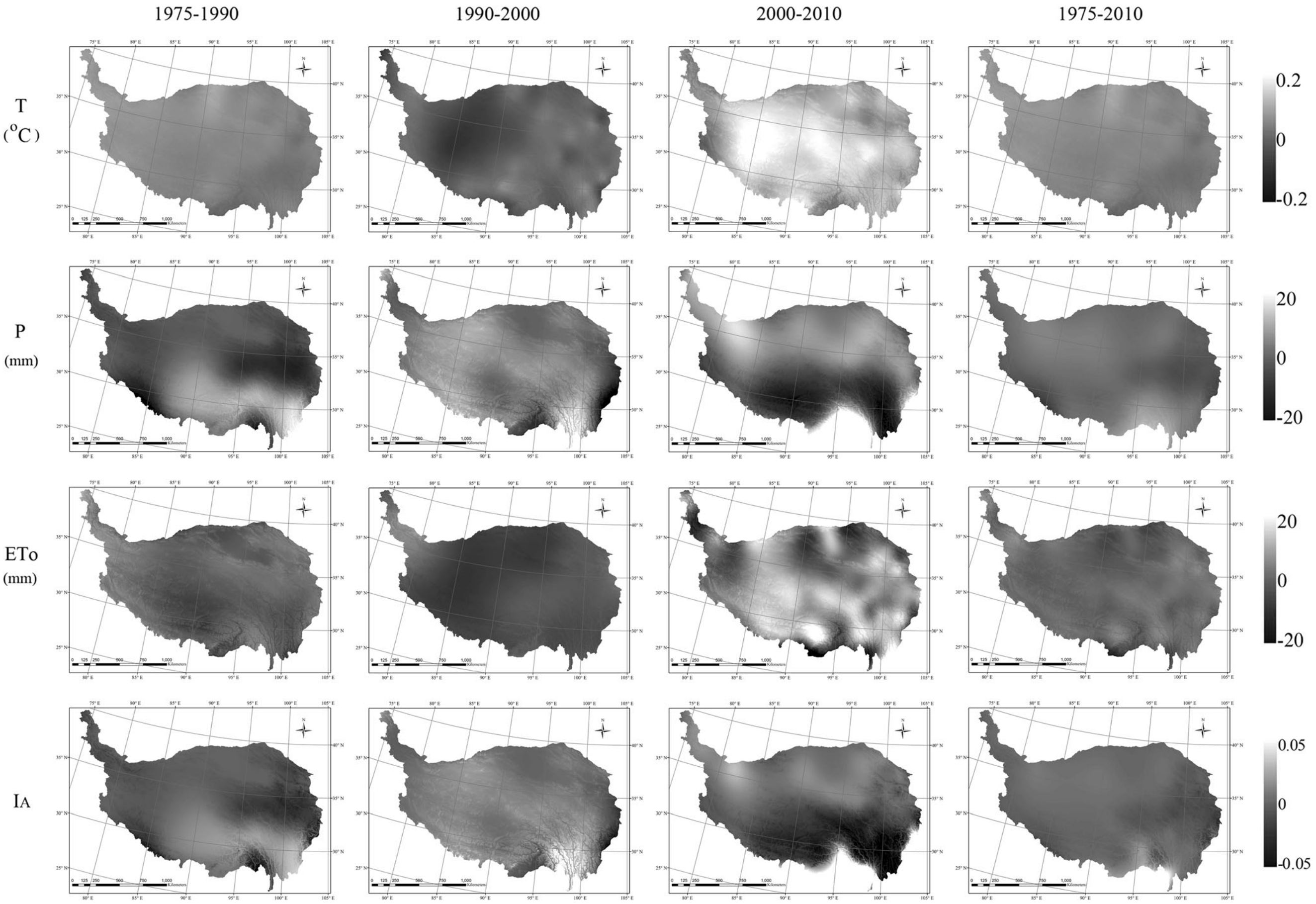

Fig. 2 Annual change rate of interpolated T, P, ET_o, and I_A on the Tibetan Plateau during 1975–1990, 1990–2000, 2000–2010, and 1975–2010

for each kind of glacier distance classification was much greater than 1 in the last four decades. From *G1* to *G4*, I_E reduced from 204.54 to 10.92. I_E increased in permafrost regions from 0.64 to 601.84, and decreased in seasonally frozen ground from 7.71 to 0.90 in the last three periods (Table 1).

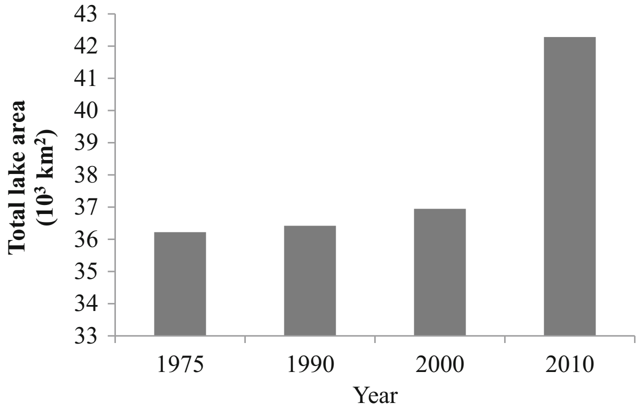

Fig. 3 Total lake area of the Tibetan Plateau in 1975, 1990, 2000, and 2010

The influence of different factors on lake surface area change

Panel regression results of all 314 lakes model and 285 inland lakes model showed significant correlations between climatic variables and LSA (Table 2). Change in T (0.0676 and 0.0709 with $p = 0.000$) and P (0.0013 and 0.0014 with $p = 0.000$) positively correlated with LSA while change in ET_o negatively (−0.0007 and −0.0008 with $p = 0.000$) correlated with it.

In all 23 models for each kind of lakes, P showed significant impacts in all models, T showed significant impacts in 21 models, and ET_o showed significant impacts in 15 models (Table 3). From the extremely arid region to semi-humid region, the coefficients between P and LSA reduced from 0.0050** to 0.0002*. The coefficients (absolute value) of T, P, and ET_o reduced from the small lakes model to the large lakes model (T reduced from 0.0939** to 0.0425*, P reduced from 0.0014** to 0.0002*, ET_o reduced from 0.0009* to 0.0003). From low-elevation to high-elevation regions, the T coefficient increased from 0.0566* to 0.0786**, and the ET_o coefficient (absolute value) reduced from 0.0016* to 0.0007. The coefficients between T and LSA reduced from 0.1178* in

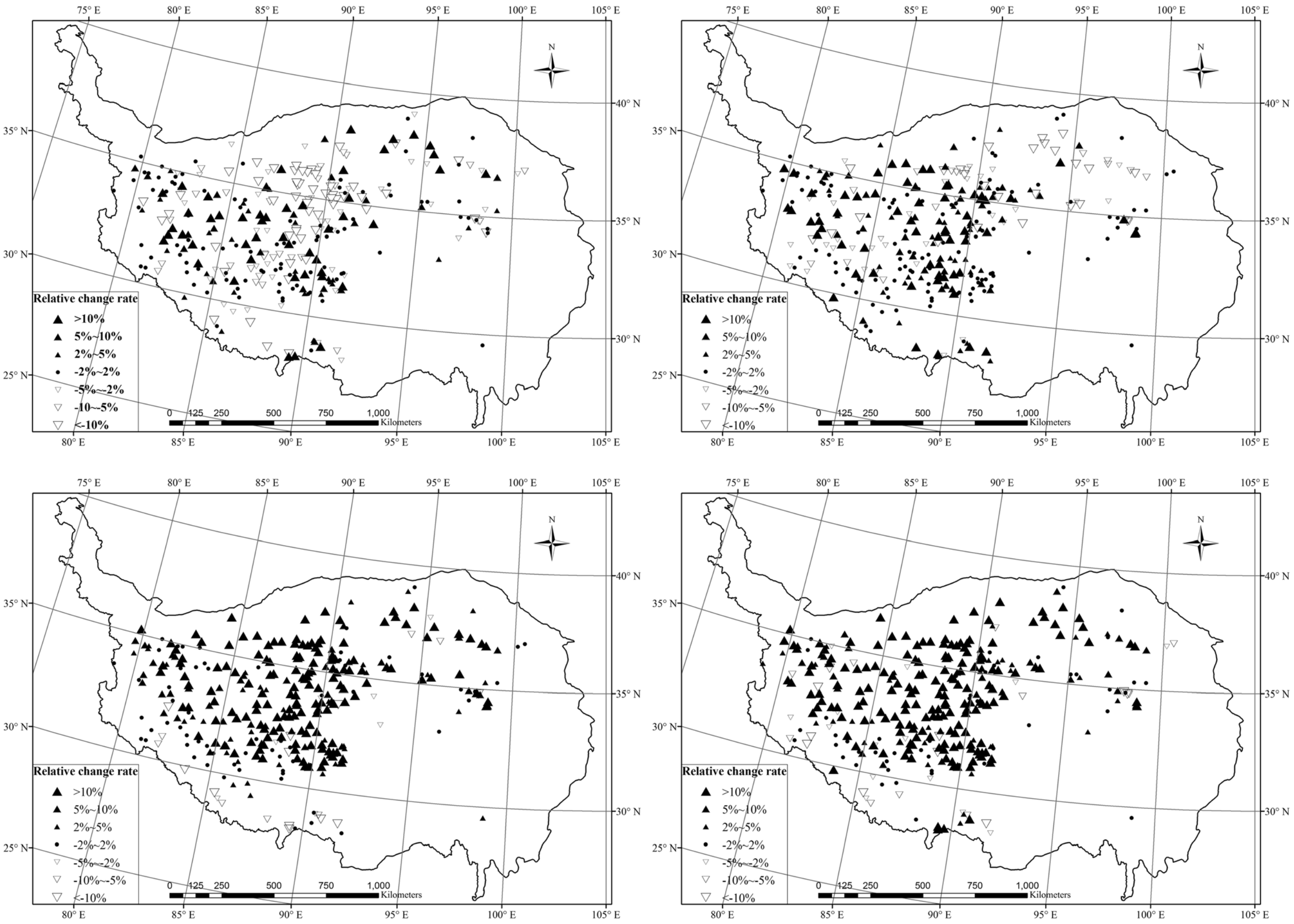

Fig. 4 Statistics of relative lake area change rate and I_E during 1975–1990, 1990–2000, 2000–2010, and 1975–2010

the *G1* model to 0.0372** in the *G4* model. From the permafrost region to the seasonally frozen ground region, the coefficients of T and P reduced from 0.0795** and 0.0020** to 0.0251* and 0.0001*, respectively, and the absolute value of the ET_o coefficient increased from 0.0010 to 0.0005*.

Discussion

The panel regression model is an advanced method for regression analysis, and one of the advantages of the panel regression method is that it can be used to analyze multi-time spatial data simultaneously, and obtain the results through a comprehensive analysis (Jeffrey 2009). Thus, we can analyze the effects of change in T, P, and ET_o on LSA change over the full periods of time across the whole TP.

Climate and lake surface area change on the Tibetan Plateau

Results about T, P, and ET_o change in the current study were in agreement with former studies (Liu et al. 2009; Yue et al. 2013). The TP climate shifts from cold-arid to warm-humid with a tipping point in 1998 in last four decades (Fig. 1, accumulated anomaly series). Change in interpolated P was contrasted in the northern and southern TP. The increase in P in the northern TP and decrease in the southern TP consolidated the observed wetting in the northwestern area and drying in the eastern and southern area (Gao et al. 2015). Weakened water vapor exchange between the Asian monsoon region and the TP due to wind stilling was considered to be responsible for the reduced precipitation in the monsoon-impacted southern and eastern TP (Yang et al. 2014). Interpolated climate variables demonstrated the same trend as the observed data. The displayed spatial variations derived from interpolated data were more clearly than observed values. Similar to the results of several specific lakes (Liao et al. 2013; Wang et al. 2013), lake area in the whole TP expanded, especially in the last 10 years, which suggested the expansion of lakes was widespread on the TP region in the last few decades. Spatially, lakes in central TP expanded significantly while those in southern and eastern TP shrank notably (Fig. 4).

Table 1 I_E statistics of different kinds of lakes

Classification (lake count)		1975–1990	1990–2000	2000–2010	1975–2010
Catchment	Chiangtang Plateau: *Ca1* (237)	1.19	5.71	94.70	64.70
	Northeastern basin: *Ca2*, 8 (33)	1.30	0.10	50.29	7.36
	River source region: *Ca3*, *5*, *6*, *9* (25)	0.83	1.07	11.77	4.48
	Southern TP: *Ca4*, *7* (18)	0.96	52.04	0.01	0.63
	Indus river catchment: *Ca10* (1)	Stable	Expanded	Stable	Expanded
Climate zone	Extremely arid (17)	2.71	0.03	47.78	No shrank lake
	Arid (37)	0.89	3.82	No shrank lake	443.08
	Semi-arid (240)	1.06	5.71	19.25	15.05
	Semi-humid (20)	0.49	0.87	24.18	4.74
Lake size (average area: x, km^2)	Small-sized: $10 \le x < 30$ (106)	0.64	2.09	24.23	15.78
	Medium-sized: $30 \le x < 100$ (127)	1.06	4.30	16.05	38.18
	Large-sized: $100 \le x < 500$ (68)	1.87	0.77	90.86	59.12
	Super-sized: $x \ge 500$ (13)	0.49	No shrank lake	20.47	6.55
Elevation (y, m)	Low: $y < 4000$ (23)	1.50	0.11	63.52	10.32
	Mid-low: $4000 \le y < 4500$ (53)	1.69	3.57	4.90	9.51
	Mid-high: $4500 \le y < 5000$ (205)	1.01	5.83	51.44	46.71
	High: $y \ge 5000$ (33)	0.48	10.16	21.41	9.54
Distance to glacier (z, km)	*G1*: $z < 30$ (114)	3.23	6.35	89.47	204.54
	G2: $30 \le z < 60$ (105)	0.75	5.65	13.80	29.86
	G3: $60 \le z < 100$ (53)	0.78	3.25	18.91	11.22
	G4: $z \ge 100$ (42)	1.71	0.74	40.19	10.92
Frozen ground type	Permafrost[a] (163)	0.64	4.26	601.84	154.32
	Island permafrost (19)	1.94	1.18	12.98	11.80
	Seasonally frozen ground (132)	7.71	3.85	0.90	3.68

[a] Hala Lake is the only one lake allocated in the discontinuous permafrost region. And because this lake is situated in a relatively continuous permafrost region (the northeastern part of the TP), it was classified as a permafrost region lake

LSA change was generally consistent with climatic variables, especially with the change in P (Figs. 2 and 4). A significant effect of P on LSA in all 23 models (Table 3) also implied that P was a crucial driving force of LSA changes. The influences of T, P, and ET_o on LSA varied among different kinds of lakes. The distance to glaciers and frozen ground also affected the LSA change, which suggested that LSA was comprehensively affected by different factors.

Table 2 Results of panel regression model estimations

314-lake model			285-lake model		
Variables	Coefficient	p value	Variables	Coefficient	p value
Constant	0.3045*	0.042	Constant	0.2012	0.211
T	0.0676**	0.000	T	0.0709**	0.000
P	0.0013**	0.000	P	0.0014**	0.000
ET_o	−0.0007**	0.000	ET_o	−0.0008**	0.000
R^2	0.27	0.000	R^2	0.29	0.000

Dependent variable: standardized LSA

*Significance level, 5%; **significance level, 1%

The responses of different kinds of lakes to climate warming on the Tibetan Plateau

The balance between water input from precipitation and output from evapotranspiration affects the lake water storage. The significant positive correlation between P and LSA (Tables 2 and 3) indicates the effect of P through direct water recharge into the lake. The significant negative correlation between ET_o and LSA suggests (Tables 2 and 3) the impact of water output from the lake basin on LSA. Thus, the increase in P accompanied by a decrease in ET_o (Figs. 1 and 2) could lead to an overall lake expansion across the TP in the last four decades (Bracht-Flyr et al. 2013; Wang et al. 2013).

A warmer climate can reshape the water environment remarkably (e.g., Hinzman et al. 2005; Pu et al. 2008). For instance, warming-induced glacier retreat and permafrost degradation are thought to be important water sources for lake expansion (Zhang et al. 2011; Walvoord and Kurylyk 2016). Groundwater storage has been found to increase in the last decade on the TP (Xiang et al. 2016). The increase in groundwater storage indicates a considerable amount of melting water, and more infiltration into the underground, thus results in

Table 3 Panel regression results of each kind of lakes

Classification (lake count)		Constant	T	P	ET_o	R^2
Catchment	Chiangtang Plateau: *Ca1* (237)	0.2229	0.0725**	0.0015**	−0.0008*	0.32
	Northeastern basin: *Ca2*, *8* (33)	−0.3442	0.1074*	0.0005**	−0.0014**	0.19
	River source region: *Ca3*, *5*, *6*, *9* (25)	0.8911*	0.0100	0.0004*	−0.0001	0.07
	Southern TP: *Ca4*, *7* (18)	1.5969**	0.0169	0.0013**	−0.0008	0.12
Climate zone	Extremely arid (17)	−3.9200*	0.0032*	0.0050**	−0.0039*	0.46
	Arid (37)	−0.3928*	0.0248*	0.0022**	0.0016	0.42
	Semi-arid (240)	0.4283*	0.0686**	0.0012*	−0.0005**	0.26
	Semi-humid (20)	0.9328**	0.0149*	0.0002*	1.16e-06	0.13
Lake size (average area: x, km^2)	Small-sized: $10 \le x < 30$ (106)	0.0777	0.0939**	0.0014**	−0.0009*	0.30
	Medium-sized: $30 \le x < 100$ (127)	0.4327	0.0898**	0.0014**	−0.0005*	0.31
	Large-sized: $100 \le x < 500$ (68)	0.4158	0.0687*	0.0009**	−0.0006	0.18
	Super-sized: $x \ge 500$ (13)	1.2178**	0.0425*	0.0002*	0.0003	0.25
Elevation (y, m)	Low: $y < 4000$ (23)	−1.1105	0.0566*	0.0014**	−0.0016**	0.27
	Mid-low: $4000 \le y < 4500$ (53)	1.1785**	0.0560**	0.0007*	−0.0004*	0.18
	Mid-high: $4500 \le y < 5000$ (205)	−0.0501	0.0693**	0.0016*	−0.0010*	0.33
	High: $y \ge 5000$ (33)	0.2720	0.0786**	0.0010*	0.0007	0.28
Distance to glacier (z, km)	*G1*: $z < 30$ (114)	0.1679	0.1178*	0.0012**	−0.0008*	0.25
	G2: $30 \le z < 60$ (105)	0.3666	0.1173**	0.0016**	−0.0005*	0.33
	G3: $60 \le z < 100$ (53)	0.6479	0.0582**	0.0007*	−0.0004**	0.33
	G4: $z \ge 100$ (42)	−0.1079	0.0372**	0.0016**	−0.0010*	0.25
Frozen ground type	Permafrost (163)	0.0197	0.0795**	0.0020**	0.0010	0.36
	Island permafrost (19)	0.4144	0.0386**	0.0007**	−0.0004*	0.16
	Seasonally frozen ground (132)	1.3922**	0.0251*	0.0001*	−0.0005*	0.18

Dependent variable: standardized LSA

*Significance level, 5%; **significance level, 1%

lake expansion. The different responses of each kind of lakes to climate change will be discussed according to the classifications listed in Table 1.

Catchment

According to the division basis (National Administration of Surveying, Mapping, and Geoinformation 1982), lakes classified in the same catchment share almost the same natural condition and drainage characteristics. A lake is an important part of the TP water environment, and the area is much easier to monitor than other water elements. Thus, the most meaningful and effective way to understand regional water environmental change is to analyze lake area change and its response to climate change in the catchment scale.

A significant effect of T, P, and ET_o on LSA in the Chiangtang Plateau and northeastern basin (inland catchments), and only significant effect of P in the river source region and southern TP (inland and outflow catchments) suggested that inland lakes were more sensitive to climate variables (Table 2). Many previous studies of specific lakes indicated the same result. For instance, the shrinkage of Qinghai Lake (in Northeastern Basin) during 1959–2000 (Li et al. 2007; Qin and Huang 1998) and the expansion of Nam Co (in the Chiangtang Plateau) in the last four decades (Zhu et al. 2010) were attributed to changes in T, P, and ET_o. The shrinkage-expansion of Eling Lake (in the river source region) in the last three decades (Li et al. 2010) and the expansion-shrinkage of lakes in the Peiku-Yamdrok basin (in Southern TP) in the past three decades were related to rainfall variation. The similar trend of specific lakes and lakes all over the TP and the similar driving forces implied that the overall response of all lakes could be obtained by examining several typical lakes in the catchment level.

Climate zone

The significant effect of T and P on LSA in all climate zones but the effect of ET_o on LSA only in the extremely arid and semi-arid regions implied that the influences of T and P on LSA were greater than ET_o. Moreover, the decreasing coefficients of LSA with P from the semi-humid region to extremely arid region suggested the greater impact of P on LSA with increasing aridity, which indicated that P change was a primary factor of LSA change, especially in water-limited environments.

Lake size

The significant effect of T and P on LSA in all sizes of lakes but the effect of ET_o on LSA only in small- and medium-sized lakes also implied that the influences of T and P on LSA were greater than ET_o. The higher absolute regression slopes of LSA to T, P, and ET_o in small lakes than in large lakes (Table 3) supported the findings that small lakes were more sensitive to climate change than large lakes (Song et al. 2013; Zhang et al. 2014). Generally, large lakes have wider basins with complicated environments and ecosystems, which ensured their strong capacities to keep stable and resistance to climate change.

Elevation

The higher regression slopes of LSA to T but lower of LSA to ET_o (Table 3) with increasing elevation might imply the indirect effect of glaciers on lakes, as most of the glaciers (> 80%) across the TP are in a high-elevation region (≥ 5000 m). In the higher elevation region, melting water from the glaciers is a more important source of water recharge into lakes, which supplies a more sensitive response of LSA to T change.

Coupled with our results of ET_o change had a smaller influence on LSA in higher elevation regions (Table 3, Elevation), ET_o change also had a less influence on LSA in permafrost regions than island permafrost and seasonally frozen ground regions (Table 3, Frozen ground type). As there was more frozen water stored in glaciers and permafrost regions, we conjectured that less liquid water (free water) in the lake environments might be a reason for the minor impact of ET_o on LSA. Nevertheless, more researches are required.

Glacier retreat

Lakes closer to glaciers have more dramatic LSA expansion tendencies. Greater influence of T on LSA and more dramatic LSA expansion in lakes closer to glaciers than those far from glaciers suggested the indirect effect of glacier melting resulted from an increase in T on LSA change. The melting could recharge into lakes, thus leads to lake expansion. Among climatic factors, T was the key factor in the development and retreat of glaciers (Su et al. 1999). Although glacier changes were time-lagged to temperature changes, they had a well-coupled correlation (Gao et al. 2000). A few studies have demonstrated that the glaciers retreat across the TP in the last few decades due to a warmer climate (Nie et al. 2010; Yao et al. 2007). Quantitative studies in Nam Co also suggested that increased glacier melt could be part of the most important reasons for lake expansion (Zhu et al. 2010; Zhang et al. 2011). As P was another important reason for lakes' change, different change tendencies of LSA should be attributed to the coupled influences of P and glacier melt changes. Furthermore, as the distance between the lake and glacier increases, glacier melt has less impact on LSA while P has a greater influence on LSA. To those lakes far from glaciers, LSA changes mainly depended on P changes.

Permafrost degradation

The influence of permafrost degradation on LSA is more complex than glacier retreat. Subsurface water flow in permafrost can occur above permafrost (seasonally and perhaps perennially depending on conditions), below permafrost, and within taliks (Kane et al. 2013; Walvoord and Kurylyk 2016). LSA became less sensitive to T and P, and more sensitive to ET_o from permafrost to island permafrost and seasonally frozen ground. Permafrost degradation across the TP due to climate warming led to the thaw of ice in the frozen soil (Hinzman et al. 2005; Li et al. 2012) and enhanced groundwater discharge through activated aquifers (Kurylyk et al. 2014; Walvoord and Kurylyk 2016), and could partly explain the expansion of lakes (Liao et al. 2013). However, further degradation of permafrost would form new open taliks, thus facilitate groundwater movement to subpermafrost aquifers at lower head, and thereby drain lakes (Peng et al. 2003; Cheng and Wu 2007; Walvoord and Kurylyk 2016). Lakes would expand firstly and then shrink along with the permafrost degradation process. Coupled with the influence of notable decreased P (−2.76 mm/year) and increased thaw water during 1975–1990 in permafrost regions, lakes in these regions were generally shrinking. And after that, lakes were expanding dramatically due to increased P (6.40 mm/year during 1990–2010) as well as the increased permafrost melt. Moreover, along with permafrost degradation, the water environment of the lake basin became more complicated and less stable, more factors such as underground water were also worked in the lake recharge and discharge cycle, which probably weakened the sensitivity of LSA to climatic factors in seasonally frozen ground regions.

Conclusion

A warm-humid climate trend of the TP was evident in the last four decades and thereby led to a remarkable lake expansion. Among the climatic variables, P change was the key factor of LSA change, especially in water-limited environments. Compared to larger lakes, smaller lakes were more sensitive to climate change. Lakes in the higher elevation regions were more sensitive to T due to the widespread glaciers. Warming-induced glacier's retreat led to a lake expansion. Even in lakes with glacier melting as important water supply, LSA change was still mainly induced by *P* change, and glacier melt was the secondary affecting factor. Unlike the influence of glacier retreat, warming-induced permafrost degradation led to a lake shrinkage. Compared to permafrost regions, *T* and *P* had less impacts on LSA while the influence of ET_o was increasing. Our result also implied that overall response of all the lakes to climate change could be obtained by examining several typical lakes in the catchment level.

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References

Allen RG, Pereira L, Raes D, Smith M (1998) Crop evapotranspiration-guidelines for computing crop water requirements. FAO irrigation and drainage paper no. 56. Food and Agriculture Organization of the United Nations, Rome

Bracht-Flyr B, Istanbulluoglu E, Fritz S (2013) A hydro-climatological lake classification model and its evaluation using global data. J Hydrol 486:376–383. doi:10.1016/j.jhydrol.2013.02.003

Cheng GD, Wu TH (2007) Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau. J Geophys Res 112:F02S03. doi:10.1029/2006JF000631

Duan KQ, Yao TD, Wang NL, Tian LD, Xu BQ (2008) The difference in precipitation variability between the north and south Tibetan Plateaus. J Glaciol Geocryol 30(5):726–732 (in Chinese, with English Abstr.)

Gao XQ, Tang MC, Feng S (2000) Discussion on the relationship between glacial fluctuation and climate change. Plateau Meteorology 19(1):9–16 (in Chinese, with English Abstr.)

Gao YH, Li X, Leung LR, Chen DL, Xu JW (2015) Aridity changes in the Tibetan Plateau in a warming climate. Environ Res Lett 10: 034013. doi:10.1088/1748-9326/10/3/034013

Ge SX, Zonggha (2005) A preliminary study on the change of lake areas in western Naqu, Tibet. Tibetan Sci Technol 144:14–18 (in Chinese)

Hinzman LD, Bettez ND, Bolton WR, Chapin FS, Dyurgerov MB, Fastie CL, Griffith B, Hollister RD, Hope A, Huntington HP, Jenesen AM, Jia GJ, Jorgenson T, Kane DL, Klein DR, Kofinas G, Lynch AH, Lloyd AH, McGuire AD, Nelson FE, Oechel WC, Osterkamp TE, Racine CH, Romanovsky VE, Stone RS, Stow DA, Sturm M, Tweedie CE, Vourlitis GL, Walker MD, Walker DA, Webber PJ, Welker JM, Winker KS, Yoshikawa K (2005) Evidence and implications of recent climate change in northern Alaska and other arctic regions. Clim Chang 72:251–298. doi:10.1007/s10584-005-5352-2

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

IPCC (2014) Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core writing team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland

Jeffrey MW (2009) Introductory econometrics—a modern approach, 4th edn. Nelson Education, Canada

Jiang Y, Luo Y, Zhao ZG, Tao SW (2010) Changes in wind speed over China during 1956-2004. Theor Appl Climatol 99:421–430. doi:10.1007/s00704-009-0152-7

Kane DL, Yoshikawa K, McNamara JP (2013) Regional groundwater flow in an area mapped as continuous permafrost, NE Alaska (USA). Hydrogeol J 21(1):41–52. doi:10.1007/s10040-012-0937-0

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

Kendall MG (1975) Rank correlation methods. Charles Griffin, London

Kleinherenbrink M, Lindenbergh RC, Ditmar PG (2015) Monitoring of lake level changes on the Tibetan Plateau and Tian Shan by retracking Cryosat SARIn waveforms. J Hydrol 521:119–131. doi:10.1016/j.jhydrol.2014.11.063

Kurylyk BL, MacQuarrie KTB, McKenzie JM (2014) Climate change impacts on groundwater and soil temperatures in cold and temperate regions: implications, mathematical theory, and emerging simulation tool. Earth Sci Rev 138:313–334. doi:10.1016/j.earscirev.2014.06.006

Lei YB, Yao TD, Bird BW, Yang K, Zhai JQ, Sheng YW (2013) Coherent lake growth on the central Tibetan Plateau since the 1970s: characterization and attribution. J Hydrol 483:61–67. doi:10.1016/j.jhydrol.2013.01.003

Li SD, Cheng GD (1996) Map of Frozen Ground on Qinghai-Xizang Plateau. Gansu Culture Press, Lanzhou. Provided by Cold and Arid Regions Science Data Center at Lanzhou (http://westdc.westgis.ac.cn)

Li XY, Xu HY, Sun YL, Zhang DS, Yang ZP (2007) Lake-level change and water balance analysis at Lake Qinghai, west China during recent decades. Water Resour Manag 21:1505–1516. doi:10.1007/s11269-006-9096-1

Li H, Xiao PF, Feng XZ, Wan W, Ma RH, Duan HT (2010) Lake changes in spatial evolution and area in source region of three rivers in recent 30 years. J Lake Sci 22(6):862–873 (in Chinese, with English Abstr.)

Li JL, Sheng YW, Luo JC, Shen ZF (2011) Remotely sensed mapping of inland lake area changes in the Tibetan Plateau. J Lake Sci 23(3): 311–320 (in Chinese, with English Abstr.)

Li X, Jin R, Pan XD, Zhang TJ, Guo JW (2012) Changes in the near-surface soil freeze–thaw cycle on the Qinghai–Tibetan Plateau. Int J Appl Earth Obs Geoinf 17:33–42. doi:10.1016/j.jag.2011.12.002

Liao JJ, Shen GZ, Li YK (2013) Lake variations in response to climate change in the Tibetan Plateau in the past 40 years. Int J Digit Earth 6(6):1–16. doi:10.1080/17538947.2012.656290

Liu XD, Chen BD (2000) Climatic warming in the Tibetan Plateau during recent decades. Int J Climatol 20:1729–2742

Liu JS, Wang SY, Yu SM, Yang DQ, Zhang L (2009) Climate warming and growth of high-elevation inland lakes on the Tibetan Plateau. Glob Planet Chang 67:209–217. doi:10.1016/j.gloplacha.2009.03.010

Mann HB (1945) Non-parametric tests against trend. Econometrica 13: 245–259

Meng K, Shi XH, Wang E, Liu F (2012) High-altitude salt lake elevation changes and glacial ablation in Central Tibet, 2000-2010. Chin Sci Bull 57(5):525–534. doi:10.1007/s11434-011-4849-5

National Administration of Surveying, Mapping and Geoinformation (1982) National Earth System Science Data Sharing Infrastructure. Data set of catchment system on the Qinghai-Tibetan Plateau (1:1 000 000). (http://www.geodata.cn)

Nie Y, Zhang YL, Liu LS, Zhang JP (2010) Glacial change in the vicinity of Mt. Qomolangma (Everest), central high Himalayas since 1976. J Geogr Sci 20(5):667–686. doi:10.1007/s11442-010-0803-8

Nie Y, Zhang YY, Ding MJ, Liu LS, Wang ZF (2013) Lake change and its implication in the vicinity of Mt. Qomolangma (Everest), central high Himalayas, 1970-2009. Environ Earth Sci 68:251–265. doi:10.1007/s12665-012-1736-6

Palazzi E, Hardenberg JVH, Provenzale A (2013) Precipitation in the Hindu-Kush Karakoram Himalaya: observations and future scenarios. J Geophys Res Atmos 118:85–100. doi:10.1029/2012JD018697

Pekel JF, Cottam A, Gorelick N, Belward AS (2016) High-resolution mapping of global surface water and its long-term changes. Nature 540:418–422. doi:10.1038/nature20584

Peng XM, Wu QB, Tian MZ (2003) The effect of groundwater Table lowering on ecological environment in the headwaters of the Yellow River. J Glaciol Geocryol 25(6):667–671 (in Chinese, with English Abstr.)

Phan VH, Lindenbergh R, Menenti M (2012) ICESat derived elevation changes of Tibetan lakes between 2003 and 2009. Int J Appl Earth Obs Geoinf 17:12–22. doi:10.1016/j.jag.2011.09.015

SinoMaps Press, Data Sharing Infrastructure of Earth System Science (1990). Map of Climate Regionalization on the Qinghai-Tibetan Plateau (1:1 000 000) (http://www.geodata.cn)

Pu JC, Yao TD, Yang MX, Tian LD, Wang NL, Ageta Y, Fujita K (2008) Rapid decrease of mass balance observed in the Xiao (lesser) Dongkemadi Glacier, in the central Tibetan Plateau. Hydrol Process 22:2953–2958. doi:10.1002/hyp.6865

Qin BQ, Huang Q (1998) Evaluation of the climatic change impacts on the inland lake-a case study of Lake Qinghai, China. Clim Chang 39:695–714

Song CQ, Huang B, Ke LH (2013) Modeling and analysis of lake water storage changes on the Tibetan Plateau using multi-mission satellite data. Remote Sens Environ 135:25–35. doi:10.1016/j.rse.2013.03.013

Song CQ, Huang B, Ke LH (2014a) Inter-annual changes of alpine inland lake water storage on the Tibetan Plateau: detection and analysis by integrating satellite altimetry and optical imagery. Hydrol Process 28:2411–2418. doi:10.1002/hyp.9798

Song CQ, Huang B, Ke LH, Richards KS (2014b) Remote sensing of alpine lake water environment changes on the Tibetan Plateau and surroundings: a review. ISPRS J Photogramm Remote Sens 92:26–37. doi:10.1016/j.isprsjprs.2014.03.001

Su Z, Liu ZX, Wang WT, Yao TD, Shao WZ, Pu JC, Liu SY (1999) Glacier fluctuations responding to climate change and forecast of its tendency over the Qinghai-Tibet Plateau. Adv Earth Sci 14:607–612 (in Chinese, with English Abstr.)

UNESCO (1979) Map of the world distribution of arid regions. Explanatory note. Man and Biosphere (MAB)

Walvoord MA, Kurylyk BL (2016) Hydrologic impacts of thawing permafrost—a review. Vadose Zone J 15(6). doi:10.2136/vzj2016.01.0010

Wan W, Xiao PF, Feng XZ, Li H, Ma RH, Duan HT (2014) Monitoring lake changes of Qinghai-Tibetan Plateau over the past 30 years using satellite remote sensing data. Chin Sci Bull 59(10):1021–1035. doi:10.1007/s11434-014-0128-6

Wang XW, Gong P, Zhao YY, Xu Y, Cheng X, Niu ZG, Luo ZC, Huang HB, Sun FD, Li XW (2013) Water-level changes in China's large lakes determined from ICESat/GLAS data. Remote Sens Environ 132:131–144. doi:10.1016/j.rse.2013.01.005

Wang LZ, Cao LG, Deng XJ, Jia PH, Zhang W, Xu XWH, Zhang KX, Zhao YF, Yan BJ, Hu W, Chen YY (2014) Changes in aridity index and reference evapotranspiration over the central and eastern Tibetan Plateau in China during 1960-2012. Quat Int 349:280–286. doi:10.1016/j.quaint.2014.07.030

Wu LZ, Li X (2003) China glacier information system (1:100 000). China Ocean Press, Beijing

Xiang LW, Wang HS, Steffen H, Wu P, Jia LL, Jiang LM, Shen Q (2016) Groundwater storage changes in the Tibetan Plateau and adjacent areas revealed from GRACE satellite gravity data. Earth Planet Sc Lett 449:228–239. doi:10.1016/j.epsl.2016.06.002

Yang W, Yao TD, Xu BQ, Wu GJ, Ma LL, Xin XD (2008) Quick ice mass loss and abrupt retreat of the maritime glaciers in the Kangri Karpo Mountains, southeast Tibetan Plateau. Chin Sci Bull 53(16):2547–2551. doi:10.1007/s11434-008-0288-3

Yang K, Ye BS, Zhou DG, Wu BY, Foken T, Qin J, Zhou ZY (2011) Response of hydrological cycle to recent climate changes in the Tibetan Plateau. Clim Chang 109:517–534. doi:10.1007/s10584-011-0099-4

Yang K, Wu H, Qin J, Lin CG, Tang WJ, Chen YY (2014) Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: a review. Glob Planet Chang 112:79–91. doi:10.1016/j.gloplacha.2013.12.001

Yao TD, Pu JC, Lu AX, Wang YQ, Yu WS (2007) Recent glacial retreat and its impact on hydrological processes on the Tibetan Plateau, China, and surrounding region. Arct Antarct Alp Res 39(4):642–650. doi:10.1657/1523-0430%2807-510%29%5BYAO%5D2.0.CO%3B2

You QL, Fraedrich K, Ren GY, Pepin N, Kang SC (2012) Variability of temperature in the Tibetan Plateau based on homogenized surface stations and reanalysis data. Int J Climatol doi. doi:10.1002/joc.3512

Yue TX, Zhao N, Ramsey RD, Wang CL, Fan ZM, Chen CF, Lu YM, Li BL (2013) Climate change trend in China, with improved accuracy. Clim Chang 120:137–151. doi:10.1007/s10584-013-0785-5

Zhang YL, Li BY, Zheng D (2002) A discussion on the boundary and area of the Tibetan Plateau in China. Geogr Res 21(1):1–8 (in Chinese, with English Abstr.)

Zhang B, Wu YH, Zhu LP, Wang JB, Li JS, Chen DM (2011) Estimation and trend detection of water storage at Nam Co Lake, central Tibetan Plateau. J Hydrol 405:161–170. doi:10.1016/j.jhydrol.2011.05.018

Zhang GQ, Xie HJ, Yao TD, Kang SC (2013) Water balance estimates of ten greatest lakes in China using ICEsat and Landsat data. Chin Sci Bull 58(31):3815–3829. doi:10.1007/s11434-013-5818-y

Zhang GQ, Yao DT, Xie HJ, Zhang KX, Zhu FJ (2014) Lakes' state and abundance across the Tibetan Plateau. Chin Sci Bull 59(24):3010–3021. doi:10.1007/s11434-014-0258-x

Zhu LP, Xie MP, Wu YH (2010) Quantitative analysis of lake area variations and the influence factors from 1971 to 2004 in the Nam Co basin of the Tibetan Plateau. Chin Sci Bull 55(13):1294–1303. doi:10.1007/s11434-010-0015-8