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ORIGINAL ARTICLE

Local background climate determining the dynamics of plateau lakes in China

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Abstract Lakes under natural conditions are potential indicators of climate change, but limited evidence has been proposed to explicitly explain the mechanisms of large-scale lake changes associated with climate. In this paper, satellite imageries from the 1970s to 2010 were compared to track the dynamic change patterns of plateau lakes. It aims to identify the forcing of climate change on the lakes in plateau regions of China. Results revealed that: (1) widespread expanding trends in the area and abundance of lakes on wetter plateau regions, by increasing precipitation and snow presented a positive effect on lake levels, as well as warming resulted glacier melting and permafrost degrading contributed to expansion of lakes in the regions covered by glaciers on the Tibetan Plateau by 58–62 % and of 13–20 % on the western Inner Mongolia and Xinjiang Plateau; (2) shrinkage lakes in the main portion of the arid regions were mainly caused by the decreasing wind speed resulted water balance change, irrigation and other human utilization of water resources. Although precipitation decreased, wind speed also has the most dominant impact on decreasing evaporation, followed by solar radiation, both of which offset the effect of increasing temperature, especially in eastern Inner Mongolia and Xinjiang Plateau; (3) thawing permafrost led to shrinkage of lakes in an area of seasonal permafrost, the shrinking and splitting of lakes in a discontinuous permafrost zone, and the rising of lake levels in an area of continuous permafrost; (4) the future of the plateau lakes under climate change must be in question, because the glacier and snow melting water is not sustainable for wetter regions, and the increasing water consumption caused by the farmland expansion for arid regions.

Keywords Climate change · Plateau lakes · Glacier · Permafrost · China

Introduction

Inland lakes have the potential to serve as excellent indicators of climate change. The disappearance, expansion, or shrinkage of lakes is the synthetic consequences of water balance and thermal dynamics (Benson and Paillet 1989; Shi 1990; Chen et al. 2009; Huang et al. 2011). Lake fluctuation sensitively not only indicates climate changes through variations in water quantity, but variations in lake area also have an influence on climate change by altering the land surface conditions (Schneider and Hook 2010; Zhu et al. 2010) and the regulation of the carbon cycle (Kosten et al. 2010; Abnizova et al. 2012).

Although scattered studies have been conducted on the dynamics of either one or a limited number of lakes (e.g., Qin 1999; Wu et al. 2001a; Hu et al. 2002; Guo et al. 2003; Ma et al. 2003; Sun et al. 2005; Li et al. 2008; Ye et al. 2008; Bian et al. 2010; Zhu et al. 2010; Wang et al. 2011),

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and on lake variations at a regional or national level (e.g., Bian et al. 2006; Liao et al. 2013; Ding et al. 2006; Ma et al. 2010; Huang et al. 2011; Zhang et al. 2011; Yang and Lu 2014; Tao et al. 2014), limited evidence has been proposed to explain the dominant driving mechanisms behind the observed patterns of changing lakes, which could either be the consequence of climatic, or non-climatic factors (Shi et al. 2002; Hu et al. 2006; Ding et al. 2006; Ma et al. 2010; Huang et al. 2011). Liao et al. (2013) showed the variations in lake surface areas of Tibetan Plateau are closely related to the warming. Tao et al. (2014) suggested that in Inner Mongolia exploitation of underground mineral and groundwater resources was the leading factor for the deterioration of lakes. However, the exact reasons for the changes on a regional scale still require targeted research to confirm such a supposition (Ma et al. 2010).

In relation to climate change, we need to further analyze the historical trends, variability, geographical scope, and mechanisms of changes in plateau lakes, and discover which factors cause such changes and which factors are responsible for the dominant forcing. In this paper, we compared satellite imageries from the 1970s to 2010, to investigate the landscape-level changes of the plateau lakes in China. The forcing of climate change on lakes on the Tibetan Plateau (TP) and the Inner Mongolia and Xinjiang Plateau (IMXP) during 1970–2010 was compared by direct climate factors and indirect factors through hydrological processes, to show the different hydrological changes related to landscape variations in plateau lakes. We present an analysis of climatic and hydrological trends, based on well-observed data, the recent literature, and published data. The primary goal of this study is to improve our understanding of the role that climate change plays in affecting the surface water balance of plateau lakes on a large scale.

Materials and methods

Study area

Tibetan Plateau (TP) is the world's highest and largest plateau, which contains 1091 lakes with areas greater than 1 km^2 (the majority of which are saline), and covers a total area of 44,993.3 km^2 and counts for 49.5 % of the total lake area of China (Wang and Dou 1998). Glaciers, permafrost, and snow are widespread, owing to the average elevation of more than 4000 m (Fig. 1). While precipitation

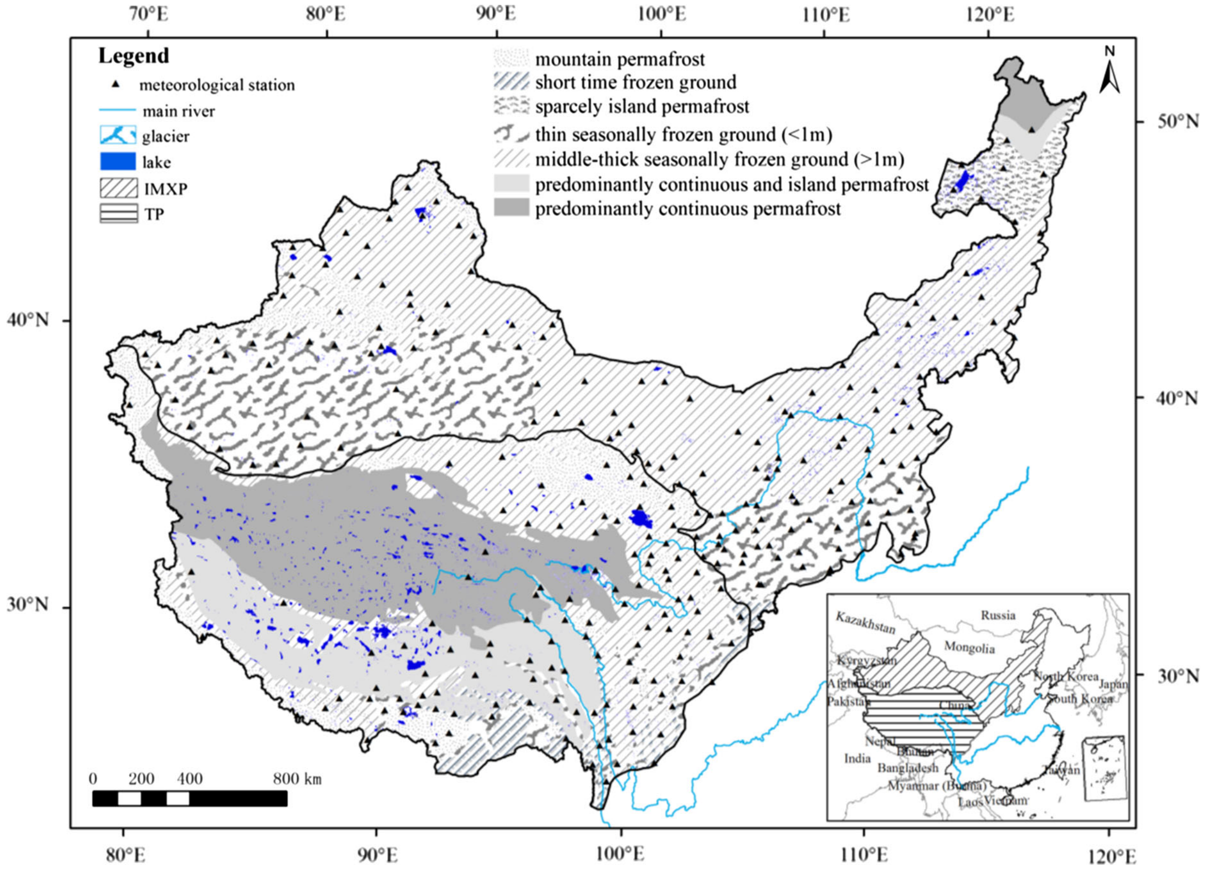


Fig. 1 Locations of study area and distributions of lake, glacier, permafrost surfaces, and meteorological stations

significantly increased by averaging 20–60 mm per 10 years and wetter climate, most of the enlarged and new lakes have appeared here in the past half-century. The Inner Mongolia and Xinjiang Plateau (IMXP) located in northern arid China, which contains 7772 lakes with areas greater than 1 km^2, and covers a total area of 19,700.3 km^2 and accounting for 21.5 % of the total lake area of China (Wang and Dou 1998). The regional distribution of precipitation shows that the decrease in annual precipitation was significant in most of the northern and northwestern China by averaging 20–40 mm/10a, which have caused lakes to shrink or vanish over the past half-century.

Detection the changes of lakes

For historical land cover changes in the lakes, spatial data were extracted and summarized by Liu et al. (2005). A time series of spatially aligned images including Landsat TM, ETM+, and MSS for the entire plateau region in the late 1970s (1976/1977), late 1990s (1989/1990), 2000, and 2010 were collected and applied to investigate maximum lake surface water changes and glacier variations. Each image was collected in rainy season from June to September to ensure the consistency of data source. The threshold boundary of lakes was manually distinguished. In addition, the statewide coverage of 1:50,000 and 1:100,000 topographic maps was applied to image correction and to the relative accuracy lake recognition from MSS. The interpretation of satellite images and lake cover classifications was validated against extensive field surveys. We conducted ground truth checking, and field photos were taken using cameras equipped with global position systems. We did not take field photos and out-door survey in the late 1970s and 1990, but evaluated TM-based classification against historical records including aerial photo and tabular data in a large number of field sites and interviewed with many local people as well as experts to test the validity of our interpretations.

Hydrological balance analysis of lakes

The changes in the water level of a lake are specified by the difference between the input and output sides of the water balance and the water surface area. In a closed plateau lake, the water input is derived from precipitation and runoff, and any water loss is mainly attributed to evaporation. Precipitation on the lake surface is controlled by macro-scale atmospheric and orographic factors. Surface and groundwater inflows originate from rainfall, and melting of snow and ice and are affected by hydrogeological and orographic conditions within the drainage area (Szesztay 1974). Evaporation represents one of the major elements of the radiation and heat balance of the lake and its surroundings. The water balance equation of lake can be presented as the following:

$$\begin{aligned}\Delta V &= \text{Total input} - \text{Total output}\\ &= (P + Q_S + Q_G + Q_P) - E \pm \varepsilon \qquad (1)\end{aligned}$$

where ΔV is the mean annual change of the lake; P is the mean annual precipitation in the lake water zone; Q_S is the mean annual surface runoff depth derived from precipitation; Q_G is the mean annual glacier melting water inflow into the lake; Q_P is the mean annual water inflow into the lake via thawing of permafrost or the water loss penetrating into soils; E is the mean annual evaporation from the lake's surface; and ε is combined with groundwater inflow or outflow and errors. Q_S was analyzed from the annual runoff recorded at key hydrological stations between 1970 and 2010. Changes in runoff during the period are expressed as integrated ecological and climatic effects rather than solely expressed as climate change.

Meteorological and permafrost observation data

Only a few existing national and local stations (274 stations) in China are situated close to lakes in plateau regions and have weather records spanning from 1970 to 2010. Therefore, in this study, it was necessary to use a number of stations that are located hundreds of kilometers from the lake observation area and with continuous records. We obtained datasets of the daily average air temperature, annual total precipitation, annual average wind speed, and annual total sunshine duration in 183 long-term meteorological stations from the Chinese Meteorological Bureau. In addition, the data of annual total pan evaporation in 156 stations and annual maximum snow depth (MSD) in 179 were also collected. We applied 10, 25, 50, 75, and 100 km buffers at the meteorological stations to calculate the net area change of lakes in the vicinity of each station. Due to few stations in buffer zones less than 50 km, and insignificant difference between the buffers of 75 and 100 km, we eventually choose 50 and 100 km buffers. The climate moisture index (I_m) illustrates the relationship between plant water demand and available precipitation. We estimated the I_m by applying the improved Penman–Monteith and Thornthwaite Moisture Index to fusion processes, as described by Huang et al. (2011), and then interpolated results by a spline method of Australia National University (ANUSPLIN) developed by Hutchinson and Gessler (1994) to show the regional trends. The slope of the linear function was used as an indicator of the average year-to-year trend for each observation data; a positive slope indicated an overall increase and vice versa. The slopes were calculated as follows:

$$S = \frac{\sum_{i=1}^{n} m_i X_i \frac{1}{n} \times \sum_{i=1}^{n} m_i \times \sum_{i=1}^{n} X_i}{\sum_{i=1}^{n} m_i^2 \frac{1}{n} \times \left(\sum_{i=1}^{n} m_i\right)^2} \tag{2}$$

where X_i is the value of climatic factors in year i, $i = 1, 2, 3, \ldots, n$. m_i is the number of the year in sequence, $m_1 = 1$, $m_2 = 2$, $m_3 = 3$, …, $m_n = n$, in which $n = 41$.

The maximum permafrost depth (MPD) is sensitive to climate change. Annual permafrost observation data were collected from 99 meteorological stations from the National Climate Center in China, and the decadal changes of maximum permafrost depth over the past 40 years were analyzed.

Hydrological station data and glacier observation materials

The daily runoff data from the primary control stations on the Yellow River (Jimai station with no glacier) and on the Yangtze River (Tuotuo River station, with glacier) in the TP, and data from stations in the river source region of the IMXP (Toudaogou station with no glacier, Baiji with a glacier, and Yingbazha with a glacier and human activities) were averaged and applied to analyze the variations in annual mean runoff between 1970 and 2010. The observed land cover changes of glacier were detected based on images in the late 1970s (1976/1977), 1990 (1989/1990), 2000, and 2010. The dynamics of glacier tongue were then collected and averaged to get the annual change rate. Remote sensing observations were processed to show the change of glaciers which have been associated with plateau lakes in recent decades, and it was validated by the recent literature and published data.

Results

Different changing plateau lakes over the past 40 years

Our analysis reveals an interesting spatial heterogeneous pattern in the changes of plateau lakes and an apparent discrepancy between the opposing sets of observations in the TP and the IMXP. Over the past 40 years, there has been a widespread increase in the area and abundance of lakes on the TP, with the exception of the northeastern part. However, the main portion of the IMXP has primarily presented shrinkage trends, particularly in the northwestern part (Fig. 3). From the 1970s to 1990, the total regional lake surface area has decreased by 15.82 and 347.09 km^2 on TP and IMXP, respectively (Table 1, Fig. 2a). The expanded and shrinking lake surface area were 418.01 km^2 (0.93 %) and 433.83 km^2 (0.96 %), and 570.54 km^2 (2.90 %) and 917.64 km^2 (4.66 %), respectively. From 1990 to 2000, the lake surface area increased by 126.64 and 750.66 km^2 on TP and IMXP, respectively. The expanded and shrinkage area were 530.23 km^2 (1.17 %) and 404.24 km^2 (0.90 %), and 1246.56 km^2 (6.33 %) and 495.90 km^2 (2.52 %), respectively (Fig. 2b). From 2000 to 2010, the lake surface area increased by 560.7 km^2 and decreased by 446.63 km^2, on the TP and IMXP, respectively. The expanded and shrinkage area were 845.78 km^2 (1.87 %) and 285.08 km^2 (0.63 %), and 626.34 km^2 (3.18 %) and 1072.97 km^2 (5.45 %), respectively (Fig. 2c).

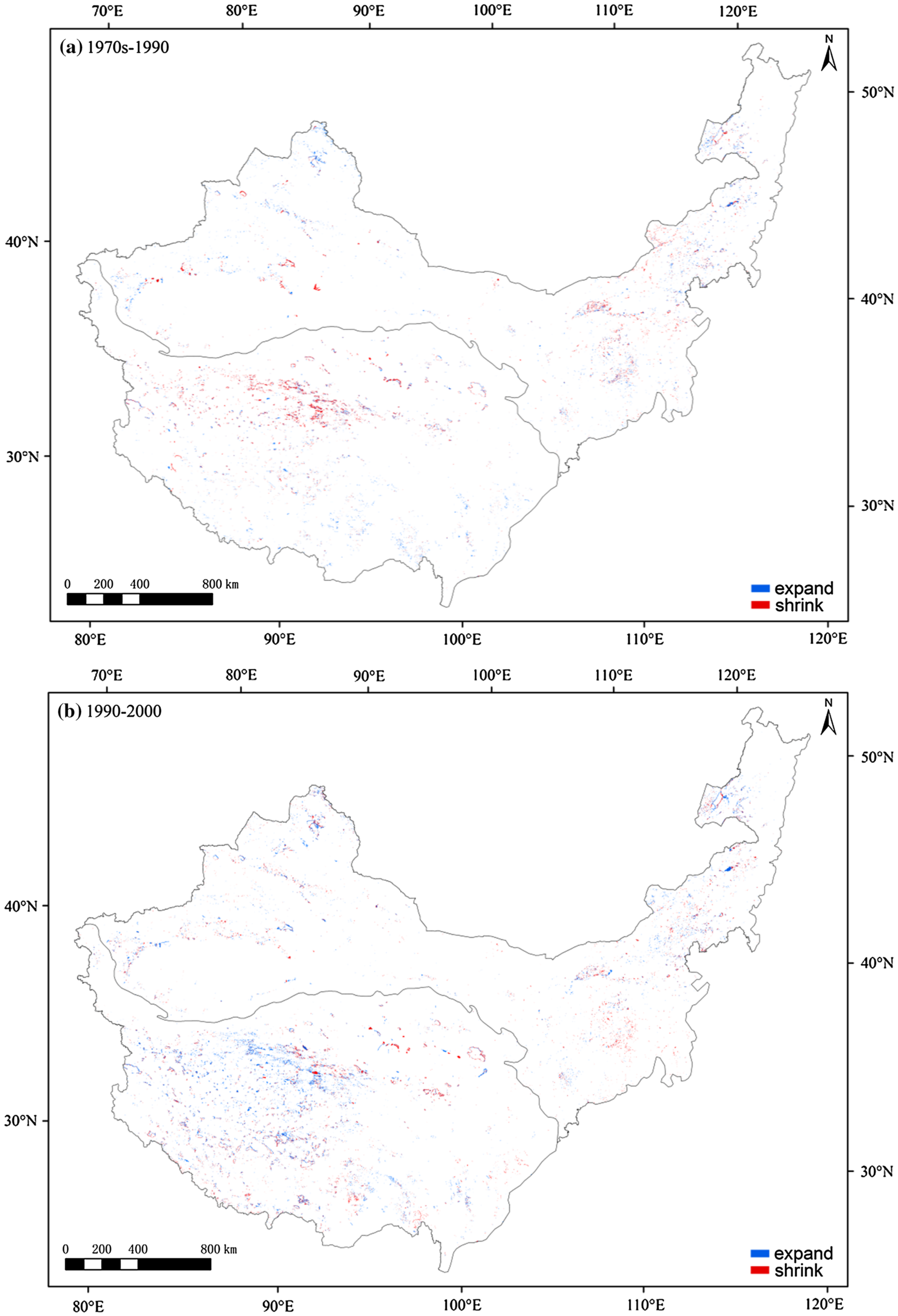
The interpretation accuracy of lake cover change over the past three time periods is 97.6 %. This high accuracy value of lake cover change detection is mainly because of the observed lakes in satellite images and manual interpretation of Landsat TM imagery. Although the average location errors of satellite images are less than 45 m, the small errors could bias our detection of lake cover change. Uncertainty also arises from the lack of direct ground truth in the late 1970s and 1990. However, we are confident that our estimates of lake cover change are a significant improvement over other earlier estimates.

Direct climate change forcing on the plateau lakes

Precipitation presented a positive effect on lake levels. Over the past four decades, the average annual total precipitation trend increased by 9.56 mm/decade at 65 % of the stations on the Tibetan Plateau, but decreased by 2.21 mm/decade at 64 % stations of stations on the eastern IMXP (Fig. 4a). There was an obvious increase of 11.72 mm/decade at 93 % of stations on the western IMXP

Table 1 Changing lake surface area in different periods for the two plateau regions, based on statistical data or remote sensing observations

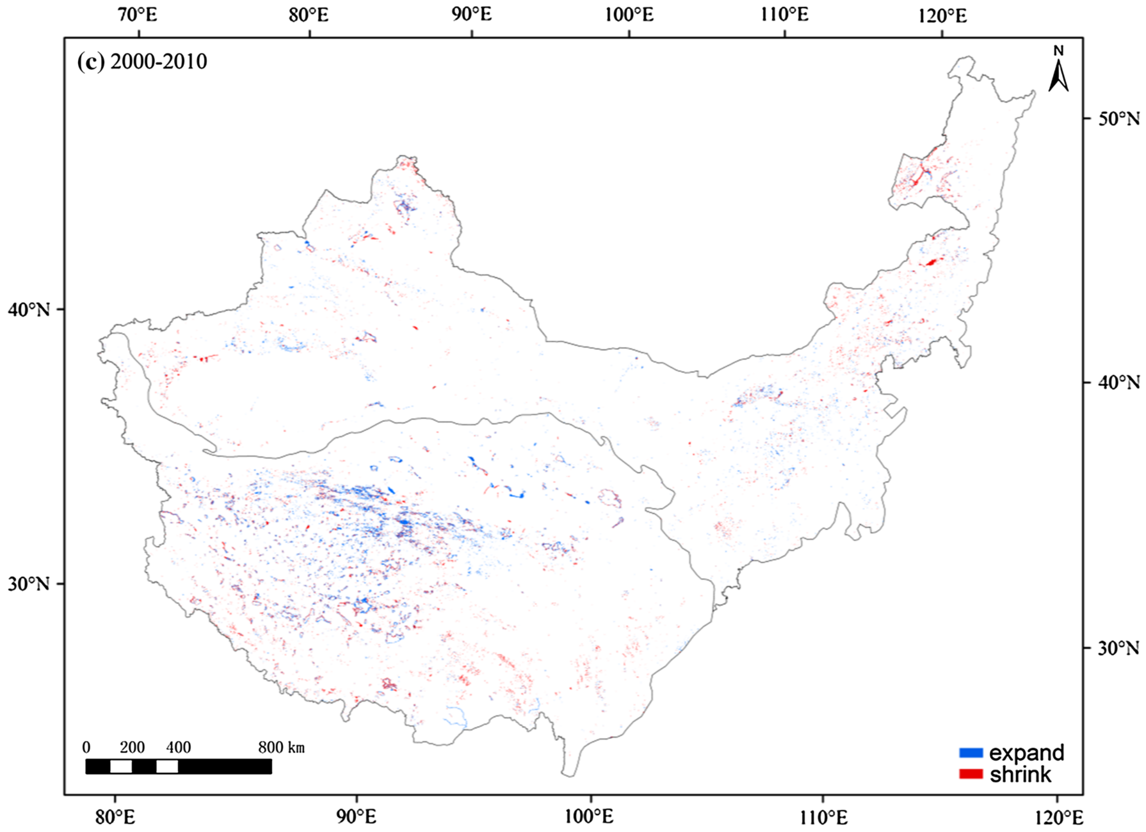
Periods	Change type	Tibetan Plateau		Inner Mongolia and Xinjiang Plateau	
		Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)
1970s–1990	Expanding	418.014	0.93	570.544	2.90
	Shrinkage	433.833	0.96	917.636	4.66
1990–2000	Expanding	530.228	1.17	1246.557	6.33
	Shrinkage	404.242	0.90	495.897	2.52
2000–2010	Expanding	845.783	1.87	626.341	3.18
	Shrinkage	285.082	0.63	1072.968	5.45



(a) 1970s-1990

(b) 1990-2000

Fig. 2 Spatial patterns of variable and stable lake surfaces in the plateau region from 1970s to 2010



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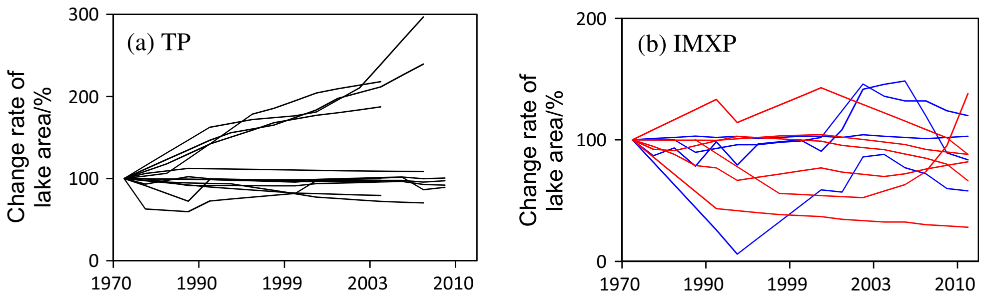


Fig. 3 Observed change rate of lake surface area in single lakes on the Tibetan Plateau (**a**) and Inner Mongolia and Xinjiang Plateau (**b**) during the period of 1970s–2010

(Table 2). Precipitation has increased on the northwestern IMXP and central TP, and this is mainly a result of larger amounts of precipitation during both summer and winter on the TP, and increased winter precipitation in the western IMXP. While the eastern IMXP exhibited a decreased tendency, this has mostly been attributed to decreased amounts of precipitation in summer and autumn (Fig. 5a, b). There was no significant trend for maximum snow depth in the plateau regions (Fig. 4f). The maximum snow depth decreased by 0.14 cm/decade at 57.3 % of stations on the TP and by 0.1 cm/decade at 56.9 % of the stations on the IMXP. It showed an apparent increase of 1.14 cm/decade at 79.2 % of stations in the western IMXP (Table 2; Fig. 5c, d).

Plateau regions experienced a strong warming, which is firmly supported by continuous measurements over the past four decades, and also proved by other studies (Xu et al. 2008; Wang et al. 2013). The largest warming was found on the IMXP, with a trend of 0.538 °C 10 year^{-1} (all stations) (Table 2; Fig. 4b). The annual average temperature on the TP and western IMXP has increased by a rate of 0.343 °C 10 year^{-1} (96.5 % stations) and by 0.392 °C 10 year^{-1} (94.6 % stations), respectively. Warming would inevitably enhance evapotranspiration.

The temperature effects on lake water were mainly presented as a negative effect through water surface evaporation (Fig. 6a, b). The mean annual pan evaporation absolutely decreased at a rate of 10.87, 23.58, and

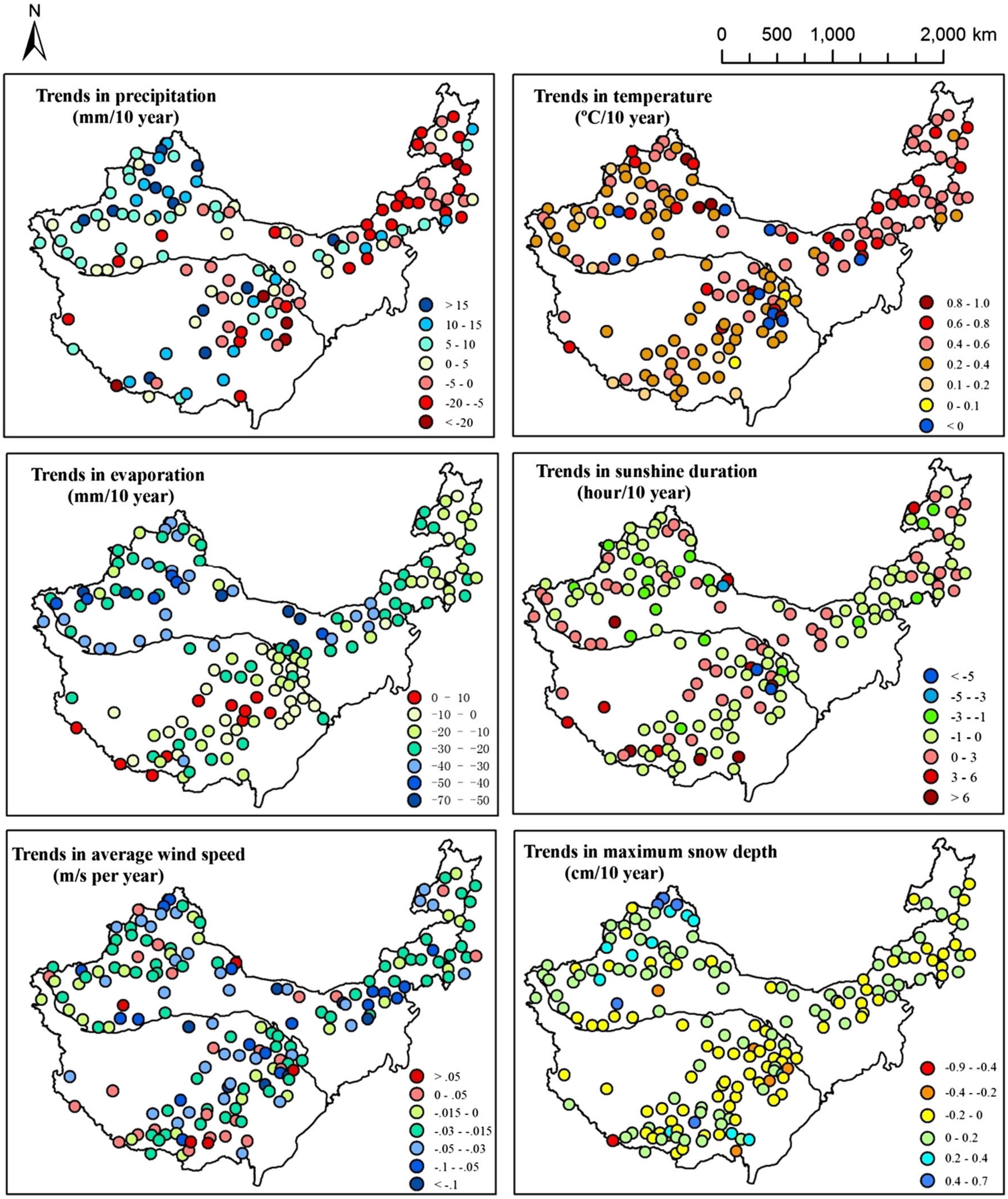


Fig. 4 Observed trends of climate on the Tibetan Plateau and Inner Mongolia and Xinjiang Plateau from 1970 to 2010. **a** Observed annual precipitation variations (mm/10 yeas) between 1970 and 2010 across the plateau region, expressed as the deviation from the mean during that period; **b** as for **a** but for mean annual temperature variations (°C/10 years); **c** for annual evaporation variations (mm/10 years); **d** for annual sunshine duration (h/10 years); **e** for average wind speed (m/s per year); **f** for average maximum snow depth (cm/10 years)

32.17 mm/decade on the TP, and in the eastern and western IMXP, respectively (Table 2; Fig. 5e, f), and was higher in the northwest part and lower in the southern part of plateau regions (Fig. 4c). However, the long-term trends do not show differences that are marked enough to cause the drying up of lakes. It contributed to 40.9–55.2 and 44.8–49.2 % of the expansion of lakes on the TP and IMXP, respectively.

Changes in the evaporation mechanism are mainly affected by the drought condition, and this relates to amounts of solar radiation, terrestrial heat flow, and other factors. There has been a pronounced tendency for a

Table 2 Annual mean trends of climatic variables at surface stations on the plateau region from 1970 to 2010 with significance level >95 %

Region	Change	Temperature (°C/10 years)	Precipitation (mm/10 years)	Evaporation (mm/10 years)	Wind speed (m s^{-1} 10 years)	Sunshine duration (h/10 years)	MSD (cm/10 years)
Tibetan Plateau	Trends	0.343 (57)	9.559 (57)	−10.865 (54)	−0.234 (57)	2.349 (57)	−0.14 (75)
	Increase	0.357 (55)	16.271 (37)	–	0.087 (10)	17.062 (18)	0.97 (32)
	Decrease	−0.291 (2)	−7.936 (20)	−10.865 (54)	−0.228 (47)	−6.331 (39)	−0.98 (43)
Eastern Inner Mongolia and Xinjiang Plateau	Trends	0.538 (47)	−2.208 (47)	−23.578 (43)	−0.267 (47)	−0.894 (47)	−0.10 (51)
	Increase	0.538 (47)	7.293 (17)	–	0.062 (4)	7.725 (17)	0.67 (22)
	Decrease	–	−7.591 (30)	−23.578 (43)	−0.298 (43)	−5.778 (30)	−0.64 (29)
Western Inner Mongolia and Xinjiang Plateau	Trends	0.392 (56)	11.715 (56)	−32.167 (44)	−0.198 (56)	−3.292 (56)	1.14 (53)
	Increase	0.401 (53)	12.484 (52)	–	0.283 (8)	5.044 (18)	1.60 (42)
	Decrease	−0.009 (3)	−4.438 (4)	−32.167 (44)	−0.246 (48)	−7.603 (38)	−0.061 (11)

The variations and numbers of stations with positive and negative trends are also shown as increase and decrease, respectively

weakening of mean wind speeds observed at the surface of the plateau regions since 1970 (Fig. 4e). On an annual basis, the mean wind speed series of the TP, eastern and western IMXP exhibit a statistically significant decreasing trend at a rate of −0.234, −0.267, and −0.198 m s^{-1} decade^{-1}, respectively (Table 2). As in the case of annual means, at least 82.5, 91.5, and 85.7 % of stations on the TP, eastern and western IMXP showed a statistically significant decrease. The weakening of mean wind speeds contributed to a 56.4 and 52.7 % reduction in evaporation on the TP and IMXP, respectively (Fig. 6c, d). On an annual basis, the mean sunshine duration series on the TP, eastern and western IMXP exhibits a statistically significant decreasing trend (Fig. 4d) with a rate of −2.349, −0.894, and −3.292 h/decade, and 68.4, 68.3, and 67.9 % of the total stations showed significant decrease, respectively (Table 2; Fig. 3). The decreasing trend in the mean sunshine series contributed to 69.1 and 64.8 % of the decreasing evaporation on the TP and IMXP, respectively (Fig. 6c, d). The proportional contribution rates of temperature, wind speed, and sunshine duration to the decreasing trend in pan evaporation from 1970 to 2010 were: −82.5, 89.8, and 30.2 % on the TP; and −72.6, 91.2, and 35.2 % on the IMXP, respectively (Fig. 4).

Climatic change forcing through hydrological processes on the plateau lakes

The temperature effects on lake water mainly presented as a positive effect through the seasonal changes in ice and snow melt water. It is certain that the current loss of glacier mass in China is affecting the lakes' water balance. Increased glacier melting is causing a rise in the level of glacial lakes, which in turn provokes more frequent lake outbursts. Regions along the Himalayas and Tianshan show the most extreme glacial shrinkage (Fig. 7b), where the length has decreased at a rate of 0.9 m year^{-1} in the eastern Pamir regions, to 48.2 m year^{-1} in the southeastern TP over the past 30 to 40 years. The accelerated glacier melting has contributed to a 59.3–62.1 % expansion of the plateau lakes on the TP, and an expansion between 12.6 and 18.8 % of the lakes on the western IMXP. From 1970 to 2010, the observed inter-annual variation in lakes and runoff on the TP with glacier supplement presented as increasing trends (Fig. 8a). Although there is accelerated glacier melting, the amount of water withdrawn for human use to develop oases on the IMXP means that the increased supply from glaciers makes no impact on lake size. Lakes and runoff without any supplement from glaciers decrease at the same period, respectively (Fig. 8b).

A decrease in average MPD occurred across plateau regions (Fig. 7a; Table 3). Over the past four decades, the MPD has undergone an accelerated decrease at a rate of 0.80 mm/y (at 72 % stations), 1.85 mm/year (at 90 % stations), and of 1.25 mm/year (at 86 % stations) on the TP, and eastern and western IMXP, respectively (Fig. 5g, h). The thawing permafrost has led to shrinkage of lake volume by 20 and 41.7 % in the area of seasonal permafrost, and to shrinkage and splitting of lakes in the discontinuous permafrost zone, on the TP and IMXP, respectively. It has also contributed to a 53.3 and 46.7 % rise in lake level in areas of continuous permafrost, on the TP and IMXP, respectively.

Discussion and conclusions

The change in status of plateau lakes is the product of combined effects of regional climatic and non-climatic factors. Lake evolution depends on the amount of water

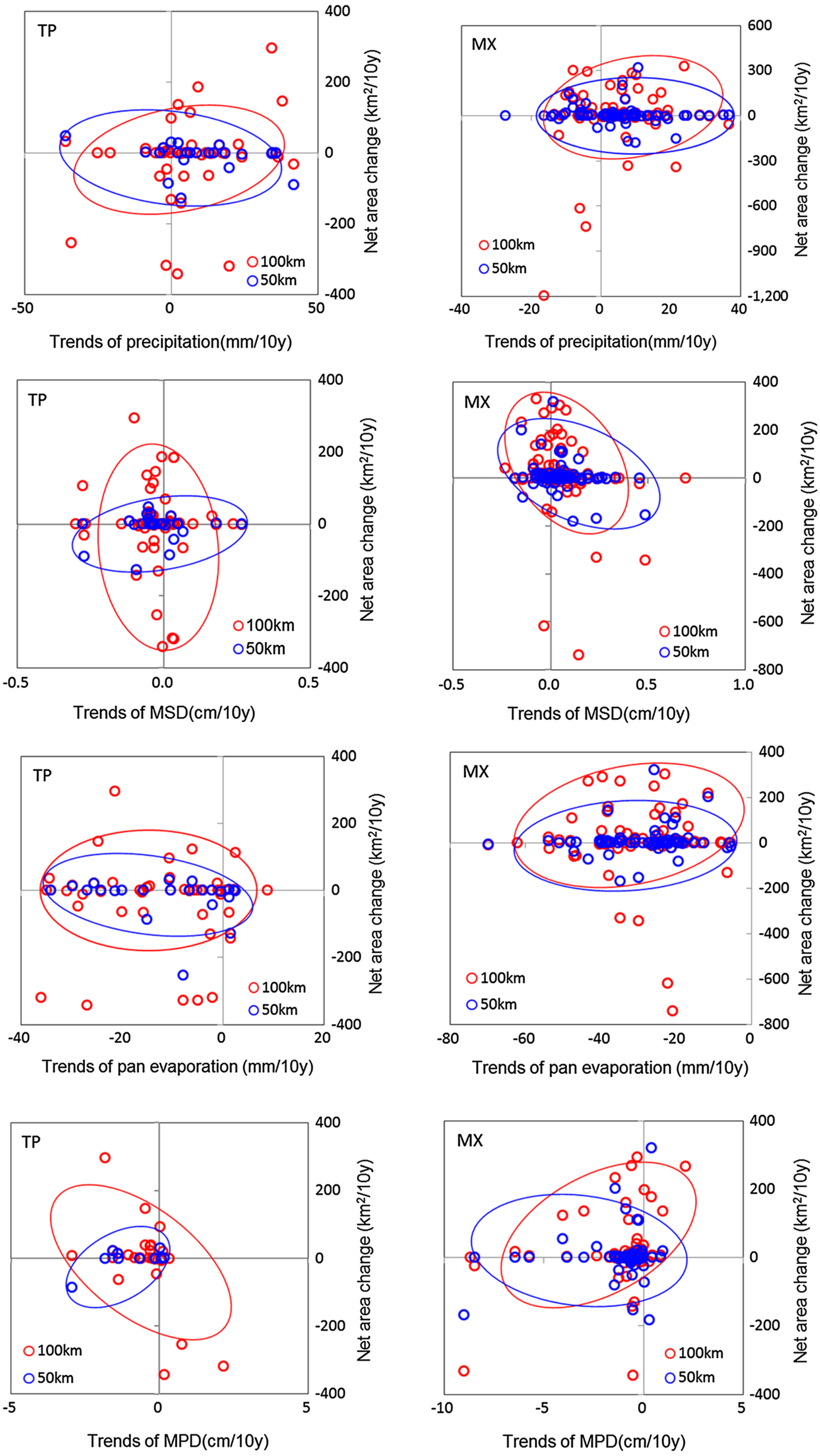
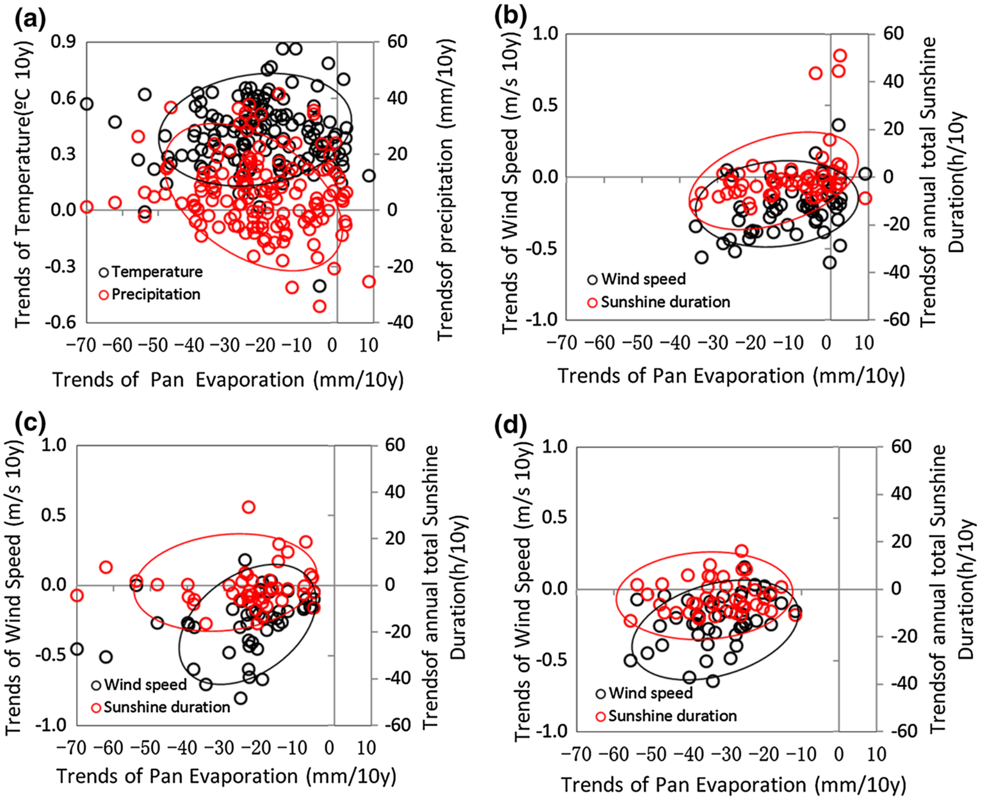


Fig. 5 Relationship between the changes of annual precipitation, maximum snow depth, pan evaporation, and maximum permafrost depth at stations, and the net area change of plateau lakes within different buffer zones of stations on the Tibetan Plateau (**a**, **c**, **e**, **g**) and Inner Mongolia and Xinjiang Plateau (**b**, **d**, **f**, **h**). Positive net area change means shrink and negative for expansion

Fig. 6 Relationship between: **a** pan evaporation, temperature, and precipitation for the Tibetan Plateau, Inner Mongolia and Xinjiang Plateau; **b** pan evaporation, wind speed, and sunshine duration for the Tibetan Plateau, **c** for the eastern part and **d** the western part of Inner Mongolia and Xinjiang Plateau



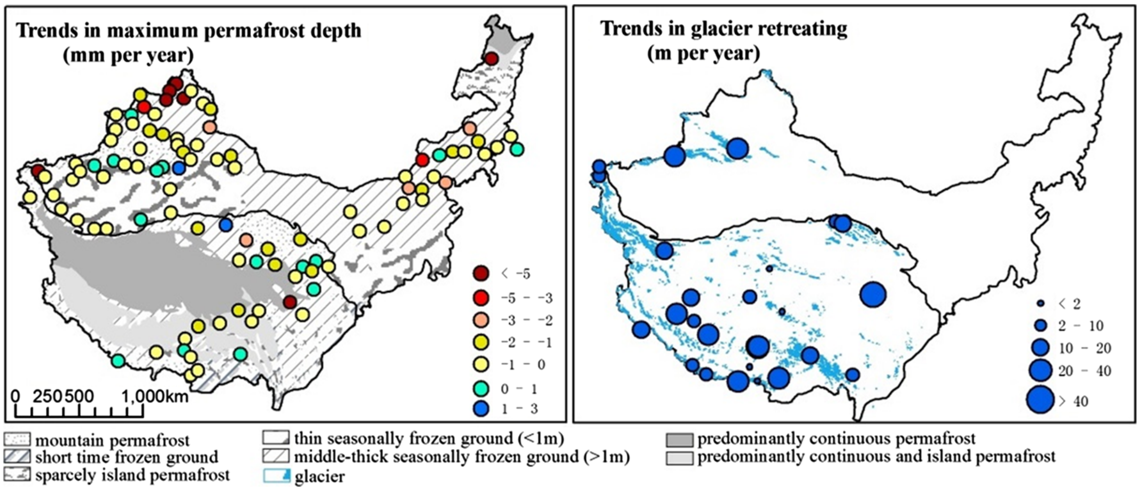
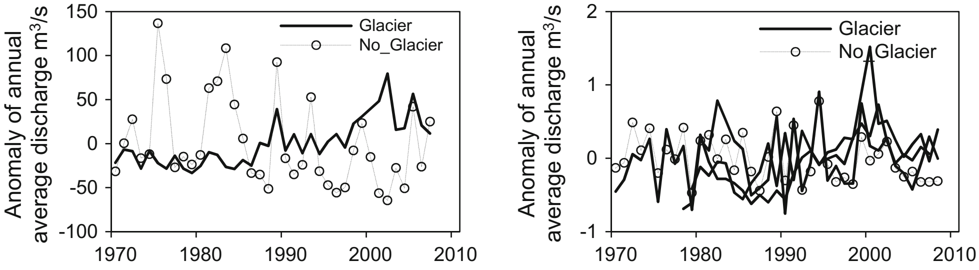


Fig. 7 **a** Observed annual maximum permafrost depth variations (cm) from 1970 to 2010 at 90 monitoring stations for plateau regions; and **b** annual change rate of glaciers over the past 30–40 years

recharge and the evaporation mechanism. Both can be expressed as products of long-term regional climate change and are manifested as intermittent changes in moist and dry periods, which correspond to the wet and dry years of basin water (Hu et al. 2006). Our results on the expansion of plateau lakes in TP could be supported by previous researches from Yan and Zheng (2015), Lei et al. (2014), and Li et al. (2014), and the dominant driver for recent lake expansions was mainly due to most retreating glaciers in the Himalayas and the Tibetan Plateau. However, the shrinkage plateau lakes in IMXP showed the same as Li et al. (2015) and Wang et al. (2014), and the shrinking of major lakes reflects severe anthropogenic impacts due to agricultural and industrial needs, in addition to the impact



(**a**) TP (**b**) IMXP

Fig. 8 Observed anomaly trends of annual runoff at key hydrological stations with and without glacier supplement in Tibetan Plateau (**a**) and Inner Mongolia and Xinjiang Plateau (**b**) from 1970 to 2010

Table 3 Annual mean trends of maximum permafrost depth with a significance level >95 % for plateau regions

Region	Change	1970–1990	1990–2000	2000–2010	1970–2010
Tibetan Plateau	Trends	−0.61 (46)	−0.28 (46)	−1.54 (46)	−0.80 (46)
	Increase	0.86 (14)	1.22 (17)	1.95 (7)	0.47 (13)
	Decrease	−1.29 (32)	−1.16 (29)	−2.12 (39)	−1.29 (33)
Eastern Inner Mongolia and Xinjiang Plateau	Trends	−0.56 (35)	−0.28 (38)	−0.35 (38)	−1.85 (38)
	Increase	2.87 (8)	1.62 (18)	2.02 (22)	0.51 (4)
	Decrease	−1.58 (27)	−1.99 (20)	−2.73 (16)	−2.09 (34)
Western Inner Mongolia and Xinjiang Plateau	Trends	−0.69 (45)	−0.30 (50)	−0.69 (49)	−1.25 (49)
	Increase	0.86 (10)	0.87 (24)	1.94 (30)	0.60 (7)
	Decrease	−1.13 (35)	−1.39 (26)	−1.27 (19)	−1.56 (42)

The variations and numbers of stations with positive and negative trends are also shown as increase and decrease, respectively

of climate change, which can provide insight into the impact of climate change and human activities on regional water resources in this arid and semiarid region.

Precipitation is probably the main source of lake water, and its quality and quantity are the main factors for maintaining the size and stability of the lakes. Owing to these special hydrological characteristics, the plateau lakes have expanded more significantly than lowland and hill lakes during the warm–wet period in the geological past (Hu et al. 2008). Song et al. (2014) indicated that the annual changes of water level showed strongly correlated with precipitation and evaporation, but may not evidently related to the glacier melting induced by global warming. The effects of temperature on lake water are mainly presented as a negative effect through water surface evaporation and a positive effect through the seasonal changes of ice and snow melt water. The effect of wind speed and solar radiation on evaporation offsets the increasing temperature across the Tibetan Plateau. The most likely causes of diminishing wind speed are the asymmetrically decreasing latitudinal surface temperature and pressure gradients over the Tibetan Plateau, which may be part of a large-scale atmospheric circulation shift (Pryor et al. 2009; Jiang et al. 2010; You et al. 2010a). Reduced heat fluxes suppress turbulent transport and adiabatic lapse rates near the surface weaken the surface cyclonic circulation and reduce wind speed locally (You et al. 2010a). In addition, surface changes on a small scale, such as land cover changes, can also affect surface wind speed (Klink 2002). To what extent such small-scale influences are important in explaining the wind speed decline is unknown and requires further study (You et al. 2010a). Sunshine duration changes on the TP (from brightening to dimming between 1970 and 2010) cannot be explained solely by changes in total cloud cover and could be related to the increase detected in the low cloud amount, precipitation, and water vapor pressure series (You et al. 2010b).

When a large proportion of the water within a lake basin is supplied by glaciers, the rising temperatures will allow the exacerbated negative mass balance state of glaciers and strengthened glacial melting recharge process, and then the increased recharge of lakes and the rise of lake levels. More than 80 % of the glaciers in western China are currently in a state of retreat (Yao et al. 2007) owing to the current pronounced warming, particularly on the Tibetan Plateau (Yao et al. 2012), and two-thirds of glaciers will disappear by 2060 under current trends (Yao et al. 2007). The accelerated glacier melting is one of the important factors for the expansion of the lakes, and it has contributed to up to between 50.6 and 60 % of the rising lake levels since 1970 (Zhu et al. 2010; Yao et al. 2010; Wang et al. 2011). The obvious warming of cold seasons, which has extended the time of glacier surface melting (Wu and Zhu

2008), and together with increasing precipitation, descending evaporation has contributed to the enlargement of Nam Co Lake (Zhu et al. 2010).

Lakes closer to glaciers and at higher altitudes, particularly those connected to glacier termini, have undergone larger area changes. Retreating glaciers not only supply meltwater to lakes, but also leave space for them to expand. Wang et al. (2015) and Zhang et al. (2015) studied the glacial lakes that classified as glacier-fed lakes and non-glacier-fed lakes according to their hydrological connection to glacial watersheds. Glacier-fed lakes are dominant in both quantity and area and exhibit faster expansion trends overall compared to non-glacier-fed lakes. Glacier meltwater may play a dominant role in the areal expansion of most glacial lakes. In addition, the patterns of the glacier-fed lakes correspond well with warming temperature trends and negative glacier mass balance patterns.

However, variations in lakes within glacial areas are not coupled in all lake catchments. Even under the same climatic background, different warming rates by altitude (Li et al. 2007) lead to differences in the melting speed of glaciers and thus result in a different rate of change in the glacial lake. Part of the shrinking lakes directly supplied by glaciers show that the injection of glacial melting water has been insufficient to compensate for the water loss, which signifies the diversity and complexity of the reasons for changes in glacial lakes (Wang et al. 2011). In addition, the development and expansion of glacial lakes may be related to the fact that they are located in the second largest precipitation zone on the upper mountain. Each peak on the Tibetan Plateau is a “heat island” in the summer, and when converged on by the surrounding valley wind become the center of water vapor condensation, and then becoming a “wet island” (Shi et al. 2006). The effect produced by this “heat–wet island” is not clear (Wang et al. 2011).

Climate warming in the permafrost regions resulted in active layer thickening, shrinkage, or expansion of thermokarst lakes. Pan et al. (2014) revealed the hydrological processes near thermokarst lakes and their influences on lake development and indicated the main direction of subsurface flow through soil on hillslopes near the lake. The ensuing recharge of the lake is balanced by drainage from the deepest end of the lake. In the discontinuous, sporadic, and isolated permafrost zone, it has been concluded that the major mechanism for the shrinking and splitting of some water bodies is a decrease in the water balance within a warming climate (Huang et al. 2011). Furthermore, the major mechanism for shrinking lakes in the permafrost-dominated area has been the formation of taliks, allowing internal drainage through the permafrost (Yoshikawa and Hinzman 2003). In areas of continuous permafrost, the total lake areas have increased, and lake numbers have risen. Recent warming on the TP has been associated with decreasing areas of permafrost and a rise in the elevation of its lower altitude, thickness active layer, as well as progressive thinning (Wu et al. 2001b; Cheng and Wu 2007; Mats et al. 2009). A numerical simulation by Nan et al. (2005) indicated that a continuous 0.02 °C/year air temperature increase would result in a 8.8 and 13.4 % reduction in the areal extent of Tibetan permafrost by 2050 and 2100, respectively, and that 46 % of the existing Tibetan permafrost would disappear over the next century (if considering an air temperature increase of 0.052 °C/year).

Lakes act as integrators of the physical parameters affecting their temperature, and similar to oceans, their high heat capacity dampens their short-term temperature variability and highlights longer-term variations (Schneider and Hook 2010). Changes in albedo brought about by changes in lake area can have positive or negative effects on climate warming. However, water bodies are inaccurately represented in models and the impacts of these lakes on local and regional-scale climate systems have not been well investigated (Mahmood et al. 2010). Although the surface temperatures and associated trends of inland water bodies can be accurately measured with thermal infrared data from satellite instruments since the emissivity of water is well known (Schneider and Hook 2010), such studies are relatively few in number and limited to water bodies using a long, regular time series of in situ measurements.

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