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LETTER

Response of inland lake dynamics over the Tibetan Plateau to climate change

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Abstract The water balance of inland lakes on the Tibetan Plateau (TP) involves complex hydrological processes; their dynamics over recent decades is a good indicator of changes in water cycle under rapid global warming. Based on satellite images and extensive field investigations, we demonstrate that a coherent lake growth on the TP interior (TPI) has occurred since the late 1990s in response to a significant global climate change. Closed lakes on the TPI varied heterogeneously during 1976–1999, but expanded coherently and significantly in both lake area and water depth during 1999–2010. Although the decreased potential evaporation and glacier mass loss may contribute to the lake growth since the late 1990s, the significant water surplus is mainly attributed to increased regional precipitation, which, in turn, may be related to changes in large-scale atmospheric circulation, including the intensified Northern Hemisphere summer monsoon (NHSM) circulation and the poleward shift of the Eastern Asian westerlies jet stream.

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1 Introduction

The Tibetan Plateau (TP), with its high elevation and vast spatial coverage, is a major geographic feature of the Northern Hemisphere. The elevated topography of the TP is of considerable importance to Asian monsoon and the atmospheric general circulation via its mechanical and thermodynamic forcing (Wu et al. 2012). During recent decades, the TP has experienced significant climate changes, characterized by an unprecedented warming (Liu and Chen 2000), wind stilling (Lin et al. 2013), a decrease in potential evaporation (Zhang et al. 2009), and an increase in water vapor amount (Yang et al. 2012). These changes have significantly altered the regional water and energy cycle (Yang et al. 2014), and have impacted the regional environment (e.g., glacier, permafrost, river runoff) and ecosystem (e.g., grassland, livestock, and even the local human population) (Yao et al. 2004). Due to the minimal human activity, the TP is an ideal place for studying how the water cycle has changed in response to large-scale climate and environmental change.

One of the TP's most prominent features is the large number and area of inland lakes widely distributed on the TP (Ma et al. 2010). Their water balance is sensitive to regional climate changes, including atmospheric precipitation, lake evaporation, and land evapotranspiration, as well as glacier melt and permafrost thawing (Yao et al. 2010; Liu et al. 2009). Lake dynamics on the TP has been extensively studied with remote sensing and field investigations (e.g., Li et al. 2011; Zhang et al. 2011; Song et al. 2013; Lei et al. 2013; Wan et al. 2014). These studies mainly focused on analyzing lake dynamic linkage with local climate change; and its relation with large-scale climate change has seldom been discussed. In this study, we made a comprehensive investigation on the inland lake dynamics on the TP through satellite images and extensive field campaigns. We first describe the inland lake dynamics on the TP interior (TPI) and Himalayas, then analyze the causes of the coherent lake growth since the late 1990s, and finally, discuss the possible relation between lake dynamics and changes in large-scale atmospheric circulation.

2 Lake area changes extracted from satellite images

Most of the inland lakes are distributed on the TP interior (TPI), but some lakes may be found in the Himalayas region. We only analyzed closed lakes larger than 20 km^2 (selection methods in the supplementary data). As shown in Fig. 1, there are a total of 109 lakes. At least four stages of satellite images were used to extract lake surface area (detailed methods in supplementary data), including Landsat Multispectral Scanner (MSS) in 1976, Thematic Mapper (TM) in 1990 and 2010, and Landsat Thematic Mapper Plus (ETM+) in 1999. Based on these images, we determined the spatial and temporal variations of water surface area of the 109 lakes, among which, there are 99 lakes on the TPI and 10 in the Himalayas region. The 99 selected lakes on the TPI have a total area of 20,300 km^2 (occupying 70 % of the total lake area in this region), and the 10 selected lakes in the Himalayas have a total area of 1,178 km^2.

Figure 2 shows the results of lake area changes on the TP between 1976 and 2010. On the TPI, the total lake area of the 99 selected lakes decreased slightly by 2.3 % from 1976 to 1990, but increased by 5.7 % from 1990 to 1999. Since 1999, the selected lakes showed an overall expansion, with a significant increase in total area by 18.2 %. The average rate of lake area increase from 1999 to 2010 was about three times that of 1990 to 1999. In the western and central Himalayas sub-region (80–86° E), on the other hand, lakes showed a continual shrinkage during the period of 1976–2010. In the eastern Himalayas sub-region (86–92° E), lakes also exhibited a decreasing trend, except the increasing period from 1997 to 2005 as

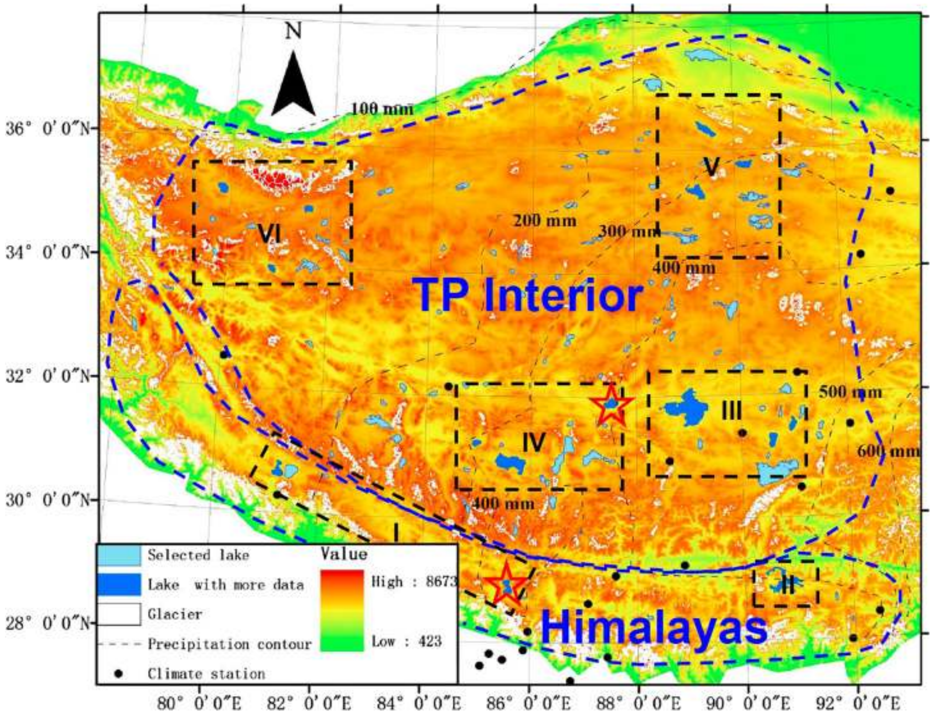

Fig. 1 Selected lakes on the TPI and Himalayas. Precipitation contours are derived from Tropical Rainfall Measurement Mission (TRMM) satellite data for the years 1998–2011 (Qi et al. 2013). The lakes with more satellite images in each sub-region are in *dashed rectangles*. The two lakes (Paiku Co and Dozeg Co) with field investigations are marked by *red stars*

indicated by lake level changes of Yamdog Yumco (Fig. 3). Therefore, there is a sharp contrast in lake dynamics on the TPI and Himalayas in the last decades.

Figure 3 shows detailed area changes of 12 typical lakes from four sub-regions on the TPI (III to VI in Fig. 1). We can see that the period from 1976 to 1999 was characterized by heterogeneous lake dynamics and a change occurred since 1999 when lakes expanded coherently and dramatically across the TPI. On the southeastern TPI (sub-region III), lake expansion was relatively slow during the period of 1976–1999, but has accelerated significantly since the late 1990s. On the southwestern TPI (sub-region IV), the total lake area contracted slightly by 0.4 % between 1976 and 1999, but expanded by 4.9 % between 1999 and 2010. On the northern TPI (sub-region V), significant lake shrinkage occurred between 1976 and 1990, with the total lake area reduction by 8.7 %, and then expanded significantly by 29.7 % between 1999 and 2010. On the western TPI (sub-region VI), the lakes shrank slightly by 1.8 % between 1976 and 1999, and expanded significantly by 21.9 % between 1999 and 2010.

Spatially, the recent lake expansion on the TPI shows an increasing trend from south to north and from west to east (Fig. 2), similar to the results of Song et al. (2013). The expansion rate on the eastern TPI was much larger than that on the west, and the largest lake expansion occurred between 87.5° and 90° E. This recent change contrasts the opposite east–west asymmetry on the geologic time scales with greater magnitude lake level changes on the western TP relative to the east (Hudson and Quade 2013). This lake expansion also shows an approximately positive correlation with its supply coefficients (the catchment/lake area ratio, Fig. S5).

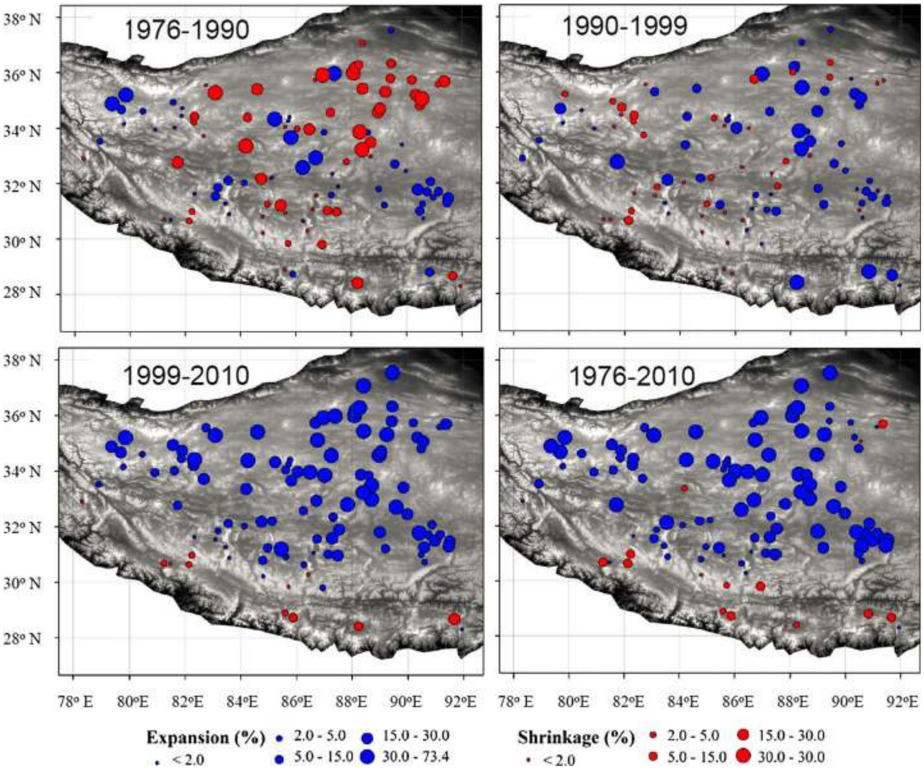

Fig. 2 Changes in lake area on the TPI and Himalayas, 1976–2010

3 Lake level changes derived from field survey

Several field campaigns were conducted to determine the long-term lake level variations. Considering the lake representativeness and harsh fieldwork conditions, we selected ten lakes on the TPI and one in the Himalayas sub-region, as shown in Table 1.

On the TPI, since there are only a very few long-term observations of lake level changes and satellite radar/laser altimetry data spans less than 10 years, bathymetric survey on individual lakes was conducted to acquire long-term lake level changes. Water level variations of ten large lakes are determined based on bathymetric surveys in 2009–2013 and the position of past shorelines (Lei et al. 2012, 2013). Results show that the lake level changes were relatively small during 1976–1999, but accelerated significantly since the late 1990s, consistent with the overall trend in lake area expansion. Taking Dazeg Co (87.53° E, 31.89° N) as an example, the lake level fell by 2.2 m from 1976 to 1999 and increased by 8.2 m from 1999 to 2012 with a much larger extent (Table 1, Fig. S4). The water level increase for the ten investigated lakes was calculated to be more than 5.5 m on average during the period 1999–2010. Therefore, the inland lakes on the TPI deepened significantly during the last decade, which is consistent with the expansion in lake area.

In the Himalayas region, an investigation on Paiku Co (85.58° E, 28.89° N) was carried out in May 2013. Clear shorelines around Paiku Co recorded a continual lake level decrease, with at least four shorelines formed since the 1970s. Combined with images from Google earth

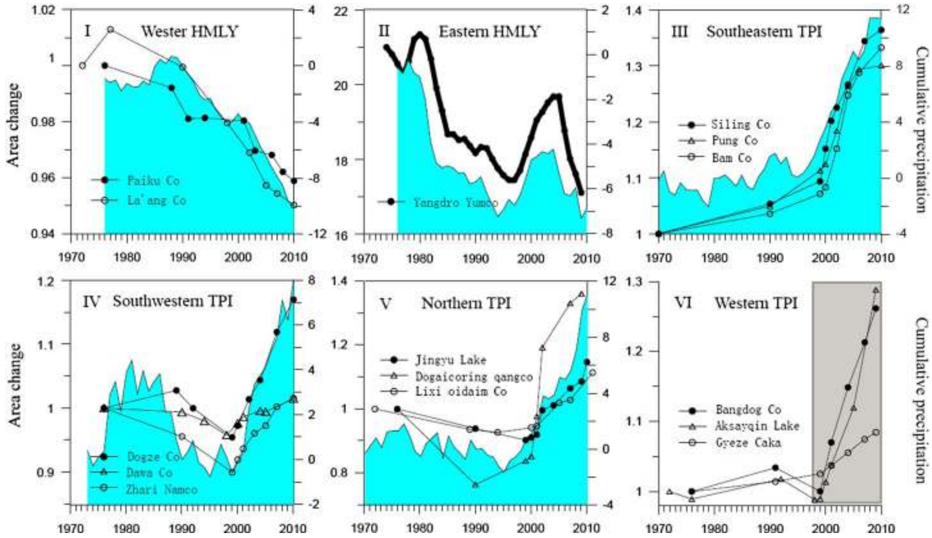

Fig. 3 Detailed lake area changes in the six sub-regions (the *left*) versus normalized cumulative precipitation recorded at nearby meteorological stations (the *right*, *blue-green area*), relative to 1976–1990. Area changes in sub-region I, III, IV, V, and VI are expressed as the area ratio with that of 1976. In sub-region II, lake dynamics is expressed as lake level change (m) of Yamdrog Yumco. Each sub-region and nearby meteorological stations used in this study are marked in Fig. 1 and supplementary material (Table S2 and S3). In sub-region VI, only lake area change is shown because there is no meteorological data available

maps from 2003 to 2012, and early satellite images taken from 1976 onwards, the decrease in lake level was reconstructed. Results show that the lake level decreased continually by 4.0 m during 1976–2013 (Fig. S4), and the lake's volume reduced by $\sim 1.1 \times 10^9$ m^3 in total. The inferred lake level changes of Paiku Co are comparable with observed water level changes at Yamzhog Yumco (90.69° E, 29.98° N), where the water level fell by 4.2 m during the period of 1974–2009 (Bian et al. 2009; Fig. 3).

Table 1 Information on the investigated lakes on the TPI and Himalayas

No.	Lake name	Longitude (°E)	Latitude (°N)	Area (km^2)	Lake level change (m) (1976–1999)	Lake level change (m) (1999–2010)
1	Dogze Co	87.53	31.89	292.4	−2.2	+8.2
2	Linggo Co	88.59	33.85	115.6	+4.7	+6.5
3	Zhari Namco	85.61	30.93	1001.3	–	+3.0
4	Tangra Yumco	86.61	31.07	842.2	–	+4.1
5	Siling Co	88.99	31.80	2222.0	+3.0	+8.8
6	Nam Co	90.60	30.74	2021.3	+2.2	+2.5
7	Bam Co	90.58	31.26	251.3	+2.1	+6.8
8	Pung Co	90.97	31.50	176.1	+4.4	+6.5
9	Darab Co	90.74	31.70	70.0	+2.5	+2.7
10	Zige Tangco	90.86	32.08	233.3	+4.0	+4.3
11	Paiku Co	85.58	28.89	269.6	−1.6	−2.4

4 Causes of lake dynamics

4.1 Climate change

Precipitation (including solid precipitation) is one of the most important factors influencing the water budget of closed lakes. A comparison of the area or water level changes of typical lakes in the six sub-regions with the cumulative precipitation recorded at nearby meteorological stations (detailed information in Table S2, S3) is shown in Fig. 3. Although only 15 lakes in six sub-regions are selected, their dynamics can be used to represent the general trend on a large scale since lakes in each sub-region varied with a similar trend (Fig. 2). In the Himalayas sub-regions (I, II), lake shrinkage corresponds to reduced precipitation. On the TPI, a significant lake growth in its three sub-regions (III to V) corresponds to a positive increase in the normalized cumulative precipitation since the late 1990s. More importantly, the lake shrinkage in sub-regions IV and V before the 2000s also corresponds well to the reduced precipitation values. This similar pattern indicates that precipitation change plays a key role in the lake dynamics. Runoff, which is mainly controlled by precipitation, shows a decreasing trend in the Himalayas, but an increasing trend on the TPI during the study period (Yang et al. 2011). This runoff pattern is similar to the lake dynamics on the TPI and Himalayas described here. On the western TPI (VI), there is no meteorological data for comparing with lake dynamics, though significant lake growth also occurred since the late 1990s (Fig. 3).

Lake evaporation is another important factor influencing the water budget of closed lakes. Potential evaporation, which can be approximately taken as lake evaporation (Rosenberry et al. 2007), shows a significant decreasing trend across the TP due to the reduction in wind speed and solar radiation (Fig. S7; Zhang et al. 2009; Yang et al. 2011). The decrease in potential evaporation could contribute to the lake growth on the TPI but did not prevent the lake shrinkage in the Himalayas, indicating that lake evaporation is not a dominant factor for the spatial difference of lake dynamics between the TPI and Himalayas. It should be noted that water balance calculation is needed to quantify the contribution of each climate factor to lake growth on the TPI, including increase in precipitation and runoff, and decrease in lake evaporation.

4.2 Glacier contribution

Substantial glacier coverage is another prominent feature of the TP (Yao et al. 2004). Based on the new Chinese glacier inventory collocated in ~2008 (Wei et al. 2014), the total glacier area in the catchment of the selected 109 lakes is about 6,500 km^2, which is about 30 % of the total lake area. Since it is still a big challenge to evaluate the total glacier mass balance on the TP (Yao et al. 2004, 2012; Gardner et al. 2013), we cannot quantify its contribution to the lake growth. However, a simple statistical analysis shows that the lake expansion rate matches neither the glacier coverage nor the ratio of glacier area to lake area within individual lake basins (Fig. S6). Indeed, most of the glacier-fed lakes and non-glacier-fed lakes expanded with a similar trend and magnitude (Fig. 4). Another independent evidence is the high degree of consistency between the net mass gain on the TPI derived from the Gravity Recovery and Climate Experiment (GRACE) and increase in lake volume during 2003–2009 (Zhang et al. 2013; Jacob et al. 2012; Song et al. 2013), indicating that the overall water surplus is not mainly due to glacier mass loss since the latter should not increase the total mass of this region. Based on the Ice Cloud and Elevation Satellite (ICESat) data during 2003–2009, Neckel et al (2014) found that there is a mass gain for glaciers on the north-central TP, which also indicates that the recent lake growth (sub-region VI) was not significantly contributed by glacier mass

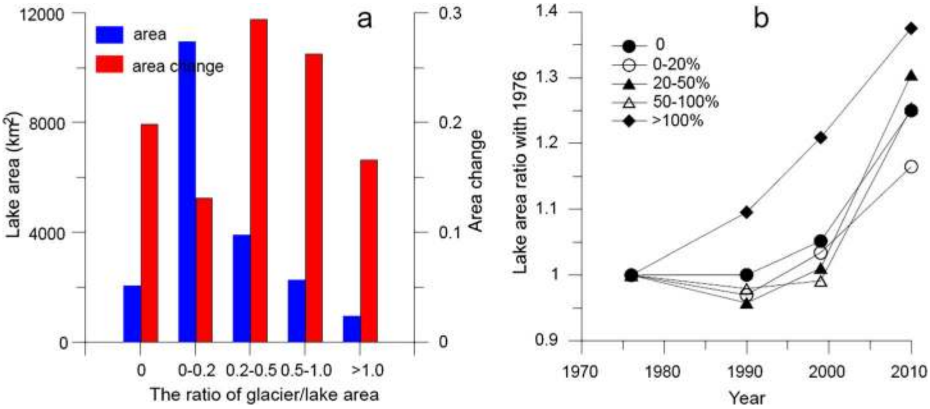

Fig. 4 Total area changes for lakes with different glacier/lake area ratio on the TPI. **a** Total water surface area (the *left*, *blue histogram*) for lakes with glacier/lake area ratio of 0, 0–.2, 0.2–0.5, 0.5–1.0, and >1.0, and their area changes (the *right*, *red histogram*) between 1999 and 2010; **b** Time series of total lake area changes with the same classification between 1976 and 2010

change there. However, we do not deny that the expansion of some lakes may be significantly affected by glacier mass loss, e.g., Nam Co (Yao et al. 2010) and Linggo Co (Lei et al. 2012).

4.3 Possible connection with regional and global atmospheric circulation

The coherent lake growth on the TPI since the late 1990s is consistent with regional climate changes. During the past decades, the TP experienced significant climate changes, which have altered the regional water cycle and thus impacted the water balance of closed lakes (Yang et al. 2014). Surface air temperature and water vapor content show significant positive trends on the TP since the mid-1980s, and convective available potential energy exhibits a positive trend since 1990 and the troposphere is becoming more unstable (Yang et al. 2012). Therefore, more convective precipitation could be triggered under the warmer and moister condition and yield more precipitation and runoff, which is in favor of the coherent lake growth on the TPI (Yang et al. 2014). It should be noted that climate change could influence the water balance of all lakes, including the glacier-fed lakes.

The coherent lake growth on the TPI could also be further connected with changes in global-scale atmospheric circulation in the late 1990s. Northern Hemisphere summer monsoon (NHSM) has been considerably intensified during recent decades by the enhanced land–sea thermal contrast and significant increase in the SST gradients over the tropical Pacific, as well as a positive phase of Atlantic multi-decadal oscillation (Wang et al. 2013). Therefore, more water vapor could be transported to the TPI during monsoon season. Figure 5 shows that there is a similar trend between water vapor on the TPI and NHSM circulation ($r=0.53$), and the significant increase in water vapor (also precipitation) correspond well to the intensification of the NHSM circulation in the late 1990s, suggesting that the former, as well as the rapid water surplus, might be related to changes in large-scale atmospheric circulation.

The spatial difference of lake dynamics between the TPI and Himalayas is consistent with changes in moisture over the TP. Both Yang et al (2011) and Gao et al (2014) found that the vast and semi-arid TPI became wetter while the humid southern TP became drier during the last 30 years. The general wetting trend on the TP is mainly attributed to the poleward shifts of the East Asian westerly jet and poleward moisture transport (Gao et al. 2014). In other

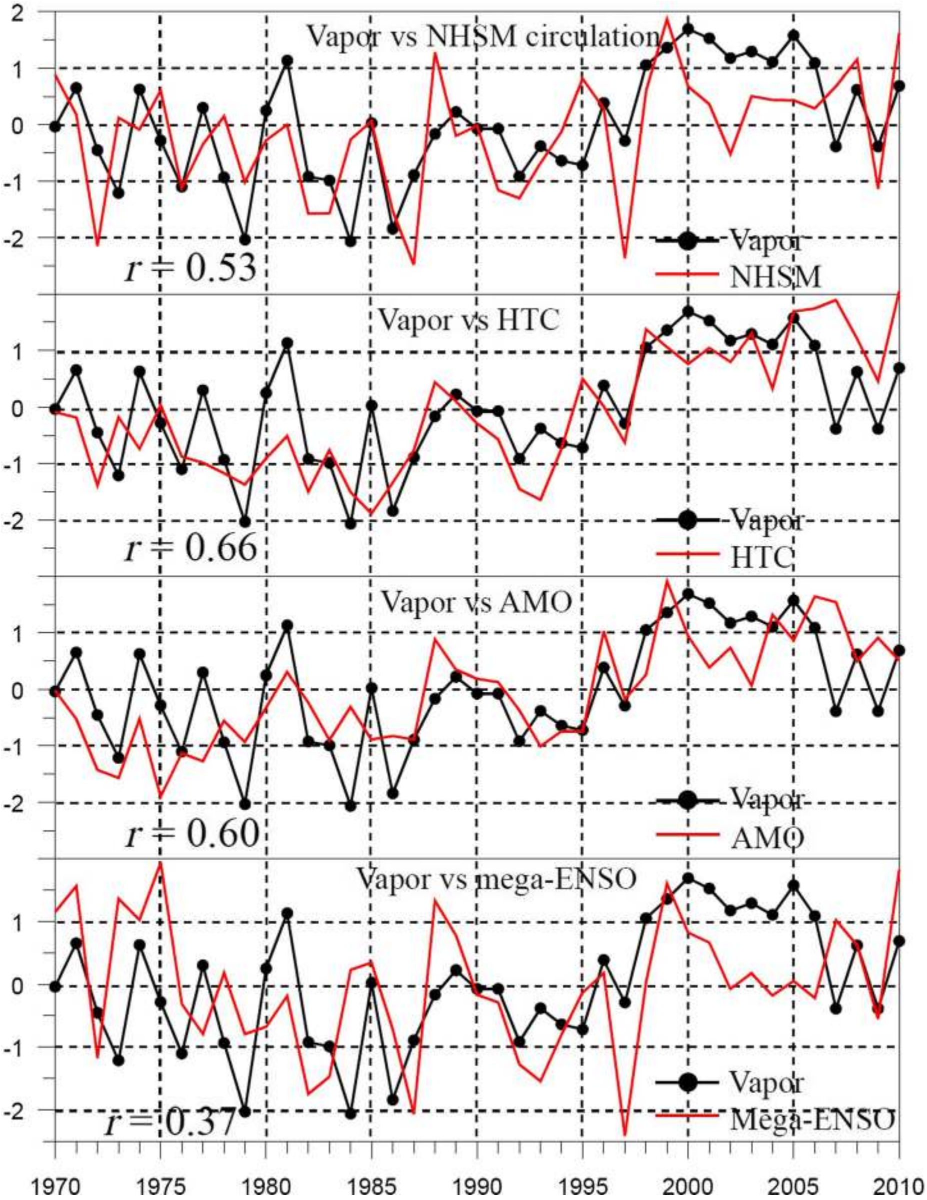

Fig. 5 A comparison of water vapor changes on the TPI with large-scale atmospheric circulation, including NHSM circulation, Hemispheric thermal contrast (HTC), Atlantic multi-decadal oscillation (AMO), and mega-ENSO. Water vapor (MJJAS) from the eight meteorological stations on the TPI, other than precipitation, is used here because water vapor can mix well and represent less regional signal than precipitation. NHSM circulation, HTC and Mega-ENSO are from Wang et al. (2013), and the AMO index was downloaded from the website (www.esrl.noaa.gov/psd/data/timeseries/AMO/)

words, the westerlies, as a dominant driver of the TPI climate, may have responses to these changes in large-scale atmospheric circulations, although the processes need to be investigated further. The spatial difference of moisture changes between the TPI and southern

TP might be related to changes in local atmospheric circulation due to the differential heating of the TP and its surroundings (Gao et al. 2014).

5 Concluding remarks

Both remote-sensing images and field investigations show that lakes on the TPI expanded and deepened significantly since the late 1990s, in sharp contrast with those in the Himalayas. These changes in lake area and water level provide robust evidence for changes in the regional water cycle under rapid climate warming and the influence of the natural internal climate feedback. Although the decreased lake evaporation and glacier mass loss contribute to the lake growth to a certain extent, the overall lake growth is mainly due to the significant increase in precipitation on the TPI, which, in turn, might be related to changes in large-scale atmospheric circulation. It should be noted that quantitative water budget study is still needed for more accurate attribution of the causes, and climate modeling is also needed for uncovering the dynamics process.

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