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Key Points:
- Dramatic lake shrinkage occurred on the TP during the 2015/2016 El Niño event, followed by rapid lake expansion in 2016 and 2017
- Considerable drought and lake shrinkage on the CTP also occurred during historical El Niño events
- ENSO may have dramatic impact on the hydroclimate of the TP, especially the CTP

Supporting Information:
- Supporting Information S1

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Extreme Lake Level Changes on the Tibetan Plateau Associated With the 2015/2016 El Niño

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Abstract Although the impact of El Niño–Southern Oscillation on the Tibetan Plateau (TP) is reflected through stable isotopes of precipitation and ice cores, the hydroclimate response of TP lakes to El Niño–Southern Oscillation is seldom investigated. Here we show that significant lake water deficit occurred on the central TP (CTP) due to a dramatic decrease in precipitation 2016 El Ni/2016 El Niño event, followed by extreme lake water surplus in 2016 and 2017 over most of the TP (except the eastern CTP). Similar but weaker lake shrinkage and afterward expansion can also be found during historical El Niño events. Further exploration reveals that the CTP dry anomaly during El Niño events tends to bridge the dry anomalies over India and northern China, thereby forming a dry zone along the northwestern edge of the Asian monsoon domain. This study may shed light on the prediction of lake level changes on the TP.

Plain Language Summary The 2015/2016 El Niño was one of the three strongest on record and had tremendous impact on global climate, but its impact on the hydroclimate of the Tibetan Plateau is seldom investigated. Between 2013 and 2017, we carried out extensive fieldwork to monitor lake level changes on the central Tibetan Plateau and were fortunate to capture the whole process of lake level changes during this event. We found that lakes on the central Tibetan Plateau experienced significant shrinkage due to a dramatic decrease in precipitation in 2015. In the following 2016 and 2017, most lakes over the Tibetan Plateau expanded at unusually high speed. Similar but weaker lake shrinkage and afterward lake expansion also occurred during historical El Niño events. We further investigate how El Niño–Southern Oscillation can influence the climate of the Tibetan Plateau on a large scale and find that the central Tibetan Plateau dry anomaly tends to bridge the dry anomalies over India and northern China, thereby forming a dry zone along the northwestern edge of the Asian monsoon domain during an El Niño developing summer. This study may shed light on the prediction of lake level changes on the Tibetan Plateau.

1. Introduction

El Niño–Southern Oscillation (ENSO) is the dominate mode of interannual climate variability in the tropical Pacific (Trenberth et al., 1998). ENSO is characterized by a quasiperiodic warming (El Niño) and cooling (La Niña) of sea surface temperature (SST) in the central eastern equatorial Pacific (Rasmusson & Carpenter, 1982). Numerous studies show that Indian monsoon rainfall is closely associated with ENSO through the large-scale east-west shifts in tropical circulation (e.g., Kumar et al., 1999). During El Niño years, sinking anomalies dominate the large area from the western Pacific to the Indian subcontinent, which suppresses the convection and precipitation in these regions (Ropelewski et al., 1987). Later studies show that not every El Niño leads to decrease in Indian monsoon rainfall and the drought events in India are more sensitive to the warming in the central equatorial Pacific than that in the eastern Pacific (Kumar et al., 2006). The 2015/2016 El Niño was one of the three strongest on record (Wang et al., 2017; Xue & Kumar, 2017) and had tremendous impact on global climate (e.g., Thompson et al., 2017; Avery et al., 2017; Siderius et al., 2017; Li et al., 2018).

The ENSO effect on the Tibetan Plateau (TP) climate has been investigated through stable isotopes of precipitation and ice cores (J. Gao et al., 2018; Yang et al., 2018). Cai et al. (2017) found that precipitation stable isotopes at Lhasa exhibited a positive response to ENSO events and the interannual variation of precipitation stable isotopes is mainly related to upstream convection rather than moisture source changes. ENSO signal can also be found in the variations of ice core stable isotopes on the northwestern TP (Yang et al., 2018). Although the stable isotopes of precipitation and ice cores is a good indicator of water vapor transportation and changes in large-scale atmospheric circulation, the impact of ENSO on the hydroclimate over the TP has seldom been investigated (Hwang et al., 2005). Closed lake dynamics, as an integrator of water cycle in the catchment, is instrumental for the local water budget on the interior TP. Investigating the relationship between lake level changes and large-scale circulation is an effective way to understand the hydroclimate processes in the Third Pole region.

Since the late 1990s, lakes on the interior TP have expanded rapidly in response to the significant increase in precipitation, glacier melting, and permafrost thawing (e.g., Lei et al., 2013, 2014; Li et al., 2014; Song et al., 2014; Zhang et al., 2017). Studies also showed that abrupt lake level changes occurred on the TP due to extreme precipitation (Li et al., 2011; Yao et al., 2012; Song et al., 2014; Song & Sheng, 2015). Although large-scale lake dynamics can be observed by satellite altimetry with increasing accuracy and frequency (Crétaux et al., 2011, 2016; Kleinherenbrink et al., 2015; Phan et al., 2012; Zhang et al., 2011), in situ observations at specific lakes provide more details. Nevertheless, only very limited in situ observations of lake level changes on the TP have been available until now (Lei et al., 2017). Between 2013 and 2017, we carried out extensive fieldwork to monitor lake level changes on the central Tibetan Plateau (CTP) and were fortunate to capture the whole process of lake level changes during the strong 2015/2016 El Niño event. In this study, the hydrological response of Tibetan lakes to the 2015/2016 El Niño was analyzed. We also examined the response of lake dynamics to the recent El Niño events since the 1990s. Finally, we analyzed the changes in atmospheric circulation in El Niño/La Niña events and their impact on the hydroclimate of the TP.

2. Material and Methods

2.1. In Situ Observation of Lake Level Changes

About 400 closed lakes (>1 km2), with a total area of ~35,500 km^2, are distributed on the interior TP (Y. Gao et al., 2018). In this study, a total of 22 large lakes, with a total area of 14,000 km^2, are selected, including 13 lakes on the central TP (CTP), 6 lakes on the northern TP (NTP) and three lakes on the northwestern TP (NWTP, Figure 1 and supporting information Figure S1). More detailed information about these lakes can be found in the supporting information (Tables S1–S3). Both in situ observation and satellite data are used to investigate lake level changes. On the central TP, there are nine lakes with in situ observation. For other lakes, LEGOS altimetry and Landsat image data are used.

Between 2013 and 2017, we carried out lake level observations at nine closed lakes on the CTP (Figure 1). Lake level changes during and after the 2015/2016 El Niño event were recorded. Of the nine lakes, three are located on the western CTP (Cuoqin-Nima County): Zhari Namco, Dawa Co, and Dazeg Co; three are located on the eastern CTP (Bange-Naqu County): Nam Co, Bam Co, and Pung Co; and the others are located on the northern CTP (Shuanghu County): Amur Co, Eya Co, and Cedo Caka. The method of lake level observation can be found in Lei et al. (2017). Lake level changes in 2017 at Dazeg Co and Dawa Co were missing because the loggers at the two lakes were lost. The water level at Cedo Caka on the northern CTP was monitored one or two times a year by measuring the height relative to an abandoned bridge.

2.2. Satellite Observation of Lake Level/Area Changes

In order to check the possible impact of previous El Niño events on TP lake dynamics, we investigated long-term lake level changes during summer monsoon season by using LEGOS altimetry data (Crétaux et al., 2011). Four lakes on the CTP (Nam Co, Siling Co, Tangra Yumco, and Ngangzi Co) and three lakes on the NTP (Ayakkuh Lake, Dogai Coring, and Ulan Ul Lake) are selected (Table S2). When using LEGOS data, we deleted some outliers which are obviously not the real lake level changes. Lake level changes during summer monsoon season are defined as the lake level difference between early autumn (September–October) and early summer (April–May). ICESat altimetry data and in situ observation at Nam Co and Zhari Namco were used to validate LEGOS data.

We also investigated the intra-annual/interannual changes in lake area between 1987 and 2017 by using Landsat images. Eight lakes on the CTP (Zhari Namco and Zige Tangco), NTP (Jingyu Lake, Xiangyang

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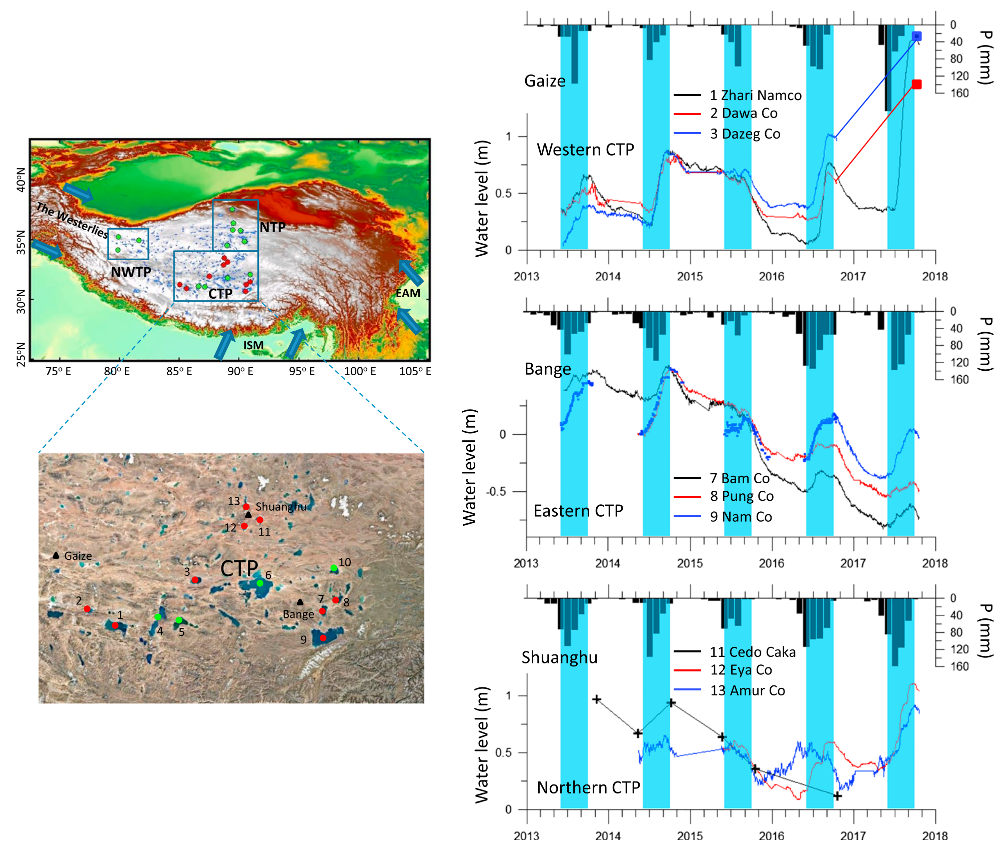

Figure 1. Location of the selected lakes in this study (left) and observed lake level changes on the CTP between 2013 and 2017 (right). Lakes with in situ observation and satellite observation are marked with red and green circles, respectively. The blue stripes in the right indicate monsoon seasons (June to September). The bars represent monthly precipitation (note that the *Y* axis is descending) at Gaize, Bange, and Shuanghu Counties (black triangles in the lower left). CTP: central Tibetan Plateau; NWTP: northwestern Tibetan Plateau.

Lake, and Lixi oidaim Lake) and NWTP (Aksayqin Lake, Bamgdog Co, and Chem Co) are selected (Table S3). Bathymetry survey of the lakeshore was conducted in 2011–2013 on the CTP (Lei et al., 2013, 2014). Past lake level changes since 1987 at Zige Tangco on the eastern CTP were reconstructed relative to 2011 according to the relationship between lake area and the relative lake level changes, which was established using linear regression. At Zhari Namco on the western CTP, the relationship between lake level and surface area was established based on in situ observation between 2009 and 2017 and the corresponding lake area.

2.3. Reanalysis Data

To understand the background of hydroclimate changes over the TP, changes in large-scale circulation in summer 2015 and 2017 (June–September) are analyzed. The ERA-interim reanalysis (Dee et al., 2011), which were provided by the European Centre for Medium-Range Weather Forecasts, are used in this study. The data cover the period 1979–2017 with a resolution of $0.75° \times 0.75°$. The composite analysis is applied for the El Niño (1994, 1997, 2002, 2006, 2009, and 2015) and La Niña years (1999, 2000, 2008, 2011, and 2017). The total column water vapor and vertical wind field are analyzed to investigate the atmospheric circulation changes. The monthly data from the Global Precipitation Climatology Project (GPCP) are hired to examine the changes in the large-scale precipitation. The SST from the National Oceanic and Atmospheric Administration is also used to inspect the global SST changes.

3. Results

3.1. Abnormal Lake Level Changes on the CTP During the 2015/2016 El Niño Event

In normal years (e.g., 2013 and 2014), lake levels on the CTP increase considerably by 0.3–0.6 m during the summer monsoon season, with the highest level in middle to late September, then lake levels decrease

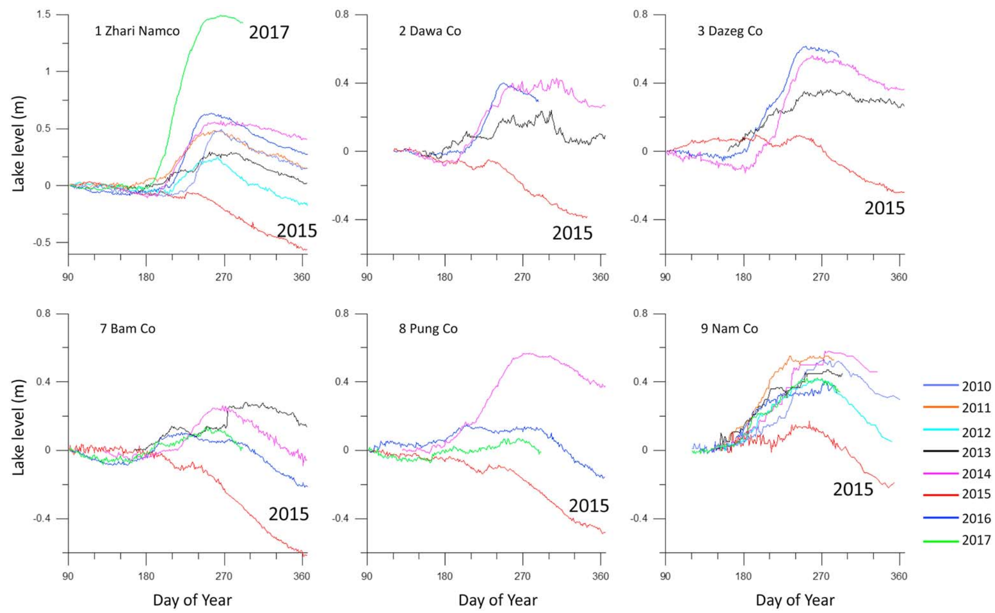

Figure 2. The anomalous lake level change in 2015 at the six observed lakes on the central Tibetan Plateau. The *X* axis represents the number of days from 1 January of each year. The *Y* axis represents the lake level anomalies. There was no water level data at Dawa Co and Dazeg Co in 2017.

gradually with the lowest level in early June (Lei et al., 2017). However, this seasonal pattern changed at all the observed lakes during the strong 2015/2016 El Niño event (Figure 1). The lake levels did not show considerable increase in summer 2015 but remained stable or even decreased slightly between June and August. The lake levels began to decrease rapidly in late August, about 1 month earlier than that in normal years (late September). Furthermore, the rate of lake level drop after September was much faster relative to normal years. As a result, lakes shrank dramatically and there was unique lake level seasonality on the CTP in 2015 (Figure 2).

After the strong 2015/2016 El Niño, contrasting lake changes occurred on the CTP. On the western and northern CTP, lakes recovered in 2016, with moderate lake level increase in summer at the observed lakes. A very dramatic lake level increase occurred in summer 2017. At Zhari Namco, lake level increased abruptly by 1.6 m. The loggers at Dawa Co and Dazeg Co were lost, but the reference point at the shoreline showed that the water level at the two lakes increased by at least 1 m from October 2016 to October 2017. The amplitude of lake level increase in summer 2017 was 2 to 3 times larger when compared with that in normal years. Dramatic lake expansion also occurred on the north CTP in summer 2016 and 2017 (Figure 1), with lake level increase of 0.5–0.8 m. As a result, lakes on the western and northern CTP exhibited an overall expansion during the study period.

In contrast to the rapid lake expansion, lake levels on the eastern CTP continued to decrease considerably after the 2015/2016 El Niño event. Lake levels at Bam Co and Pung Co increased moderately in summer 2016 and 2017 but decreased more in winter. Altogether, the lake levels decreased by 1.2 and 1.0 m at Bam Co and Pung Co, respectively, between 2014 and 2017. This contrasting pattern of lake dynamics indicates there may be distinct climate regimes between the eastern and western CTP.

Because in situ lake level observation at Zhari Namco and Nam Co had relatively long records, lake level changes at these two lakes were investigated as a case study (Figure S2). At Zhari Namco, in situ observation of lake level started in 2009, and lake level increase in summer fluctuated in a range of 0.3–0.7 m between 2010 and 2014. In summer 2015, lake level even decreased by 0.13 m from May to August. At Nam Co, in situ observation of lake level started in 2005, and lake level increase in summer varied in a range of 0.2–0.8 m between 2006 and 2014, with an average value of 0.44 m. In summer 2015, lake level only increased by about 0.13 m, which was the lowest since 2006. During the 2006 and 2009 El Niño events, lake level increased by 0.25 and 0.31 m in summer, respectively, which were the second and third smallest during the observation period.

The extreme lake level changes on the CTP were consistent with regional rainfall (Figure 1). On the western and northern CTP, summer precipitation (June to September) at Gaize and Shuanghu decreased significantly by 51.1% and 35.9% in 2015, respectively, relative to the mean value in 2013–2017. In contrast, the summer precipitation at the two stations increased dramatically by 44.3% and 37.3% in 2017 relative to the mean value in 2013–2017. On the eastern CTP where there are relatively more meteorological stations; summer precipitation at Bange and Amdo decreased significantly by 45.5% on average in 2015, but it returned to normal values in 2016 and 2017. We can find that although lake water budget can be affected by many factors, extreme lake level changes on the CTP were mainly related to changes in precipitation, which is consistent with model result from lake water balance (Biskop et al., 2016; Li et al., 2017; Tong et al., 2016; Zhou et al., 2015).

3.2. Response of Lake Level Changes on the CTP to the Historical El Niño Events

We further investigated the response of lake dynamics on the CTP to historical El Niño events by examining lake level changes during summer monsoon season since the early 1990s (Figure 3). The good correspondence between the LEGOS satellite altimetry and in situ observation at Nam Co indicates the reconstruction is reliable (Figure 3). On the western CTP, considerable lake shrinkage can be found at Zhari Namco, Tangra Yumco, and Ngangzi Co during the 1994, 1997, 2002, 2006, and 2009 El Niño events (Figure 3), corresponding well with the dramatic decrease in precipitation. The most dramatic lake shrinkage occurred during the period of 1993–1995 due to much lower precipitation. Since 1998, precipitation increased dramatically and the lake turned to expand rapidly. The rapid lake expansion was interrupted by considerable droughts during the 2002, 2006, and 2009 El Niño events. Notably, obvious lake shrinkage at Zhari Namco and Tangra Yumco did not occur in 2006 but occurred in 2007, indicating that there may be a time lag between lake level change and precipitation.

On the eastern CTP, dramatic lake shrinkage can be also found at Nam Co, Siling Co, and Zige Tangco during the 1994, 1997/1998, 2006, and 2009 El Niño events. The most dramatic drought, as indicated by lower precipitation and considerable lake shrinkage, occurred during the 1994 El Niño event, which was comparable to the 2015 drought. The lake shrinkage on the CTP during the strong 1997/1998 El Niño was not as obvious as that in 1994 due to the slight decrease in precipitation. After 1998, lakes on the eastern CTP turned to expand rapidly. There was no significant drought at the three selected lakes on the eastern CTP during the 2002 El Niño event, which is different from the western CTP. Although there are some exceptions, we can see that dramatic lake shrinkage on the CTP corresponds well with historical El Niño events due to significant decrease in precipitation, which indicates that not only the strong 2015/2016 El Niño event but also historical El Niño events can exert dramatic impact on the hydroclimate of the CTP (Figure 3).

In contrast, considerable lake expansion (1998–2001, 2008, and 2011) occurred on the CTP during La Niña events. After the 1997/1998 El Niño, the most rapid lake expansion on the CTP occurred between 1999 and 2001 due to anomalously high precipitation during the strong La Niño events. However, high rainfall and rapid lake expansion did not always occur in La Niña years. For example, lakes on the CTP expanded rapidly between 2003 and 2005 (Figure 4), which was not a typical La Niña year. In 2016 and 2017, when La Niña was also not well developed, precipitation was anomalously high and most lakes over the interior TP (except the eastern CTP) expanded dramatically. The following may have contributed to this inconsistency: first, the negative phase of Pacific Decadal Oscillation may favor more rainfall over the CTP after the late 1990s, providing an interdecadal background with more rainfall there (Gao et al., 2014; Zhu et al., 2011); second, ENSO's climate effect is asymmetric; that is, the climate influence of El Niño is usually stronger than La Niña; and third, other factors in addition to ENSO intensity may also contribute to the rapid lake expansion on the TP, for example, North Atlantic Oscillation (Liu & Yin, 2001; Wang et al., 2016).

3.3. The Extent of El Niño's Influence on the TP Hydroclimate

The response of lake dynamics on the NTP and NWTP to El Niño events was not as sensitive as that on the CTP, especially after 2000 (Figures S3 and S4). Considerable lake shrinkage on the NTP occurred during the 1994 and 1997 El Niño events. After that, lake dynamics on the NTP did not respond sensitively to the 2002, 2006, and 2009 El Niño events (Figure S2). In fact, lakes still expanded rapidly during these El Niño years due to much higher precipitation (e.g., 2002 and 2009). During the strong 2015/2016 El Niño, precipitation at Tuotuohe station decreased by 25.9%, but lakes did not exhibit dramatic shrinkage on the NTP

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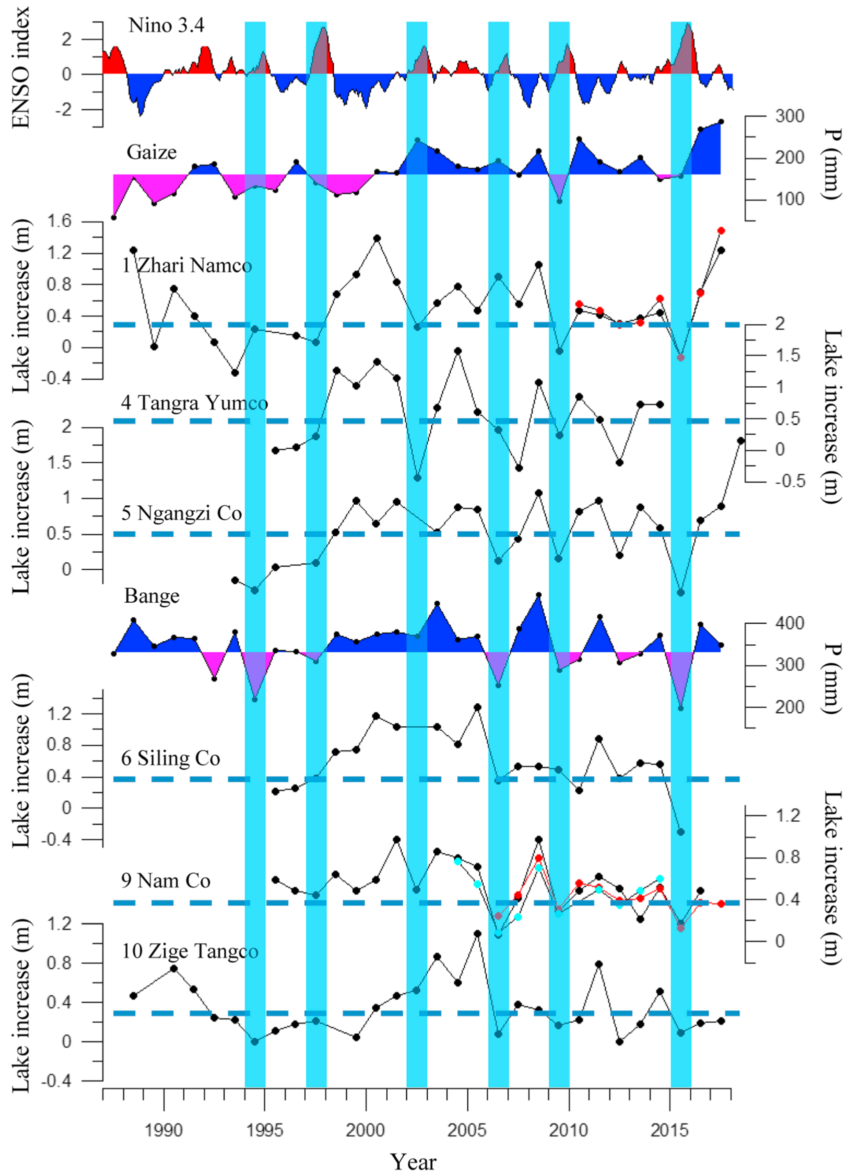

Figure 3. Time series of Nino 3.4 indices, summer precipitation (June to September, mm) at Gaize and Bange meteorological stations, and summer lake level increase on the western and eastern central Tibetan Plateau between 1988 and 2017. The cyan stripes indicate El Niño years. In situ observation (the red circles) and ICESat data (the blue circles) at Zhari Namco and Nam Co are also used.

(Figure S3), indicating that although dry conditions may extend to the NTP, the lake's response was not as sensitive as those on the CTP. Rapid lake expansion occurred on the NTP in 2016 and 2017 due to higher precipitation, which is consistent with the CTP (except the eastern CTP). Generally, lake expansion on the NTP did not show considerable differences between El Niño and La Niña years, indicating that the impact of El Niño events on the NTP climate was relatively weak. This insensitivity is consistent with the result from precipitation stable oxygen isotopes, which reveals that the northern limit of the Indian summer monsoon is at about 34°N on the NTP (Tian et al., 2001; Yao et al., 2013).

On the NWTP, the teleconnection between lake dynamics and ENSO becomes further weaker than that on the NTP. The three selected lakes on the NWTP expanded steadily since 2000, even in 2015, but lake expansion was more dramatic in 2016 and 2017 (Figure S4). This steady lake expansion is a common feature of lake dynamics on the NWTP, as indicated by other lakes such as Lumajiangdong Co and Meima Co (Jiang et al., 2017; Kleinherenbrink et al., 2015). Since glaciers are widely distributed on the NWTP, the insensitivity of

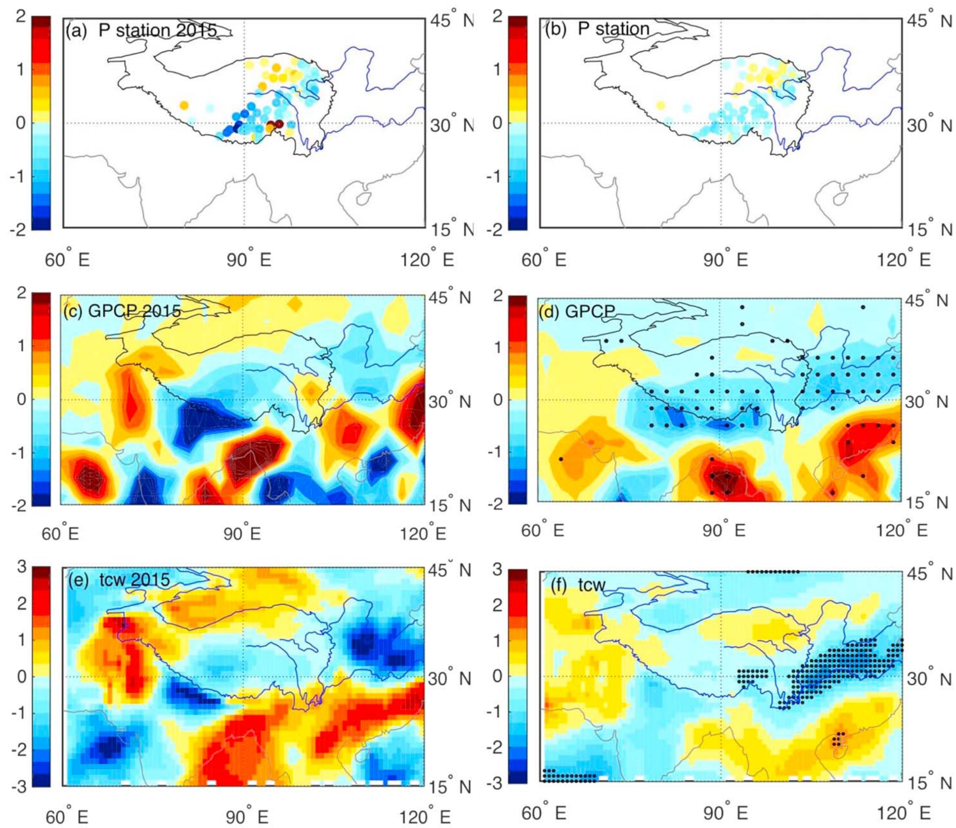

Figure 4. The anomalies in summer mean station rainfall (mm/day; a, b), GPCP rainfall (mm/day; c, d), and total column water vapor (g/m^2; e, f), in (a, c, e) 2015 and (b, d, f) developing El Niño years (1994, 1997, 2002, 2006, 2009, and 2015) relative to the climatological mean during 1979–2017. The black dots in (d) and (f) indicate significant values at 90% confidence level. GPC Global Precipitation Climatology Project; tcw = total column water vapor.

lake dynamics on the NWTP to El Niño events may be partly attributed to higher contribution of glacier melt to lake level change. Lei et al. (2017) showed that although the total mass on the NWTP decreases due to decrease in precipitation in dry years, lakes can still expand rapidly in summer due to the large contribution of glacier melt to lake water budget.

3.4. Circulation Changes Related to El Niño Event

The anomalous lake level changes in 2015 are generally consistent with summer rainfall anomalies in both station observations (Figure 4a) and GPCP rainfall on a large scale (Figure 4c). In summer 2015, less rainfall occurred over most of the TP, including the central and southern parts. Note that the reduced precipitation on the CTP is in phase with the rainfall reduction over the southwest and northern India and northern China. Meanwhile, enhanced rainfall occurs over the Bay of Bengal, especially its head region and most parts of south China (Figure 4c). The total column water vapor on the TP (Figure 4b) exhibits a consistent pattern with precipitation anomalies, which features a southwest-northeast tilted, sandwiched (positive-negative-positive) anomalous belt structure. The vertical wind velocity shows less organized features (not shown), but there are anomalous sinking anomalies over most of the TP, including the CTP. The decreased total column water vapor and vertical velocity show consistency with the decreased summer rainfall over most parts of the southern TP.

In 2015–2016, there occurred the strongest El Niño event after 1997. Is there any connection between the strong warm ENSO (or El Niño) and depressed summer rainfall over the TP? Although many studies revealed the significant impact of ENSO on the East Asian climate (e.g., Yuan & Yang, 2012), few explored the possible impact of ENSO on the TP hydroclimate (Wang & Ma, 2018). To answer this question, we further performed a composite analysis on the developing El Niño summers, including 1994, 1997, 2002, 2006, 2009, 2014, and 2015 as denoted in Figure 3.

The results from both the station and GPCP data showed consistent decreased rainfall over most areas of TP during the El Niño years (Figures 4b and 4d). Similar to the situation in 2015 (Figure S5), large-scale negative rainfall anomalies occurred over the Maritime Continent and positive anomalies were observed over the central eastern equatorial Pacific and equatorial central Indian Ocean. The suppressed rainfall over the maritime continent extends northward to the South Asia monsoon trough region, including southern India, Indochina peninsula, South China Sea, and southwest Philippine Sea. This suppressed rainfall pattern is closely related to the developing El Niño event, with positive SST over the central eastern equatorial Pacific and rising anomalies there. The Walker circulation is thus weakened, and the convection over the Maritime Continent and Philippines is inhibited.

The local meridional circulation was adjusted accordingly, with rising anomalies over the Bay of Bengal and the East Asian subtropical front extending from south China to western Japan and sinking anomalies over the TP (Figure 4d). For the total column water vapor, we can see corresponding increased and decreased anomalies over the central eastern equatorial Pacific and Maritime Continent, respectively, due to changes in the SST-related evaporation. The total column water vapor decreased over the central and southern TP (Figure 4e), which is because less water vapor is transported over the TP through the Bay of Bengal and the subsidence over the CTP. This is consistent with the southerly wind anomalies over the southeastern TP at 500 hPa, which is related to the weakened water vapor transport from the Bay of Bengal. The decreased total column water vapor and the sinking anomalies (Figures 4d and 4f) together induced negative rainfall anomalies over most areas of the TP. For the La Niña years, summer rainfall over some area of TP increased significantly, but the signals showed less significance and weaker consistency over the TP than that during the developing El Niño years (Figures S7 and S8).

4. Implications

This study broadens our perspective on the ENSO-Asian monsoon linkage. It has been known that during El Niño developing summer, (i) India tends to be dry due to the atmospheric descending Rossby wave response to the suppressed convection over the Maritime Continent, and (ii) northern China also tends to be dry due to the Northern Hemispheric circumglobal teleconnection (Ding & Wang, 2005) excited by El Niño-induced tropical heat source changes (Wang et al., 2017). However, little is known about what happens in the CTP. The CTP is located at the northwestern edge of the Asian summer monsoon domain. These findings here reveal that during an El Niño developing summer, the CTP dry anomaly tends to bridge the dry anomalies over India and northern China, thereby forming a dry zone along the northwestern edge of the Asian monsoon domain, which implies that the northern edge of the Asian monsoon domain tends to retreat equatorward (expand poleward) during El Niño (La Nina).

The impacts of ENSO on the summer monsoon over the TP involve complex dynamic processes that interact with the immense TP orographic and thermodynamic effects on the atmospheric general circulation. The mechanism discussed in this work is primarily from a local perspective and based on the general concept of the ENSO influence. The precise physical processes by which ENSO affects the three-dimensional circulation anomalies over the TP certainly call for further in-depth investigation involving numerical model experiments.

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