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Key Points:

- Contrasting patterns of lake change between the Mongolian Plateau (MP) and Tibetan Plateau (TP)
- A clear inflection point of lake change during 1997/1998 on both plateaus
- The warmer-drier climate in MP, contrasting the warmer-wetter climate in TP, has driven drastically different patterns of lake evolutions

Supporting Information:

- Supporting Information S1

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






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Extensive and drastically different alpine lake changes on Asia's high plateaus during the past four decades

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Abstract Asia's high plateaus are sensitive to climate change and have been experiencing rapid warming over the past few decades. We found 99 new lakes and extensive lake expansion on the Tibetan Plateau during the last four decades, 1970–2013, due to increased precipitation and cryospheric contributions to its water balance. This contrasts with disappearing lakes and drastic shrinkage of lake areas on the adjacent Mongolian Plateau: 208 lakes disappeared, and 75% of the remaining lakes have shrunk. We detected a statistically significant coincidental timing of lake area changes in both plateaus, associated with the climate regime shift that occurred during 1997/1998. This distinct change in 1997/1998 is thought to be driven by large-scale atmospheric circulation changes in response to climate warming. Our findings reveal that these two adjacent plateaus have been changing in opposite directions in response to climate change. These findings shed light on the complex role of the regional climate and water cycles and provide useful information for ecological and water resource planning in these fragile landscapes.

1. Introduction

Lakes are dynamic systems, and changes in alpine lakes, such as their appearing/disappearing, expansion/shrinkage, can be an important indicator of environmental change. These changes integrate the effects of climate and human activity, such as land use change [Adrian et al., 2009; Huybers et al., 2016; Mason et al., 1994; Tao et al., 2015]. Lake changes can be monitored from space, making them particularly useful indicators in remote and inaccessible mountain regions [Crétau et al., 2011, 2016; Ma et al., 2010; Song et al., 2013; Zhang et al., 2011]. Regional-scale comparative studies are important in providing the understanding of different regional responses to global climate change. For alpine lake systems, their response to climate change could be drastically different depending on how they are influenced by the atmospheric circulation or by cryospheric processes [Gronewold and Stow, 2014; Smith et al., 2005; Song et al., 2014; G. Zhang et al., 2013]. Despite the substantial efforts that have been made in identifying alpine lake changes within relatively homogeneous regions [Lei et al., 2013; Tao et al., 2015; Zhang et al., 2014b], there have been few studies that quantify the possible diverse response of lake systems to climate change between regions that have different regional climates and cryospheric and geomorphological conditions.

Along with the Arctic region and Antarctica, the Tibetan Plateau (TP) and the Mongolian Plateau (MP) are among the world's most sensitive regions to climate change [Sha et al., 2015]. The TP, with an average elevation higher than 4000 m, has an extensive distribution of glaciers and discontinuous permafrost [Li et al., 2008; Yao et al., 2012; Zhao et al., 2010], which differ significantly from the MP, which geographically includes

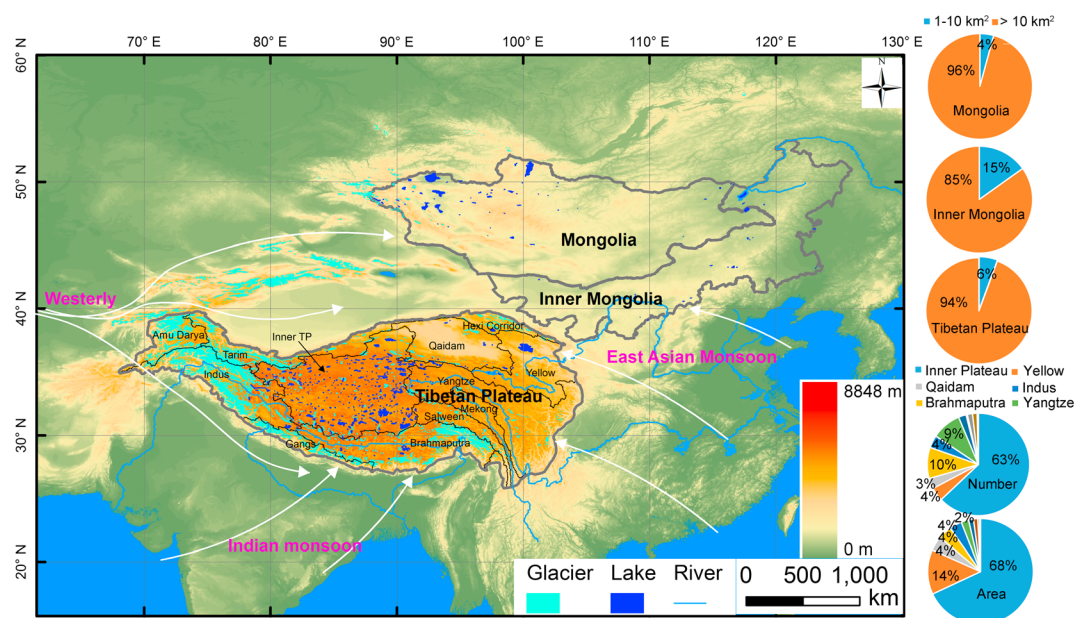


Figure 1. Locations of lakes, glaciers, and major river basins on the Tibetan Plateau and the Mongolian Plateau. Lakes larger than 10 km^2 and glacier coverage are outlined. The fractional areas (%) covered by lakes with areas of $1\text{--}10 \text{ km}^2$ (blue) and $>10 \text{ km}^2$ (orange) on each of the plateaus are shown (right). The six largest basins of the TP are labeled with fractional lake number and area (%); these basins account for 93% and 96% of the total number and area of the TP lakes, respectively.

the Inner Mongolia Autonomous Region of China and the Mongolian People's Republic (Figure 1). A more detailed description of study area can be found in the supporting information [Barnett *et al.*, 2005; Immerzeel *et al.*, 2010; Qiu, 2008; G. Zhang *et al.*, 2015]. In recent decades, the two plateaus have been experiencing similarly higher rates of warming than the rest of the world [Duan and Xiao, 2015; Tao *et al.*, 2015; Zhang *et al.*, 2014a]. Given the more drastic environmental changes and their location at the intersection of the westerlies, monsoonal systems, and other climatic phenomena [Chen *et al.*, 2015; Sha *et al.*, 2015], significant impacts on the water, cryospheric, and energy balances of the two plateaus can be expected.

In particular, both the TP and the adjacent MP have numerous natural lakes (Figure 1), which are important components of the water, cryospheric, and energy cycles. Under the intensified recent global warming, the states of the lakes on the two plateaus could have changed in different directions, although some studies of lake changes have been reported fragmentally [Tao *et al.*, 2015; Zhang *et al.*, 2011, 2014b; G. Zhang *et al.*, 2013]. Here for the first time, we quantify drastically different alpine lake changes for Asia's two largest and adjacent plateaus and their evolutions over the last four decades. We further explore the possible links between climate change and lake area change on these plateaus. Our results provide important information for water and ecosystem managements of these two climate-sensitive regions and potentially allow appropriate adaptation and management strategies to be developed at regional scale.

2. Data and Methods

2.1. Remote Sensing Data

Starting in 1972, the Landsat program comprised seven successful missions that have yielded the longest climate record of satellite-based land surface observations. The historical Landsat archive has contributed a uniquely long record of climatic observations for monitoring water resources on the Earth's surface [Alsdorf *et al.*, 2007; Pekel *et al.*, 2016; Verpoorter *et al.*, 2014; Yamazaki *et al.*, 2015]. The daily high cloud cover fraction ($>40\%$) over the TP precludes the mapping of lakes at annual intervals [Yu *et al.*, 2016]. Therefore, Landsat images over 3 year intervals with little or no cloud/snow coverage and the highest satellite repeat cycles were selected for the continuous time series of lake observations. Sixty Landsat scenes mapped by the multispectral scanner, thematic mapper (TM), Enhanced Thematic Mapper (ETM), ETM plus (ETM+), and Operational Land Imager (OLI) sensors over a single period covered all the targeted lakes ($>10 \text{ km}^2$) in the TP. Data from

more than 540 scenes were used to delineate the lakes in the TP between 1976 and 2013 for nine 3 year periods. For the MP, 41 scenes from the Landsat OLI imager were selected to delineate lakes in 2013. The lake area data for the MP between 1976 and 2010 over nine 3 year periods were obtained directly from *Tao et al.* [2015]. Lake area data for the period 1981–1985 were not derived for the TP due to limited availability of Landsat images, but these data were utilized for the MP [Tao et al., 2015]. Uncertainties in Landsat measurements can be found in the supporting information [Bolch et al., 2008; Huggel et al., 2002].

Many studies have reported methods of identifying water bodies in Landsat images [Ji et al., 2009; Li and Sheng, 2012; McFeeters, 1996; Xu, 2006]. However, we found that the automatic extraction of lake boundaries was not possible without manual intervention, because the lake boundaries could be obscured by clouds, snow/ice, and mountain shadows [Zhang et al., 2017]. Here the normalized difference water index [McFeeters, 1996] was used for separating water from nonwater features. The vector boundary of each lake was further modified by visually inspecting the original Landsat imagery. The TP was further divided into 12 subbasins according to major river and catchment characteristics [G. Zhang et al., 2013] (Figure 1). Lakes in the TP are mainly located in six basins, with 96% of the total lake area being found in the Inner-TP, Yellow, Qaidam, Indus, Brahmaputra, and Yangtze River basins.

2.2. Climatic Data Set

The annual temperature and precipitation data were collected for Inner Mongolia of China and the TP from the China Meteorological Administration (CMA) stations (<http://data.cma.cn/>) during the period 1976–2013 and for Mongolia from meteorological stations during the period 1976–2010. The downscaled precipitation from the Weather Research and Forecasting (WRF) simulation (30 km resolution) and the Global Land Data Assimilation system (GLDAS, 1° resolution) were also utilized for the TP [Gao et al., 2015]. The monthly gridded climate data set produced by the Climate Research Unit (CRU) was obtained from <http://www.cru.uea.ac.uk/cru/data/hrg>. The CRU time series data (v. 3.22) have a relatively high resolution ($0.5^\circ \times 0.5^\circ$ latitude/longitude) and include six mostly independent climate variables [Harris et al., 2014]. The annual temperature and precipitation from CRU data for the period 1976–2013 were used to examine the spatial changes in climate in the MP.

2.3. Pettitt Test for Change Point Detection

The Pettitt statistic was used to detect single change points. A change point appears when a statistically significant difference exists between the mean value (climatology) of the variable before and after a certain point (change point) based on the *t* test [Wang et al., 2007]. The Pettitt test is a nonparametric test which is less sensitive to outliers and skewed data compared to other tests [Pettitt, 1979]. The null hypothesis (no change in the mean of the time series tested) against the alternative (an upward or downward change point in a given year) is tested to see if there is a significant change in the mean values of the variables examined. Synchronized changes in several variables may indicate a close relationship among the variables.

3. Results and Discussion

Using satellite observations of lake size, we find the following major points. On the TP, more than 73% of the number and area of lakes ($>1 \text{ km}^2$) are located in the Inner-TP, an endorheic basin. The outflowing (exorheic) subcatchments of the great river basins within the TP have a rather small proportion of lakes: 18% of the total number and 27% of total area (Figure S1). From the 1970s to 2010, 99 new lakes ($>1 \text{ km}^2$) appeared in the TP, 53% of which were in the Inner-TP (Figure 2a). Among the existing lakes, most of them (81%) expanded in area, by a total of 18.4% (7240 km^2) (Figure 2b and Table S1). All-sized lakes showed an increase in total number and area (inset of Figure 2b). Particularly, the glacier-fed lakes experienced faster area increases than nonglacier-fed lakes (Figure S2).

The long-term evolution of relatively large lakes ($>10 \text{ km}^2$) has shown an apparent increase in area since 1998, which also predominantly occurred in the Inner-TP (Figures 3a and S3). Changes in lake area were not as prominent in the other basins of the TP (Figure S4). The evident shrinkage of the lake area in the Yangtze River basin from 2010 to 2013 was due to a severe drought that occurred in 2011 [Z. Zhang et al., 2015]. The lake area in the Brahmaputra basin decreased during the period 1976–1997 and then increased during 1997–2000, followed by another continuing decline. Lake level and terrestrial water storage changes

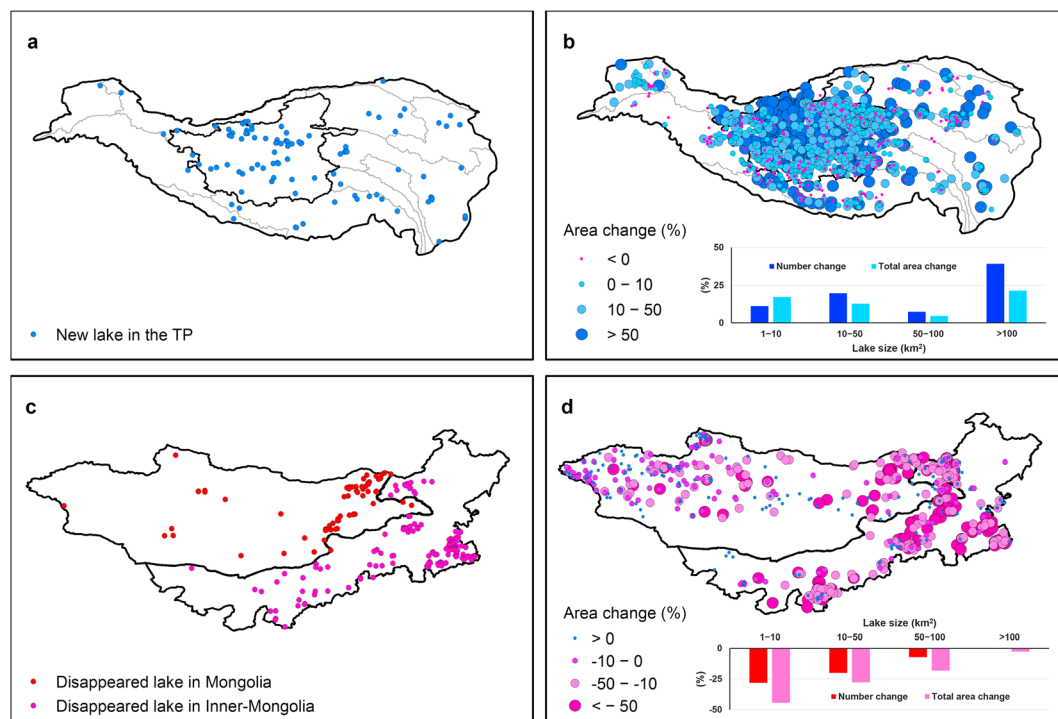


Figure 2. Emerged/expanded lakes on the Tibetan Plateau (TP) and disappeared/shrunk lakes on the Mongolian Plateau (MP). (a) New lakes on the TP between the 1970s and 2010. Ninety-nine new lakes were found in the TP, within which 52 were found in the Inner-TP. (b) area changes in lakes (>1 km²) in the TP between the 1970s and 2010. Inset shows changes in total number and area of lakes of different sizes between the 1970s and 2010. (c) Disappeared lakes on the MP between ~1987 and 2010. There were 63 and 145 lakes that disappeared in Mongolia and Inner Mongolia, respectively [Tao *et al.*, 2015]. (d) Area changes in lakes (>1 km²) in the MP between ~1987 and 2010. Inset shows changes in total number and area of lakes of different sizes between 1987 and 2010 [Tao *et al.*, 2015].

can be found in the supporting information [Gardner *et al.*, 2013; Jackson and Bilham, 1994; Liang *et al.*, 2013; Yi *et al.*, 2015].

These changes in lake area on the TP, particularly the expansion during recent decades, have been attributed to multiple factors, including precipitation and evaporation [Biskop *et al.*, 2016; Yang *et al.*, 2014], glacier/snow melting [Neckel *et al.*, 2014; Yao *et al.*, 2012], permafrost degradation [Li *et al.*, 2014], and lake water seepage [Zhou *et al.*, 2013]. Consistent with the lake area increase, cumulative precipitation from available meteorological stations in the TP shows a clear increasing trend after 1998, which is consistent with lake area change patterns (Figure 3c). Precipitation changes from 1976 to 2013 show that the majority of the stations (81%) have increased precipitation, except some stations in the southeast TP (Figure 4a). However, meteorological stations are mainly located in the eastern TP (Figure S5). Precipitation changes from both a high-resolution simulation with the WRF model and GLDAS between 1979 and 2011 show an obvious increase of precipitation in the Inner-TP (Figures S6a and S6c) [Gao *et al.*, 2015]. In addition, the time series of cumulative net precipitation (precipitation minus evapotranspiration) in the Inner-TP from the WRF simulation and GLDAS also displays an increase after 1998 (Figures S6b and S6d). These provide additional evidence to support the contention of an overall wetter climate in the TP since 1998, especially in the Inner-TP with its greater number of lakes. The spatial patterns and time series of lake change in the southern TP, especially in the Brahmaputra basin, show a slight decrease of lake area after 1998 (Figures S3 and S4), which is also observed from lake level changes [Zhang *et al.*, 2011]. The magnitude of lake area change in this basin is small compared with the lake expansion in the Inner-TP (Figures 3 and S4). The decrease in lake area (level) in the Brahmaputra basin is due to decreased precipitation revealed by using the WRF model (Figure S6) and by surface water budget from a land surface model [Yang *et al.*, 2011].

Changes in the cryosphere appear to have contributed to the increase in lake water balance. The glaciated areas of the six TP basins showed a decrease of 9.5–26% of their original extent between the 1970s and

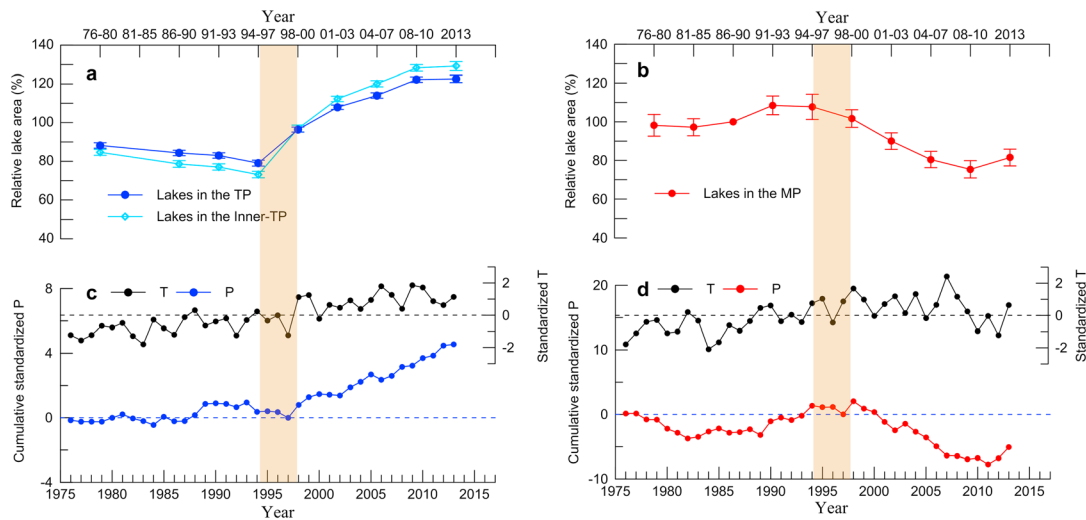


Figure 3. Lake area, surface air temperature, and precipitation changes in the Tibetan Plateau (TP) and the Mongolian Plateau (MP). (a) Relative lake area changes in the TP and Inner-TP. The mean lake area between 1976 and 2013 in the TP is used as the reference. Error bars indicate the standard error of changes in large lakes ($>10 \text{ km}^2$). (b) Relative lake area changes (%) in the MP. Lake area in 1976–2010 was from *Tao et al.* [2015]. (c) Standardized temperature (T) and cumulative standardized precipitation (P) from available China Meteorological Administration (CMA) stations (Figure S11) in the TP during the period of 1976–2013. (d) Standardized surface air T and cumulative standardized P from CRU data for the MP.

2010, based on data from the Second Chinese Glacier Inventory [Guo *et al.*, 2015]; the shrinkage in the Inner-TP was 9.5% (Figure S7). The Xiaodongkemadi glacier in the Inner-TP, which has the longest mass balance observations since the 1960s [Yao *et al.*, 2012], exhibited continuing mass losses, particularly after 1998 (Figure S8). A recent study also suggests the potential contribution of permafrost thawing to lake enlargement [Li *et al.*, 2014]; the maximum frozen depth observed at the Anduo station, Inner-TP, has shown an obvious trend of permafrost thinning since 1998 [Du *et al.*, 2012], which was confirmed by a Pettitt test (Figure S8). However, apart from the measurements along the TP highway, permafrost monitoring is very limited. The soil moisture observations using the Special Sensor Microwave/Imager showed a significant wetting trend during the warm seasons of 1987–2008 in the Inner-TP [Velde *et al.*, 2014]. Other factors, such as snow-pack changes, are considered small because no significant snow cover trends have been found on the TP [Shen *et al.*, 2015]. The greater net precipitation together with glacier melt and permafrost degradation since 1998 appears to have contributed to the rapid enlargement of lake area in the TP, especially in the Inner-TP.

We estimate that glacial meltwater could have made a substantial contribution to the water balance in the Inner-TP. The laser elevation measurements from the ICE, Cloud, and land Elevation Satellite (ICESat) have been used to estimate the mass budget of the glaciers in the TP and surroundings [Kääb *et al.*, 2012; Neckel *et al.*, 2014], but these elevation data are only available for the time period 2003–2009. Based on the ICESat data, Neckel *et al.* [2014] reported a total mass balance of $-1.7 \pm 1.9 \text{ Gt yr}^{-1}$ for glaciers ($\sim 80\%$ of the area covered by the analysis) in the TP's endorheic basin between 2003 and 2009. Combined with the lake water storage change (8.06 Gt yr^{-1}) between 2000 and 2009 from a recent study [G. Zhang *et al.*, 2013], glacier meltwater could have contributed a fraction of roughly 25% to the lake water balance in the Inner-TP.

These results of lake expansion on the TP are in contrast to patterns in the adjacent MP. From 1987 to 2010, the number of lakes on the MP decreased from 785 to 577. A larger proportion of lake loss within the MP was found in the Inner Mongolia region of China (34%) than in Mongolia (17.6%) [Tao *et al.*, 2015] (Figure 2c). For those lakes which had not disappeared by 2010, a majority of them (75%) were found to have shrunk in area between ~ 1987 and 2010 (Figure 2d) and the total area of lakes had decreased by 1591.9 km^2 (8.9%) [Tao *et al.*, 2015] (Table S2). Small lakes ($1\text{--}10 \text{ km}^2$) showed relatively greater response in the MP (shrinking) (inset of Figure 2d).

The specific timing of the shift in lake area is coincident in both plateaus and is centered in 1997/1998. On the TP, the time point of the shift (1994–1999) was identified as a marginally significant change point (Pettitt test, $p=0.07$) for lake area change. Here most lakes (72%) clearly shrank between 1976 and 1997, with a few

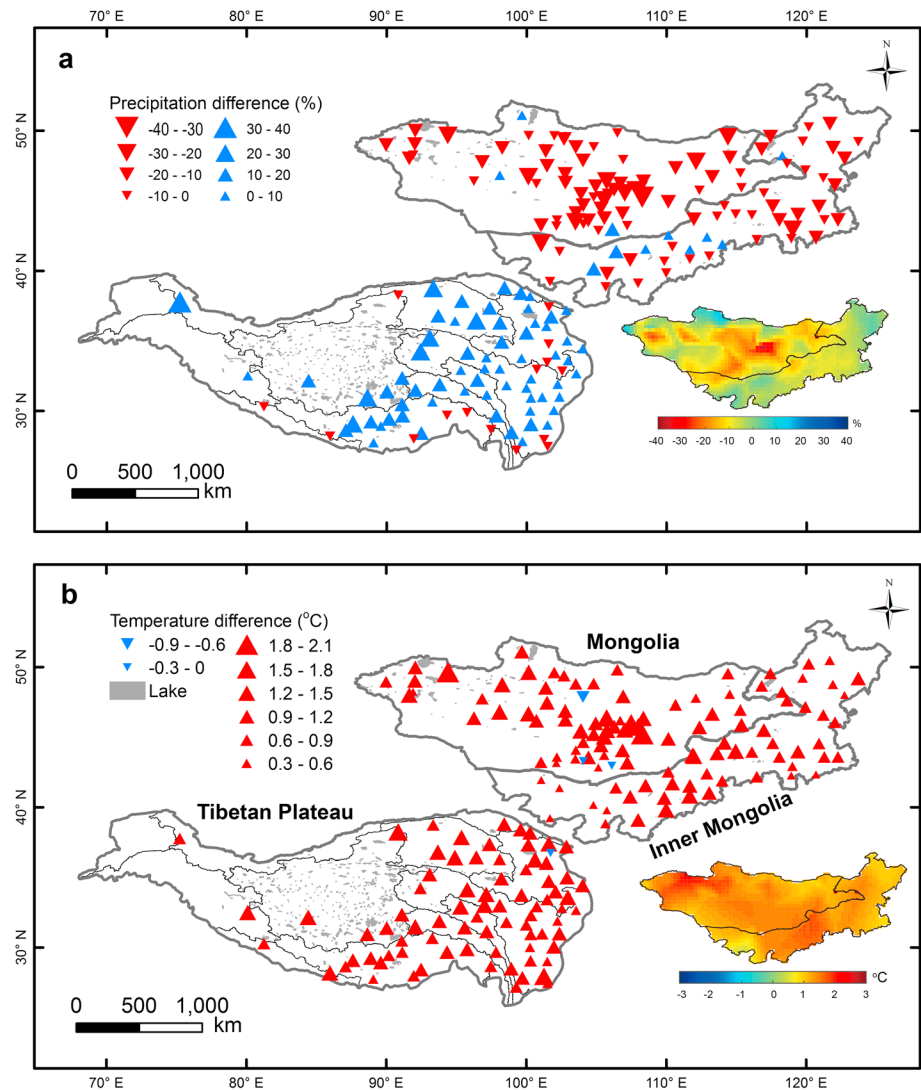


Figure 4. Differences in precipitation and temperature between 1998–2013 and 1976–1997 on the Tibetan Plateau (TP) and Mongolian Plateau (MP). (a) Precipitation difference from meteorological station data. Inset shows gridded precipitation difference from CRU data. (b) Temperature difference from meteorological station data. Inset shows gridded temperature difference from CRU data. The temperature and precipitation from China Meteorological Administration (CMA) stations and CRU data between 1976 and 2013 are used. The temperature and precipitation from meteorological stations in Mongolia are available only between 1976 and 2010.

exceptions (e.g., Nam Co and Selin Co (Figure S3), which are two of the highest large lakes in the world), whereas between 1998 and 2013, the majority of the lakes (73%) expanded—with greater expansion in the north ($>32^{\circ}\text{N}$) than in the south. In contrast, the total lake area on the MP increased slightly over the period 1976–1997, followed by a decreasing trend in 1998–2013 (Figure 3b). A marginally significant change point ($p=0.09$) in the year 1998 (to 2000) has been identified based on the Pettitt test [Pettitt, 1979]. The distinctly different patterns on the two plateaus appear to be a result of changes in the hydrological cycle induced by regional climate change.

Although air temperature trends are similar, precipitation patterns differed between the two plateaus. The warming trends are $0.40 \pm 0.05^{\circ}\text{C}$ per decade ($p < 0.001$) for the TP and $0.50 \pm 0.10^{\circ}\text{C}$ per decade ($p < 0.001$) for the MP (Figures 3c and 3d) between 1976 and 2013. It was much warmer after 1998 than before, for both plateaus (Figures 3c and 3d), and the difference in temperature from meteorological stations between 1998–2013 and 1976–1997 for both the TP and the MP shows overall warming (Figure 4b). In contrast to the TP, the cumulative precipitation on the MP shows a decrease after 1998 (Figure 3d), coinciding

with the pattern of the observed lake area changes. The spatial structure of precipitation differences from meteorological observations and gridded CRU data between 1998–2013 and 1976–1997 shows an overall decreased precipitation in the MP (inset of Figure 4a). The drier climate could have been the dominant driver of the shrinkage of lakes in the MP. The decrease in lake area in Inner Mongolia is more prominent than in Mongolia as a whole, which could be due to additional factors associated with intensive human activities [Tao *et al.*, 2015]. The warmer climate since 1998 has produced different effects on the water and energy balances on the two plateaus. In addition, clear inflections of expansion of lake area over the TP and shrinkage over the MP in 2008–2010 have also been identified, which is consistent with lake level changes [Crétaux *et al.*, 2016]. This is also consistent with precipitation change. For example, the average precipitation at available stations in the Inner-TP increased from 304 mm in 1976–1997 to 349 mm in 1998–2007 and 370 mm in 2008–2010. Lakes on both plateaus are integrators of climate change at both the regional and global scales. Their patterns with abrupt changes depend on the climate conditions and morphology [Crétaux *et al.*, 2016; Mason *et al.*, 1994]. The response time could be related with multiple factors affecting the lake water balances, e.g., by the lake morphology. In this study, more than 40 years of lake area variations were examined, which allowed to detect patterns of lake evolution.

These contrasting climatic and water cycle variations may have been driven by changes in large-scale and/or regional atmospheric circulation on both plateaus. The interplay of large-scale circulation systems determines the atmospheric flow over a specific region to be more zonal or more meridional [Farinotti *et al.*, 2015]. A remarkable phenomenon in global change is the poleward shift of the westerlies [Wu *et al.*, 2012; X. Zhang *et al.*, 2013] and enhanced Northern Hemisphere summer monsoon [Wang *et al.*, 2013]; these occur as a result of both the enhanced hemispheric thermal contrast through meridional pressure gradients and the enhanced Atlantic Multidecadal Oscillation [Wang *et al.*, 2013] (Figure S9). This zonal and meridional anomaly has intensified over the TP since 1998 because of the larger contrast of the thermal changes [Gao *et al.*, 2014]. The intensified meridional flow transports more water vapor to the TP [Lu *et al.*, 2015]. Since 1998, this warming and moistening makes the atmosphere more unstable, triggering more deep clouds and thus more precipitation over the TP [Yang *et al.*, 2012]. The continuous increase of lake area in the Inner-TP is consistent with the increase of precipitation that is attributed to the enhanced meridional water vapor transport and redistribution by the local circulation. For the MP, however, the poleward shift of the westerlies has produced a more zonal and less meridional anomaly. The reduced meridional anomaly brings less water vapor from the south (Figure S10) and results in less precipitation (Figure 3), leading to reduced lake area. Thus, we hypothesize that these regional differences in lake area trends are likely related to changing circulation patterns in response to global warming.

Clearly, the impacts of climate change on lake water balance are complex and can be sharply different across regions. This, together with the diverse lake ecosystem properties in biology, biophysics, and biogeochemistry, calls for management strategies that explicitly identify environmental changes and potential risks associated with region-specific hydrological and ecosystem dynamical processes. Our results highlight the importance of better understanding the teleconnections among various large-scale circulation systems and their contributions to regional-scale hydrologic cycles and lake water balances. Interactions among current climate warming and climate phenomena are complicated and poorly understood, and the regime shifts that they generate are not yet predictable. Understanding of all the major contributing drivers of lake dynamics and using a region-wide network of observations will provide a crucial foundation for knowledge-based lake ecosystem management.

4. Conclusion

Lake area changes are found to be distinctly different between the two large East Asian plateaus, the TP and the MP. A clear, statistically significant inflection point occurred at 1997/1998. After 1997/1998, reduced precipitation along with intense human activities is thought to be linked to lake loss/shrinkage in the MP, especially in Inner Mongolia. Increased precipitation and the rapid ablation of mountain glaciers have contributed to the continuing expansion of most lakes on the TP, particularly in the Inner-TP. Comparing the climate patterns of the two plateaus showed that the MP was getting warmer and drier, whereas the TP was getting warmer and wetter. Lake water balances integrate the effects of the precipitation–evaporation balance, glacier/snowmelt runoff, permafrost degradation, and lake bottom leakage. A quantitative evaluation of

these variables for lakes on the TP is currently not feasible because of scarce in situ observations, which are in part limited by the rugged environment. Observation data produced by the creation of the High-cold region Observation and Research Network (<http://www.horn.ac.cn/>) and ongoing programs in the Third Pole region (including the Pamir-Hindu Kush-Karakoram-Himalayas and the Tibetan Plateau) will improve our understanding of climate change and water resources variability or scarcity in this region.

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