Changing pattern of water level trends in Eurasian endorheic lakes as a response to the recent climate variability

Running title:

Eurasian lake water levels under climate change

Authors:

Xin Zhang[1,2]*, Abilgazi Kurbaniyazov[3], Georgiy Kirillin[2]

Affiliatious:

[1] College of Global Climate and Earth System Science, Beijing Normal University, Beijing, China

[2] Department of Ecohydrology, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany

[3] Akhmet Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan

Corresponding author:

Xin Zhang(xin.zhang@igb-berlin.de)

Keywords:

Lake water level, altimetry satellite data, climate change, change point

Acknowledgements:

The study is part of the research project “Lakes of Tibet in the Climate System” (LaTiCS) supported by the Sino-German Center for Research Support (CDZ Project GZ1259) and German Research Foundation (DFG Project KI 853-13/1). GK and AK were supported by the Ministry of Education and Science of the Republic of Kazakhstan within the project “Ecological state and economic potential of arid endorheic lakes investigated on example of the residual basins of the Aral Sea” (Project ID: AP05134202).

Abstract

Lake level is a sensitive integral indicator of climate change on global and regional scales, especially in enclosed endorheic basins. Eurasia contains the largest endorheic zone with several large terminal lakes whose water levels recently underwent remarkable variations. To address the common patterns of these variations and their links to global climate change, we investigated interdecadal variabilities in lake levels in 15 selected large lakes located at three neighboring Eurasian endorheic regions— Central Asia, the Tibetan Plateau, and the Mongolian Plateau. Satellite altimetry data revealed a heterogeneous pattern of lake levels among the three regions during the period of 1992-2018: the lake levels increased significantly in Central Asia and the Tibetan Plateau but decreased in the Mongolian Plateau. The water levels of Central Asian and Tibetan lakes revealed a shift in their trends during the observation period: the increasing trend was more evident since 1997 in Central Asia, since 2005 in the northern part of the Tibetan Plateau and since 1998 in the southern part of the Tibetan Plateau. To further quantify the climatic factors contributing to these patterns, precipitation and air temperature records were analyzed by merging three global gridded climate datasets and then applying cumulative analysis and change point tests. The precipitation over the lake basins was considered the main contributor to the heterogeneous pattern of lake levels in the three regions. The shift in air temperature in around 1997 and the shifts in precipitation in around 1998 and 2005, mainly contributed to the turning point of the trend of lake levels in those regions. Our findings reveal the linkage of the heterogeneous pattern of lake water levels to climatic factors in adjacent endorheic basins, providing a further understanding of the hydrological regime in the largest endorheic zone and its sensitivity to climate change.

Keywords: Lake water level, altimetry satellite data, climate change, change point

1. Introduction

An endorheic basin is a closed or internal drainage system without outflow into an ocean or a sea. The closed character of the hydrological cycle makes endorheic basins especially sensitive to basin-scale climate variations. Endorheic basins are inherent features of intracontinental arid and semiarid regions. Surface runoff in endorheic basins typically accumulates in large terminal lakes; the largest number of endorheic lakes worldwide is concentrated on the continent of Eurasia, covering Central Asia (CA), the Tibetan Plateau (TP), and the Mongolian Plateau (MP). The lake levels in those regions present "end points" accumulating multiple responses of the basin-scale water balance, therefore considered to be one of the most sensitive indicators for regional response to climate change. Endorheic lakes play an important role in maintaining biodiversity and providing valuable water support for ecosystem services (Dudgeon et al., 2006; Elena Lioubimtseva, 2014). The endorheic lakes in Mongolia are the main water resource for endangered species and migratory waterfowl (Shinneman, Almendinger, Umbanhowar, Edlund, & Nergui, 2009; Yakutin, Andrievskii, & Lhagvasuren, 2010). The lakes in Central Asia, such as Lake Balkhash, are important for local agriculture, vegetation and ecology (Imentai, Thevs, Schmidt, Nurtazin, & Salmurzauli, 2015). The pristine lakes of the Tibetan Plateau that remain generally undisturbed by anthropogenic activities have gained attention as "sentinels" of regional climate change (Lei et al., 2013; Li et al., 2017; Song, Huang, Ke, & Richards, 2014; Zhang, Yao, Xie, Kang, & Lei, 2013). Several recent studies indicated significant climate variations in those three regions, such as the warmer temperature (Hu, Zhang, Hu, & Tian, 2013), a weakened aridity in Central Asia (F. Chen, Huang, Jin, Chen, & Wang, 2011), and a wetter environment in the central part of the Tibetan Plateau (K. Yang et al., 2014). The corresponding changes in the large-scale hydrological cycle (Oki & Kanae, 2006) affect the water levels of the terminal endorheic lakes as integrated indicators of the hydrological cycle response to climate change (Y. Zhao, Liao, Shen, & Zhang, 2017).

The Eurasian endorheic zone is affected by several global circulation patterns: Central Asia and the Mongolian Plateau are influenced by westerlies, whereas the Tibetan Plateau is affected by the intersection of the westerlies and the monsoonal system. Therefore, the water levels of the endorheic lakes in the three large continental regions are expected to have heterogeneous responses to global change. Several previous studies (J. L. Chen et al., 2017; Kouraev, Kostianoy, & Lebedev, 2009; Song, Huang, & Ke, 2015; Zhang, Yao, Piao, et al., 2017; Y. Zhao et al., 2017) investigated water level dynamics in terminal lakes with a projection on climate change. However, no attempt has been made to date to compare the responses of neighboring endorheic basins covering the largest continental area. Such a comparative analysis of lake changes at the regional scale can hint at global tendencies in climate change. With this purpose in mind, we selected 5 lakes in Central Asia, 7 lakes in the Tibetan Plateau, and 3 lakes in the Mongolia Plateau as objects to investigate changes in their water levels and to reveal their links to the regional climatic patterns.

In situ data on lake water levels and relevant meteorological records are extremely scarce in this area compared to that in other parts of the world. The related records in Central Asia were limited for the past 30 years, since the relatively dense network of meteorological stations established in the Soviet Union was discontinued in the early 1990s. The gauge stations in the Tibetan Plateau were also few due to the harsh environment and high elevation. The rapid development of remote sensing technology has provided an opportunity to collect continuous data for lakes in recent decades, especially at a large regional scale. In particular, satellite altimetry data has developed as an alternative tool for lake level estimation, because of its high accuracy from centimeters to decimeters and the availability of data since 1992 (Crétaux et al., 2016; Crétaux et al., 2011). In our study, we use multi-altimetry datasets to (1) obtain records of lake water level and (2) describe the dynamic changes in lake water level and their spatial patterns in three adjacent regions and (3) assess the relationship between lake dynamics and climatic factors. Finally, we discuss the potential climate drivers for the spatial heterogeneity of lake-level variations.

2. Study area

The study region comprised 15 inland lake basins located in Central Asia (5 lakes), the Tibetan Plateau (7 lakes), and the western Mongolia Plateau (3 lakes), as shown in Figure 1. The basic characteristics of the selected lake basins are summarized in Table 1.

The term "Central Asia" referred here to the geographical region bounded by the Caspian Sea on the west, the Tian-Shan Mountains on the south, the Altai Mountains on the east, and by basins of the Ural and Ob Rivers on the north. The strongly continental arid climate of the region is characterized by cold winters and hot dry summers. Central Asia (CA) comprises many large inland water bodies of major ecological and economic importance. In our study, four typical terminal lakes—the Aral Sea, Lake Balkhash, Lake Sarykamysh and Lake Issyk-Kul an exorheic (open) lake (Lake Zaysan)—were selected in this region.

The Tibetan Plateau is the largest and the highest plateau worldwide, known as "the Third Pole" and is surrounded by several large mountain ranges: the Himalayas on the south, the Kunlun Mountains on the north, and the Hengduan Mountains on the southeast. The climate pattern over the Tibetan Plateau (TP) is mainly dominated by the Indian monsoon and westerlies, with limited influence from the East Asian monsoon, combined with the large topographic landform (J. Sun et al., 2018; Yao et al., 2013). Depending on the dominant atmospheric circulation (Yao et al., 2013; Yao, Thompson, Yang, et al., 2012), we divided the TP into two lake regions—southern and northern TP—separated by the Kunlun

Mountains. Based on Yao et al. (2013), the region north of 35°N (north part of the Kunlun Mountains) is dominated by the westerlies. Three lakes were selected in this region: Lake Qinghai, Lake Ayakkum and Lake Ngoring, the latter being exorheic lake in the Yellow River Basin. The region between 30°N and 35°N (south part of the Kunlun Mountains) is the transition domain influenced by the westerlies and Indian monsoon. Four typical lakes were selected in this southern part: Lake Namco, Lake Silingco, Lake Ngangco, and Lake Zharinamco.

The third region is the Lake Plain in the western Mongolian Plateau (MP), bounded by the Altai Mountains on the west, the Khungai Mountains on the east, the Tannu-Ola Mountains on the north and the Gobi Desert to the south. The climate is cold and dry, dominated by mid-latitude westerlies. Two closed lakes (Lake Uvs and Lake Hyargas) and an exorhehic lake (Lake Hovsgol) were selected across this basin (Table 1).

3. Data sources

3.1 Lake water level dataset from satellite altimetry data

The water levels of the target lakes were obtained from three different satellite altimetry databases: the Hydroweb from Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (http://hydroweb.theia-land.fr/) (Crétaux et al., 2011), Global Reservoir and Lake Monitor (G-REALM, https://ipad.fas.usda.gov/cropexplorer/global_reservoir/) (Birkett, 1995; Birkett & Beckley, 2010), and Database for Hydrological Time Series of Inland Waters (DAHITI, https://dahiti.dgfi.tum.de/) (Schwatke, Dettmering, Bosch, & Seitz, 2015).

In the Hydroweb database, the lake water level records were provided by combining several altimetry data, including Topex/Poseidon (T/P), Jason-1, GFO, ERS-1 and ERS-2, and Envisat satellites, and are available from 1992 to the present. The water level data were generated by applying several corrections on each altimetry data, such as ionospheric and tropospheric correction. The details on the processing procedures are described in (Crétaux et al., 2011). The mean lake level was computed by averaging the altimetry measurements over time, and the lake level anomaly was calculated by subtracting the mean lake level. The long-term time series of lake water levels since 1992 was generated on a monthly basis by merging several altimetry data using T/P data as a reference during the overlap periods (Crétaux et al., 2016; Crétaux et al., 2011). The lake level records from this dataset were compared with gauge data and showed acceptable height accuracy (Crétaux et al., 2016). In the G-REALM altimetry database, the water levels were utilized from T/P, Jason-1 and Jason-2 and Envisat satellites and are available from 1992 to present. The relative water level records were provided from G-REALM by merging T/P, Jason-1 and Jason-2 time series at 10-day intervals. This time series has been smoothed with a median-type filter to eliminate outliers and reduce high-frequency noise, using the mean value of the Jason-2 water level as the reference (Birkett et al. 2017). The DAHITI database also combined many altimetry satellite products, such as T/P, Jason 1, Jason-2 Envisat, ERS-2, and SARAL/AltiKa. The processing strategy was based on a Kalman filtering approach and extended outlier detection (Schwatke et al., 2015). These databases have been widely used in related studies on lake water levels because of their fine temporal resolution and good validated accuracy (Schwatke et al., 2015; Song et al., 2014; C. Tan, Ma, & Kuang, 2017).

In our study, the annual time series of the water levels was calculated for each lake from three altimetry datasets. The consistency and accuracy of the time series from the three products were verified by correlation analysis and cross-evaluation, taking into account the different datum/reference systems when combining the records from different satellite data. In our study, the bias of vertically shift was not removed among the different products when the consistency of water level records was significantly good, to avoid unnecessary errors.

Thereafter, the statistical information for evaluating the water level variability, such as the trends and mean values, was calculated from the Hydroweb database as the reference, considering that it had the longest record for most target lakes.

3.2 Meteorological dataset

The climate effect on lake level variation was traced with the regional precipitation and temperature patterns. Due to possible large variation and uncertainty in single-point measurements, precipitation records were selected from global gridded observation datasets to evaluate the climatic pattern. We used three in situ-based products: Global Precipitation Climatology Centre products (GPCC, https://www.dwd.de/EN/ourservices/gpcc/gpcc.html) (Becker et al., 2013; Schneider et al., 2017), precipitation products from the University of Delaware (UDEL, http://climate.geog.udel.edu/~climate/html_pages/download.html) (Cort J. Willmott. & Matsuurra, 2018), and Climate Research Unit products (CRU, http://www.cru.uea.ac.uk/data) (Harris, Jones, Osborn, & Lister, 2014). The temperature dataset was adopted from the CRU products.

The GPCC precipitation data was based on 85000 meteorological stations spread worldwide with a record duration of 10 years or longer. It collected and integrated many observations from the national meteorological agencies (NMAs), which were the primary data source, and the Food and Agriculture Organization (FAO), the Global Historical Climate Network (GHCN2), and the World Meteorological Organization (WMO), among others. The latest version of GPCC V7 (Schneider et al., 2015) provided monthly precipitation data from January 1901 to December 2016. The UDEL product was also compiled from several updated sources, and the number of stations in this dataset ranges from 4100 to 22000 globally. The newest version of UDEL (V5.01) provided the monthly precipitation spanning from January 1900 to December 2018. The CRU dataset comprised a suite of climate variables, including precipitation and temperature. This dataset was obtained based on more than 4000 meteorological stations through the NMAs, the WMO, the FAO and other sources. The latest version of CRU (TS 4.01) provided data at a monthly scale from 1901 to 2018.

These datasets were built based on a network of gauge observations and widely used as a “baseline” dataset for validation of other model outputs and satellite products (Schiemann, Lüthi, Vidale, & Schär, 2008; Q. Sun et al., 2018; Thorndahl et al., 2017). In our study, we adopted data from the newest version on a monthly basis with a spatial resolution of 0.5° × 0.5° and selected a comparable period of 1990-2016. The precipitation and temperature records for each lake were extracted at the basin scale.

4. Methods

4.1 Data integration

The precipitation datasets mentioned above have generally shown similar spatial patterns and temporal variations (Hu et al., 2018; Hu et al., 2017). The seasonal cycles of precipitation over the study areas were demonstrated from three products in the three respective lake basins (Figure 2). The three products showed a generally good agreement since they use many rain gauges in common**.** The spread showed a slight difference in summer, especially in mountainous areas (Hu, Hu, Zhang, Chen, & Li, 2016), possibly due to the differences in gridding and interpolation approaches (Pan et al., 2011).

The simple weight approach from (Aires, 2014) was employed to integrate different precipitation datasets into one single data series with a minimum root mean square error (RMSE). Specifically, the method was used as a weighted average of all the products, and the weights were determined based on the error level. First, the error variance of each product was calculated using the mean of the products as the truth. The weights were summed up to 1 and calculated as follows:

$$w_i = \frac{1}{\sigma_j^2} \Big/ \sum_{j=1}^{n} \frac{1}{\sigma_j^2}$$

where w_i is the weight for product i, σ_j^2 is the error variance of product i, and n is the total number of products to merge.

4.2 Trend analysis

We adopted the non-parametric Mann-Kendall (MK) test (Kendall, 1948; Mann, 1945) to detect the significance of trends in the time series of lake water level and climate-related variables. The MK test was minimally affected by the un-normalized distribution of variables (Hamed, 2008). However, data should be assumed to be independent. According to Von Storch (1999), autocorrelation would lead to a rejection of the null hypothesis of no trend when the null hypothesis was actually true. To eliminate this concern, the "trend-free pre-whitening" method, based on Yue, Pilon, Phinney, and Cavadias (2002) and Yue & Wang (2004), was applied prior to the MK test to preserve the magnitude of a trend. The combination can provide an accurate trend estimate of the autocorrelation process and has been widely used in hydrological and meteorological time series (Dadaser-Celik & Cengiz, 2013; Gocic & Trajkovic, 2013; X. Tan, Gan, & Shao, 2017). The slope was estimated using Sen's estimator (Sen, 1968), considering its robustness against outliers. In our study, we adopted significance levels of α =0.01 and α =0.05.

4.3 Cumulative anomaly analysis

The cumulative anomaly analysis can be used not only to identify the state of changes in the time series anomaly, i.e., above or below the average condition but also to evaluate the accumulated effects of climate variables over a certain period and their long-term tendencies.

It has commonly been used to assess variations in hydrological and meteorological factors (Lozowski, Charlton, Nguyen, & Wilson, 1989; Wu et al., 2017; Y. Yang et al., 2014). In our study, we calculated the cumulative anomaly time series of annual precipitation and temperature. The cumulative anomaly CUM_m can be expressed as:

$$CUM_m = \sum_{i=1}^{n} (\mathrm{x}_i - \bar{X})$$

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} (\mathrm{x}_i)$$

where $\bar{X}$ is the mean value of the point series xi, and n is the number of records.

4.4 Change point detection

The change point was defined as the time when the means become statistically different. This point was regarded as a possible starting point of the new regime. The Pettitt test (Pettitt, 1979) and the Bayesian change point test (Kim, Suh, & Hong, 2009; Ruggieri, 2013) were applied to detect shifts in the meteorological variables. The Pettitt test is a non-parametric trend test to estimate the occurrence of a change point and has been widely used to detect abrupt changes in hydrological and climatic series (Y. Yang et al., 2014; Yang, Zhou, Wenninger, & Uhlenbrook, 2012). The Bayesian change point test detects a change point at an unknown time point and the amount of shift in the time series under the assumption that a change had occurred. This test detects changes in the mean, trend and/or variance by using a minimum segment length between two shifts. A change point was selected only when the two methods detected the same change point; then, mean values before and after the regime shift were calculated.

5. Results

5.1 Consistency of different lake level databases

The water level changes during the period of 1992-2016 for selected lakes in our study are summarized in Figures 3-6. The time series of water levels from the three altimetry datasets showed a high consistency in all the examined lakes, as the correlation coefficients (R) were significant at the 95% confidence level, and the R values for 14 lakes were higher than 0.9 (Table 2). The results were also in good agreement in depicting intra-annual variations and abrupt changes in lake levels. For example, a sudden turning point of the water level in Lake Qinghai occurred in 2005, followed by an increasing trend from this year, which was captured by all the satellite altimetry data.

All three regions revealed diverging spatial characteristics between the CA, the TP, and the MP; the temporal patterns of water level variations in the 15 lakes were also distinguished by different trends. In the CA region, the water levels showed a generally increasing trend, except for the south Aral Sea (Figure 3). The south Aral Sea had a continuous decreasing trend since the beginning of the analyzed period (1992), which was consistent with the Aral Sea desiccation starting in 1960 and described in previous studies (Izhitskiy et al., 2016; Zavialov, 2007). However, the lake level stopped decreasing in 2009 (Figure 3f). The water levels of Lake Balkhash and Lake Issyk-Kul showed similar patterns during the whole period, increasing by 0.058 cm/yr and 0.017 cm/yr, respectively. The lake water levels grew until approximately 2008, followed by fluctuations with no obvious trends. The fluctuations in water level were found in Lake Zaysan, where the initial level decrease was replaced by an increasing trend since 2008. It is interesting to note that the latter increase in the lake level in the open lake coincided with a deceleration in the lake water level increases in the endorheic lakes of the region.

In the TP region, the water levels in the lakes showed an overall upward trend during the past three decades, with a decrease in the early stage, followed by a dramatic increase (Figures 4-5). These increasing trends were more evident since circa 1997 in the lakes located in the southern part of the TP and since approximately 2005 in the northern part of the TP. In the southern TP region, based on the time series from the Hydroweb altimetry dataset, the water levels of four lakes since circa 1997 increased by 0.178 cm/yr for Lake Namco, 0.129 cm/yr for Lake Zharinamco, 0.570 cm/yr for Lake Silingco, and 0.303 cm/yr for Lake Ngangzco (Figure 4). It was noticeable that the increasing trend of the water level in Lake Namco paused in approximately 2005 and was then followed by a fluctuation. From 1992 to 1997, the lake levels showed a decreasing trend in Lake Zharinamco and Lake Ngangzco. This decreasing trend was unclear in Lake Namco and Lake Siling as the records of the water levels in the two lakes started in 1995. In the northern TP region, the lake water levels presented noticeable increasing trends of 0.092 cm/yr (Lake Qinghai), 0.086 cm/yr (Lake Ngoring), 0.570 cm/yr (Lake Ayakkum), and 0.303 cm/yr (Lake Ngangzco). Notably, these increases were more evident since 2005 in Lake Qinghai and Lake Ngoring; before 2005, the water levels in the two lakes were stable, with a slight decrease.

In the MP region, the lake water levels in all three lakes showed generally decreasing trends. Lake Uvs and Lake Hyargas showed continuous decreasing water levels since 2002, by -0.062 cm/yr and -0.361 cm/yr, respectively (Figure 6). The water level in open Lake Hovsgol decreased slightly by -0.012 cm/yr from 1992 to 2018, with an initial positive trend before 2004 followed by an obvious level decrease. Notably, the lake levels showed clear decreases since 2002-2004 in all the lakes of the region, whereas the rate of change was different for open and closed lakes.

5.2 Climate effects on the lake levels

As shown by the above result s, the lake water levels showed increasing trends both in the CA and in the TP. However, the increasing patterns exhibited different characteristics in the two regions. There was a turning point in approximately 2005 at the northern part of the TP, and since 2005, the lake levels experienced significant rapid increases. In turn, in the southern part of the TP, except Lake Silingco, the turning point occurred in 1997, and the lake levels showed slow increases after 2005. In the CA region, the lake levels continuously increased until approximately 2005 and then showed fluctuating behavior.

To qualify the reasons for these heterogeneous patterns observed in the lake water levels, we examined the relationship between the climatic factors–precipitation and air temperature– and the lake level variations. The cumulative analysis revealed a similar spatial pattern in the air temperature over the TP and CA (Figures 7-11). The air temperature experienced a decreasing trend from 1990 to 1997, changing to an apparent increase afterwards. In contrast to the CA, the air temperature increase slowed down from 1997 to 2005 in the TP; therefore, both the TP and CA regions shifted to a warmer environment. In the western Mongolian Plateau, increasing trends of air temperature were found over three lake basins before 2007, followed by large fluctuations with an evident temperature drop in 2012. As shown in Figures 7-9, precipitation in the lake basins exhibited different patterns in the CA and TP regions. The cumulative anomaly precipitation over the lake basins was consistent with the lake level dynamics. For example, in Lake Issyk-Kul, the cumulative precipitation amount had an obvious drop in 1997, which corresponded to a lake level decrease. The precipitation values fluctuated since 2005, accompanied by simultaneous fluctuations in the lake level. In the TP region, the cumulative curves of precipitation had different patterns in the northern and southern parts. The cumulative precipitation value reached a low point in approximately 2005 in the northern TP, and since 2005, the value started to increase (Figure 8). In the southern TP, the precipitation had a large variability since 2005 with no obvious trend during this period. Except for Lake Silingco, the increase rates of the lake levels slowed down in this region (Figure 9g). Apparently, the precipitation and its cumulative effect on the regional scale played an important role in the different lake level patterns in the CA and TP. In the MP, the cumulative precipitation showed a general decrease during the entire period for three lakes (Figure 10), consistent with the pattern of lake level variations. A warmer and drier environment, especially after 2009, when the temperature increased significantly, probably mainly contributed to a lower water level in this region. Hence, precipitation change played a major role in lake dynamics on a larger spatial scale.

5.3 Regime shifts in precipitation and temperature

As shown above, the lake level changes and their different spatial patterns demonstrated their strong links to precipitation and air temperature for the lake basins. To estimate whether change in climatic conditions will further influence lake level variations or will lead to a turning trend in lake levels, it is necessary to verify whether climate shift occurred at the basin scales. Here, two methods were jointly applied to estimate the change points in the annual time series of precipitation and air temperature.

The regime shifts in precipitation and temperature in the CA, the TP and the MP were shown in Figures 11-14. Two shifts were detected in the precipitation records in the CA region. The whole period of 1990-2016 was then divided into three periods: 1990-1997, 1998-2008, and 2008-2016. Stepwise increases were found in the three periods in Lake Balkhash, Lake Issyk-Kul and Lake Zaysan that supported lake level growth since 1997 associated with the regime shift in air temperature in 1997. In the TP region, the regime shift in precipitation showed a discrepancy between the northern and southern parts. The shift in approximately 2005 was detected in the northern part (except Lake Ayakkum, where the shift was detected in 2001), whereas 1997 and 2008 were identified as shift years in the southern part. During the third regime period of 2008-2016, the precipitation showed a decreasing trend. The temperature shift occurred in 1997, similar to that in the CA region and was associated with a corresponding turning point in the lake level variation.

In the MP region, the patterns of precipitation and temperature were different from those in the other two regions, corresponding to the gradual decrease in the lake level variation. The shift years of precipitation were found in 1994 and 2003. The precipitation decreased in the first two phases and then increased in the last phase, while shifts in temperature were found in 1997 and 2009. The air temperature also showed a slight decrease since 2009.

6. Discussion

The essence of the above analysis consisted of evaluating the potential of terminal lakes as single-point indicators for multiple climate change stresses in large endorheic basins. In this way, the water level variations in endorheic lakes may provide valuable insight into both the regional hydrological regimes and global circulation changes. The patterns revealed in the three regions under study suggest diverging trends in the Tibetan Plateau, the Central Asia, and the Mongolian Plateau.

The rapidly increasing lake water levels in the TP agreed with previous studies (Lei et al., 2014; Song et al., 2014; Zhang, Yao, Piao, et al., 2017; Y. Zhao et al., 2017), whereas apparent differences between the northern and southern parts indicated different characteristics of the hydrological response in the monsoon-dominated southern part of the plateau and the westerlies-dominated northern part. The lake levels in the southern TP started to increase in 2003 but stabilized in approximately 2008, followed by fluctuations without a significant trend. This pattern is also supported by results from Zhang, Xie, Kang, Yi, and Ackley (2011), who used the ICESat altimetry data available from 2003. On the other hand, the turning point in the northern TP was in approximately 2005, with the continuous significant increase in lake levels afterwards.

All the lakes in the CA region experienced a dramatic increase in lake water levels since 1997. This consistent rise in lake water levels across all basins in the largest endorheic region is a notable result of the present study. Numerous previous studies reported an alarming decrease in lake levels from the mid- to late 20th century. The growing water use demand during this century was charged as responsible for the continuous drying of Lake Issyk-Kul (Klerkx & Imanackunov, 2002; Shnitnikov, 1973), Lake Balkhash (Kezer & Matsuyama, 2006), Lake Zaysan (Dorfman, 2011), and Lake Sarykamysh (Orlovsky, Matsrafi, Orlovsky, & Kouznetsov, 2012). These lakes were threatening to share the fate of the infamous Aral Sea, which had desiccated to 10% of its volume within 40 years between 1960 and 2000 (Borovskiy, 1980; Micklin, 2016; Zavialov, 2007). The nearly simultaneous and consistent turn to the water level increase can, in this case, be treated as a signature of a large-scale change in the hydrologic regime in the arid zone of CA. The results agreed with recent findings: Bai, Chen, Yang, and Fang (2012) investigated the lake area variation in CA based on Landsat images from 1975 to 2007 and found that most of the lake surface area had an increasing trend since 1997. Propastin (2012) and Imentai et al. (2015) also found that the water level in Lake Balkhash increased since 1993. A less pronounced rise in water level in Sarykamysh can be related to its strong regulation of the drained water, and as a result, this leads to a weaker response of the basin-scale hydrological variations.

A special case is represented by the two largest remaining water bodies of the Aral Sea: the south Aral Sea (also named Large Aral) and the north Aral Sea (also named Small Aral). The latter is mainly fed by the inflow of the Syr-Daria River, and its water level has been regulated since 2005 by the Dike Kokaral—a dam separating the Small Aral from the rest of the former Aral Sea basin. As a result, the water level in the Small Aral had quickly grown to the maximum value allowed by the construction of the dam and remained nearly constant after 2006, whereas the dam floodgates were kept open for most parts of the year. Simultaneously, the water level in the Large Aral stabilized around a constant value after decades of continuous decline. The main tributary of Large Aral, the Amu-Daria River, is strongly regulated and intensively used for irrigation and generally does not reach the lake, partially draining to Sarykamysh Lake (Figure 1). Hence, stabilization of the water level in Large Aral may be interpreted as a result of the same large-scale processes causing the water level increases in other lakes of CA.

Only one of the three regions in our study, the MP revealed a gradual decrease in lake water levels since 1997. The drying trends are apparent in both large terminal lakes in the region and, to a lesser degree, in the exorheic Lake Hovsgol (Shnitnikov, 1973). This decreasing trend is supported by previous studies reporting a significant loss in lake area and number, especially from the late 1990s to 2010 based on remote sensing image analysis (Tao et al., 2015; Zhang, Yao, Piao, et al., 2017; Y. Zhou et al., 2019). Our results exhibited decreasing rainfall and growing temperatures in this region, which could further explain this shrinking pattern of lakes that were affected by a drier and warmer climate.

The coherent pattern of the water level changes in the lakes in CA and the TP, covering the largest intracontinental endorheic area, provided an important insight into the climate change effects on the arid Eurasian regions. The consistent reversal of the water levels in the terminal lakes from long-term decreases (Dorfman, 2011; Micklin, 2016; Romanovsky, 2002; Shnitnikov, 1973; Wurtsbaugh et al., 2017) to increases suggested fundamental changes in the atmospheric circulation and water balance. Our results showed that the spatial pattern of lake water levels was considerably related to climatic variables, such as precipitation and air temperature. The “turning point” can be seen in the trend of lake water levels, for example, in 1997 in CA, 1998 in the southern TP, and 2005 in the northern TP. This phenomenon was considerably related to the climate regime shift: more rainfall and higher air temperature in the lake basins were found in CA and the TP, especially since 1997. These two regions experienced a climate shift from a warm and dry to a warm and humid environment, which was also supported by several studies (Elena Lioubimtseva, 2015; E. Lioubimtseva & Henebry, 2009; L. Zhao, Simon Wang, & Meyer, 2017). The variability in water level in Lake Zaysan (an open lake) was also highly correlated with precipitation variation. Climate regime shift would also have a profound influence on the regional hydrological cycle, and terminal lakes demonstrated their efficiency as indicators of climate shifts at basin spatial scales.

Our results suggest that precipitation was the dominant factor explaining the interannual variability in lake water levels, in particular, in the TP and CA. Our findings were also supported by previous studies(Lei et al., 2013; Song et al., 2014) and validated using hydrological models (Biskop, Maussion, Krause, & Fink, 2016; J. Zhou et al., 2015). It is very likely that glacial meltwater may also contribute to the water level increases in endorheic lakes when the basins contain glaciers. It is especially important in the TP and CA, where the meltwater from glaciers can be the major tributary to surface runoff, and most glaciers have been experiencing melting during the past decades due to the increasing air temperatures since 1997 (Yao, Thompson, Mosbrugger, et al., 2012); this provided further positive feedback on the evaporation-precipitation balance. However, satellite data and glacier mass balance suggest that increased glacial meltwater contributed only ~10% to lake expansion in the interior TP(Zhang, Yao, Shum, et al., 2017), and that the glacial runoff into lakes itself should not increase the overall water volume mass on the TP (Zhang et al., 2013). Additionally, according to hydrological modeling (Biskop et al., 2016), the glacial meltwater contribution to basin runoff played a less important role compared to precipitation in nonglacial-fed land surfaces. The study on Lake Silingco (Tong, Su, & Xu, 2016) found that glacial meltwater contributed to less than 10% of the water input to the lake basin. On the other hand, several studies have pointed to the importance of glacial meltwater in recent lake variations (Qiao & Zhu, 2019; Zhang et al., 2011). Hence, the role of glacial meltwater needs further investigation with regard to lake level variations. Furthermore, the different interactions between glacial runoff and atmospheric circulation, when analyzed in more detail, may explain the differences found in the lake responses, such as noncoincidental turning points in the water level trends between the northern and southern parts of the TP.

7. Conclusions

Based on satellite altimetry databases and global gridded climate products, we analyzed the characteristics of water levels in terminal lakes in Central Asia, the Tibetan Plateau, and the Mongolian Plateau regions where more than 50% of endorheic basins are concentrated. The synergetic comparative analysis of magnitude and variability in lake levels included cumulative analysis and change point tests and revealed their links with climatic variables. The major outcomes of this study demonstrated that the water levels in Mongolian lakes dramatically decreased during the past two decades, whereas the lake levels showed generally increasing trends in the TP and CA. The lake level patterns in the TP and CA had different interannual variabilities: the increasing trends were significant until 2008 in CA, while the increasing trends were more noticeable since approximately 1997 in the southern TP and since approximately 2005 in the northern TP. The precipitation was considered the main climatic driver of the distinct spatial patterns of lake water levels in the three neighboring regions, as it was found that the various spatial characteristics of precipitation but similar patterns of air temperature were present. The analysis of regime shifts showed that all three regions became warmer after 1997. The TP and CA became wetter while the MP became drier. The shift year of precipitation occurred in 1997 and 2008 in CA, in 2005 in the northern part of the TP, and in 1997 and 2008 in the southern part of the TP. The decadal variability and distinctly different spatial patterns of lake water level variability in the three adjacent lake zones demonstrated diverging responses to climate change within the Eurasian endorheic zone. This heterogenetic pattern helps us understand the complex roles of regional climate change, which may be closely related to the regional atmospheric circulations and needed to investigate in the further studies.

8. References

Aires, F. (2014). Combining Datasets of Satellite-Retrieved Products. Part I: Methodology and Water Budget Closure. *Journal of Hydrometeorology, 15*(4), 1677-1691. doi:10.1175/JHM-D-13-0148.1

Bai, J., Chen, X., Yang, L., & Fang, H. (2012). Monitoring variations of inland lakes in the arid region of Central Asia. *Frontiers of Earth Science, 6*(2), 147-156. doi:10.1007/s11707-012-0316-0

Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Schamm, K., Schneider, U., & Ziese, M. (2013). A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present. *Earth Syst. Sci. Data, 5*(1), 71-99. doi:10.5194/essd-5-71-2013

Birkett, C. M. (1995). The contribution of TOPEX/POSEIDON to the global monitoring of climatically sensitive lakes. *Journal of Geophysical Research: Oceans, 100*(C12), 25179-25204. doi:10.1029/95JC02125

Birkett, C. M., & Beckley, B. (2010). Investigating the Performance of the Jason-2/OSTM Radar Altimeter over Lakes and Reservoirs. *Marine Geodesy, 33*(sup1), 204-238. doi:10.1080/01490419.2010.488983

Biskop, S., Maussion, F., Krause, P., & Fink, M. (2016). Differences in the water-balance components of four lakes in the southern-central Tibetan Plateau. *Hydrol. Earth Syst. Sci., 20*(1), 209-225. doi:10.5194/hess-20-209-2016

Borovskiy, V. M. (1980). The drying out of the Aral Sea and its consequences. *Soviet Geography, 21*(2), 63-77. doi:10.1080/00385417.1980.10640323

Chen, F., Huang, W., Jin, L., Chen, J., & Wang, J. (2011). Spatiotemporal precipitation variations in the arid Central Asia in the context of global warming. *Science China Earth Sciences, 54*(12), 1812-1821. doi:10.1007/s11430-011-4333-8

Chen, J. L., Pekker, T., Wilson, C. R., Tapley, B. D., Kostianoy, A. G., Cretaux, J. F., & Safarov, E. S. (2017). Long-term Caspian Sea level change. *Geophysical Research Letters, 44*(13), 6993-7001. doi:10.1002/2017GL073958

Cort J. Willmott., & Matsuurra, K. (2018). Terrestrial Precipitation: 1900-2017 Gridded Monthly Time Series (version 5.01). Retrieved http://climate.geog.udel.edu/~climate/html_pages/Global2017/README.GlobalTsP2017.html

Crétaux, J. F., Abarca-del-Río, R., Bergé-Nguyen, M., Arsen, A., Drolon, V., Clos, G., & Maisongrande, P. (2016). Lake Volume Monitoring from Space. *Surveys in Geophysics, 37*(2), 269-305. doi:10.1007/s10712-016-9362-6

Crétaux, J. F., Jelinski, W., Calmant, S., Kouraev, A., Vuglinski, V., Bergé-Nguyen, M., . . . Maisongrande, P. (2011). SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Advances in Space Research, 47*(9), 1497-1507. doi:https://doi.org/10.1016/j.asr.2011.01.004

Dadaser-Celik, F., & Cengiz, E. (2013). Wind speed trends over Turkey from 1975 to 2006. *International Journal of Climatology, 34*(6), 1913-1927. doi:10.1002/joc.3810

Dorfman, B. F. (2011). Zaysan-the Only Surviving Cretaceous Lake-May be Lost. *Procedia Environmental Sciences, 10*, 1376-1382. doi:https://doi.org/10.1016/j.proenv.2011.09.220

Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z.-I., Knowler, D. J., Lévêque, C., . . . Sullivan, C. A. (2006). Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews, 81*(2), 163-182. doi:10.1017/S1464793105006950

Gocic, M., & Trajkovic, S. (2013). Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia. *Global and Planetary Change, 100*, 172-182. doi:http://dx.doi.org/10.1016/j.gloplacha.2012.10.014

Hamed, K. H. (2008). Trend detection in hydrologic data: The Mann–Kendall trend test under the scaling hypothesis. *Journal of Hydrology, 349*(3), 350-363. doi:https://doi.org/10.1016/j.jhydrol.2007.11.009

Harris, I., Jones, P. D., Osborn, T. J., & Lister, D. H. (2014). Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. *International Journal of Climatology, 34*(3), 623-642. doi:10.1002/joc.3711

Hu, Z., Hu, Q., Zhang, C., Chen, X., & Li, Q. (2016). Evaluation of reanalysis, spatially interpolated and satellite remotely sensed precipitation data sets in central Asia. *Journal of Geophysical Research: Atmospheres, 121*(10), 5648-5663. doi:10.1002/2016JD024781

Hu, Z., Zhang, C., Hu, Q., & Tian, H. (2013). Temperature Changes in Central Asia from 1979 to 2011 Based on Multiple Datasets. *Journal of Climate, 27*(3), 1143-1167. doi:10.1175/JCLI-D-13-00064.1

Hu, Z., Zhou, Q., Chen, X., Li, J., Li, Q., Chen, D., . . . Yin, G. (2018). Evaluation of three global gridded precipitation data sets in central Asia based on rain gauge observations. *International Journal of Climatology, 38*(9), 3475-3493. doi:10.1002/joc.5510

Hu, Z., Zhou, Q., Chen, X., Qian, C., Wang, S., & Li, J. (2017). Variations and changes of annual precipitation in Central Asia over the last century. *International Journal of Climatology, 37*(S1), 157-170. doi:10.1002/joc.4988

Imentai, A., Thevs, N., Schmidt, S., Nurtazin, S., & Salmurzauli, R. (2015). Vegetation, fauna, and biodiversity of the Ile Delta and southern Lake Balkhash — A review. *Journal of Great Lakes Research, 41*(3), 688-696. doi:https://doi.org/10.1016/j.jglr.2015.04.002

Izhitskiy, A. S., Zavialov, P. O., Sapozhnikov, P. V., Kirillin, G. B., Grossart, H. P., Kalinina, O. Y., . . . Kurbaniyazov, A. K. (2016). Present state of the Aral Sea: diverging physical and biological characteristics of the residual basins. *Scientific Reports, 6*(1), 23906. doi:10.1038/srep23906

Kendall, M. G. (1948). *Rank correlation methods*. London: Griffin.

Kezer, K., & Matsuyama, H. (2006). Decrease of river runoff in the Lake Balkhash basin in Central Asia. *Hydrological Processes, 20*(6), 1407-1423. doi:10.1002/hyp.6097

Kim, C., Suh, M.-S., & Hong, K.-O. (2009). Bayesian Changepoint Analysis of the Annual Maximum of Daily and Subdaily Precipitation over South Korea. *Journal of Climate, 22*(24), 6741-6757. doi:10.1175/2009JCLI2800.1

Klerkx, J., & Imanackunov, B. (2002). *Lake Issyk-Kul: Its Natural Environment*: Springer Science & Business Media.

Kouraev, A. V., Kostianoy, A. G., & Lebedev, S. A. (2009). Ice cover and sea level of the Aral Sea from satellite altimetry and radiometry (1992–2006). *Journal of Marine Systems, 76*(3), 272-286. doi:https://doi.org/10.1016/j.jmarsys.2008.03.016

Lei, Y., Yang, K., Wang, B., Sheng, Y., Bird, B. W., Zhang, G., & Tian, L. (2014). Response of inland lake dynamics over the Tibetan Plateau to climate change. *Climatic Change, 125*(2), 281-290. doi:10.1007/s10584-014-1175-3

Lei, Y., Yao, T., Bird, B. W., Yang, K., Zhai, J., & Sheng, Y. (2013). Coherent lake growth on the central Tibetan Plateau since the 1970s: Characterization and attribution. *Journal of Hydrology, 483*, 61-67. doi:https://doi.org/10.1016/j.jhydrol.2013.01.003

Li, B., Zhang, J., Yu, Z., Liang, Z., Chen, L., & Acharya, K. (2017). Climate change driven water budget dynamics of a Tibetan inland lake. *Global and Planetary Change, 150*, 70-80. doi:https://doi.org/10.1016/j.gloplacha.2017.02.003

Lioubimtseva, E. (2014). Impact of Climate Change on the Aral Sea and Its Basin *The Aral Sea* (Vol. 10178, pp. 405-427). Berlin,Heidelberg: Springer.

Lioubimtseva, E. (2015). A multi-scale assessment of human vulnerability to climate change in the Aral Sea basin. *Environmental Earth Sciences, 73*(2), 719-729. doi:10.1007/s12665-014-3104-1

Lioubimtseva, E., & Henebry, G. M. (2009). Climate and environmental change in arid Central Asia: Impacts, vulnerability, and adaptations. *Journal of Arid Environments, 73*(11), 963-977. doi:https://doi.org/10.1016/j.jaridenv.2009.04.022

Lozowski, E. P., Charlton, R. B., Nguyen, C. D., & Wilson, J. D. (1989). The Use of Cumulative Monthly Mean Temperature Anomalies in the Analysis of Local Interannual Climate Variability. *Journal of Climate, 2*(9), 1059-1068. doi:10.1175/1520-0442(1989)002<1059:TUOCMM>2.0.CO;2

Mann, H. B. (1945). Nonparametric Tests Against Trend. *Econometrica, 13*(3), 245-259. doi:10.2307/1907187

Micklin, P. (2016). The future Aral Sea: hope and despair. *Environmental Earth Sciences, 75*(9), 844. doi:10.1007/s12665-016-5614-5

Oki, T., & Kanae, S. (2006). Global Hydrological Cycles and World Water Resources. *Science, 313*(5790), 1068. doi:10.1126/science.1128845

Orlovsky, L., Matsrafi, O., Orlovsky, N., & Kouznetsov, M. (2012). Sarykamysh Lake: Collector of Drainage Water–The Past, the Present, and the Future *The Turkmen Lake Altyn Asyr and Water Resources in Turkmenistan* (pp. 107-140). Berlin, Heidelberg: Springer.

Pan, M., Sahoo, A. K., Troy, T. J., Vinukollu, R. K., Sheffield, J., & Wood, E. F. (2011). Multisource Estimation of Long-Term Terrestrial Water Budget for Major Global River Basins. *Journal of Climate, 25*(9), 3191-3206. doi:10.1175/JCLI-D-11-00300.1

Pettitt, A. N. (1979). A Non-Parametric Approach to the Change-Point Problem. *Journal of the Royal Statistical Society: Series C (Applied Statistics), 28*(2), 126-135. doi:10.2307/2346729

Propastin, P. (2012). Patterns of Lake Balkhash water level changes and their climatic correlates during 1992–2010 period. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use, 17*(3), 161-169. doi:10.1111/j.1440-1770.2012.00508.x

Qiao, B., & Zhu, L. (2019). Difference and cause analysis of water storage changes for glacier-fed and non-glacier-fed lakes on the Tibetan Plateau. *Science of The Total Environment, 693*, 133399. doi:https://doi.org/10.1016/j.scitotenv.2019.07.205

Romanovsky, V. (2002). Water level variations and water balance of Lake Issyk-Kul. In B. I. Jean Klerkx (Ed.), *Lake Issyk-Kul: its natural environment* (Vol. 13, pp. 45-57). Dordrecht: Springer.

Ruggieri, E. (2013). A Bayesian approach to detecting change points in climatic records. *International Journal of Climatology, 33*(2), 520-528. doi:10.1002/joc.3447

Schiemann, R., Lüthi, D., Vidale, P. L., & Schär, C. (2008). The precipitation climate of Central Asia—intercomparison of observational and numerical data sources in a remote semiarid region. *International Journal of Climatology, 28*(3), 295-314. doi:10.1002/joc.1532

Schneider, U., Finger, P., Meyer-Christoffer, A., Rustemeier, E., Ziese, M., & Becker, A. (2017). Evaluating the Hydrological Cycle over Land Using the Newly-Corrected Precipitation Climatology from the Global Precipitation Climatology Centre (GPCC). *Atmosphere, 8*(3). doi:10.3390/atmos8030052

Schwatke, C., Dettmering, D., Bosch, W., & Seitz, F. (2015). DAHITI – an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. *Hydrol. Earth Syst. Sci., 19*(10), 4345-4364. doi:10.5194/hess-19-4345-2015

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association, 63*(324), 1379-1389.

Shinneman, A. L. C., Almendinger, J. E., Umbanhowar, C. E., Edlund, M. B., & Nergui, S. (2009). Paleolimnologic Evidence for Recent Eutrophication in the Valley of the Great Lakes (Mongolia). *Ecosystems, 12*(6), 944-960. doi:10.1007/s10021-009-9269-x

Shnitnikov, A. (1973). Water balance variability of lakes Aral, Balkhash, Issyk-Kul and Chany *Hydrology of Lakes* (Adlard & Son Ltd ed., pp. 130-140). Dorking , Surrey: Bartholomew Press.

Song, C., Huang, B., & Ke, L. (2015). Heterogeneous change patterns of water level for inland lakes in High Mountain Asia derived from multi-mission satellite altimetry. *Hydrological Processes, 29*(12), 2769-2781. doi:10.1002/hyp.10399

Song, C., Huang, B., Ke, L., & Richards, K. S. (2014). Seasonal and abrupt changes in the water level of closed lakes on the Tibetan Plateau and implications for climate impacts. *Journal of Hydrology, 514*, 131-144. doi:https://doi.org/10.1016/j.jhydrol.2014.04.018

Sun, J., Zhou, T., Liu, M., Chen, Y., Shang, H., Zhu, L., . . . Sha, Y. (2018). Linkages of the dynamics of glaciers and lakes with the climate elements over the Tibetan Plateau. *Earth-Science Reviews, 185*, 308-324. doi:https://doi.org/10.1016/j.earscirev.2018.06.012

Sun, Q., Miao, C., Duan, Q., Ashouri, H., Sorooshian, S., & Hsu, K.-L. (2018). A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons. *Reviews of Geophysics, 56*(1), 79-107. doi:10.1002/2017RG000574

Tan, C., Ma, M., & Kuang, H. (2017). Spatial-Temporal Characteristics and Climatic Responses of Water Level Fluctuations of Global Major Lakes from 2002 to 2010. *Remote Sensing, 9*(2). doi:10.3390/rs9020150

Tan, X., Gan, T. Y., & Shao, D. (2017). Effects of persistence and large-scale climate anomalies on trends and change points in extreme precipitation of Canada. *Journal of Hydrology, 550*, 453-465. doi:https://doi.org/10.1016/j.jhydrol.2017.05.028

Tao, S., Fang, J., Zhao, X., Zhao, S., Shen, H., Hu, H., . . . Guo, Q. (2015). Rapid loss of lakes on the Mongolian Plateau. *Proceedings of the National Academy of Sciences, 112*(7), 2281. doi:10.1073/pnas.1411748112

Thorndahl, S., Einfalt, T., Willems, P., Nielsen, J. E., ten Veldhuis, M. C., Arnbjerg-Nielsen, K., . . . Molnar, P. (2017). Weather radar rainfall data in urban hydrology. *Hydrol. Earth Syst. Sci., 21*(3), 1359-1380. doi:10.5194/hess-21-1359-2017

Tong, K., Su, F., & Xu, B. (2016). Quantifying the contribution of glacier meltwater in the expansion of the largest lake in Tibet. *Journal of Geophysical Research: Atmospheres, 121*(19), 11,158-111,173. doi:10.1002/2016JD025424

Von Storch, H. (1999). Misuses of statistical analysis in climate research *Analysis of Climate Variability* (pp. 11-26). Berlin, Heidelberg: Springer.

Wu, L., Wang, S., Bai, X., Luo, W., Tian, Y., Zeng, C., . . . He, S. (2017). Quantitative assessment of the impacts of climate change and human activities on runoff change in a typical karst watershed, SW China. *Science of The Total Environment, 601-602*, 1449-1465. doi:https://doi.org/10.1016/j.scitotenv.2017.05.288

Wurtsbaugh, W. A., Miller, C., Null, S. E., DeRose, R. J., Wilcock, P., Hahnenberger, M., . . . Moore, J. (2017). Decline of the world's saline lakes. *Nature Geoscience, 10*, 816. doi:10.1038/ngeo3052

Yakutin, M. V., Andrievskii, V. S., & Lhagvasuren, C. (2010). Change in the main components of the destruction link of biological cycle in the series of plain soils of the Great Lakes Depression in West Mongolia. *Contemporary Problems of Ecology, 3*(3), 305-311. doi:10.1134/S1995425510030082

Yang, K., Wu, H., Qin, J., Lin, C., Tang, W., & Chen, Y. (2014). Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: A review. *Global and Planetary Change, 112*, 79-91. doi:https://doi.org/10.1016/j.gloplacha.2013.12.001

Yang, Y., Long, D., Guan, H., Scanlon, B. R., Simmons, C. T., Jiang, L., & Xu, X. (2014). GRACE satellite observed hydrological controls on interannual and seasonal variability in surface greenness over mainland Australia. *Journal of Geophysical Research: Biogeosciences, 119*(12), 2245-2260. doi:10.1002/2014JG002670

Yang, Z., Zhou, Y., Wenninger, J., & Uhlenbrook, S. (2012). The causes of flow regime shifts in the semi-arid Hailiutu River, Northwest China. *Hydrol. Earth Syst. Sci., 16*(1), 87-103. doi:10.5194/hess-16-87-2012

Yao, T., Masson-Delmotte, V., Gao, J., Yu, W., Yang, X., Risi, C., . . . Hou, S. (2013). A review of climatic controls on δ18O in precipitation over the Tibetan Plateau: Observations and simulations. *Reviews of Geophysics, 51*(4), 525-548. doi:10.1002/rog.20023

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., . . . Joswiak, D. (2012). Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change, 2*(9), 663-667. doi:10.1038/nclimate1580

Yao, T., Thompson, L. G., Mosbrugger, V., Zhang, F., Ma, Y., Luo, T., . . . Fayziev, R. (2012). Third Pole Environment (TPE). *Environmental Development, 3*, 52-64. doi:https://doi.org/10.1016/j.envdev.2012.04.002

Yue, S., Pilon, P., Phinney, B., & Cavadias, G. (2002). The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes, 16*(9), 1807-1829. doi:10.1002/hyp.1095

Zavialov, P. (2007). *Physical Oceanography of the Dying Aral Sea*: Springer Science & Business Media.

Zhang, G., Xie, H., Kang, S., Yi, D., & Ackley, S. F. (2011). Monitoring lake level changes on the Tibetan Plateau using ICESat altimetry data (2003–2009). *Remote Sensing of Environment, 115*(7), 1733-1742. doi:https://doi.org/10.1016/j.rse.2011.03.005

Zhang, G., Yao, T., Piao, S., Bolch, T., Xie, H., Chen, D., . . . Zhang, H. (2017). Extensive and drastically different alpine lake changes on Asia's high plateaus during the past four decades. *Geophysical Research Letters, 44*(1), 252-260. doi:10.1002/2016GL072033

Zhang, G., Yao, T., Shum, C. K., Yi, S., Yang, K., Xie, H., . . . Yu, J. (2017). Lake volume and groundwater storage variations in Tibetan Plateau's endorheic basin. *Geophysical Research Letters, 44*(11), 5550-5560. doi:10.1002/2017GL073773

Zhang, G., Yao, T., Xie, H., Kang, S., & Lei, Y. (2013). Increased mass over the Tibetan Plateau: From lakes or glaciers? *Geophysical Research Letters, 40*(10), 2125-2130. doi:10.1002/grl.50462

Zhao, L., Simon Wang, S. Y., & Meyer, J. (2017). Interdecadal Climate Variations Controlling the Water Level of Lake Qinghai over the Tibetan Plateau. *Journal of Hydrometeorology, 18*(11), 3013-3025. doi:10.1175/JHM-D-17-0071.1

Zhao, Y., Liao, J. J., Shen, G. Z., & Zhang, X. L. (2017). Monitoring lake level changes by altimetry in the arid region of Central Asia. *IOP Conference Series: Earth and Environmental Science, 74*, 012004. doi:10.1088/1755-1315/74/1/012004

Zhou, J., Wang, L., Zhang, Y., Guo, Y., Li, X., & Liu, W. (2015). Exploring the water storage changes in the largest lake (Selin Co) over the Tibetan Plateau during 2003–2012 from a basin-wide hydrological modeling. *Water Resources Research, 51*(10), 8060-8086. doi:10.1002/2014WR015846

Zhou, Y., Dong, J., Xiao, X., Liu, R., Zou, Z., Zhao, G., & Ge, Q. (2019). Continuous monitoring of lake dynamics on the Mongolian Plateau using all available Landsat imagery and Google Earth Engine. *Science of The Total Environment, 689*, 366-380. doi:https://doi.org/10.1016/j.scitotenv.2019.06.341

Data Availability Statement

The data that support the findings of this study are from openly public available datasets. These data related download links and citations are listed on Section 3 Data sources.

Tables

Table 1. Detailed information about the selected lakes.

Region	Lake name	Latitude (˚N)	Longitude (˚E)	Area (km^2)	Elevation (m)	country
Central Asia	Aral Sea	46.4	60.6	18999	42	Kazakhstan, Uzbekistan
	Sarykamysh	41.9	57.4	3852	5	Uzbekistan
	Balkhash	46.1	74.2	16683	349	Kazakhstan
	Issyk-Kul	42.4	77.3	6148	1619	Kyrgyzstan
	Zaysan	48.1	83.9	2913	379	Kazakhstan
Tibetan Plateau	Qinghai	37	100.1	4312	3260	China
	Ngoring	34.9	97.7	621	4292	China
	Ayakkum	37.5	89.4	856	4161	China
	Silingco	31.80	88.99	2222	4550	China
	Namco	30.74	90.60	2021	4730	China
	Zharinamco	30.92	85.61	1001	4292	China
	Ngangzco	31.10	87.10	390	4680	China
Mongolian Plateau	Uvs	50.3	92.7	3421	759	Mongolia
	Hyargas	49.1	93.1	1362	1028	Mongolia
	Hovsgol	55.1	100.5	2741	1645	Mongolia

Table 2. Trends of lake water levels from Hydroweb dataset during the period of 1992-2018 and Pearson correlation coefficients calculated between three altimetry datasets. The significance is shown in bold font. The blank in the table is due to lack of data in the corresponding altimetry databases.

	Lake name	Trend (m/yr)	Pearson Correlation Coefficient		
			Hydroweb GREALM	GREALM DAHITI	Hydroweb DAHITI
Central Asia	Balkhash	**0.058**	0.996	0.930	1.000
	Issyk-Kul	**0.017**	0.994	0.981	1.000
	Zaysan	0.061	0.865	0.982	0.968
	Aral Sea Large	-0.378	0.995	1.000	0.997
	Aral Sea Small	**0.059**	0.987	0.989	0.996
	Sarykamysh	**0.212**	0.988	0.997	1.000
Tibetan Pleteau	Qinghai	**0.105**			0.996
	Ngoring	**0.087**	0.983		
	Ayakkum	**0.326**			0.991
	Zharinamco	**0.148**	0.980	0.742	0.953
	Ngangzco	**0.301**	0.996	0.962	0.959
	Namco	**0.138**			0.940
	Silingco	**0.525**			0.999
Mongolian Pleteau	Uvs	-0.0618			0.936
	Hovsgol	-0.012	0.586	0.377	0.497
	Hyargas	**-0.361**			0.999

Figure Legends

Figure 1. The locations of lakes selected in this study. The rectangles represent the spatial extent of general endorheic regions in A) Central Asia, B) the western Mongolian Plateau, and C) the Tibetan Plateau. The lakes in Central Asia include 1) the south Aral Sea, 2) the north Aral Sea, 3) Sarykamysh, 4) Balkhash, 5) Issyk-Kul, and 6) Zaysan; the lakes in the Mongolian Plateau are 7) Uvs, 8) Hyargas, and 9) Hovsgol; and the lakes in the Tibetan Plateau are 10) Qinghai, 11) Ngoring, 12) Ayakkum, 13) Namco, 14) Silingco, 15) Ngangco, and 16) Zharinamco.

Figure 2. The seasonal cycle of precipitation from different gridded datasets over three lakes from three endorheic lake zones during the period of 1990-2016. Lake Silingco was selected from the Tibetan Plateau and Lake Balkhash was from Central Asia, and Lake Hovsgol was from the Mongolian Plateau.

Figure 3. Comparisons of water level from three altimetry datasets for five lakes in Central Asia. The plots represent the annual values of water levels between 1992 and 2018. The water level here is referred to the relative values (y-axis value). The blue curve is the data from Hydroweb and the black is the data from GREALM and the grey is from DAHITI.

Figure 4. Comparisons of water level in four lakes located in the southern Tibetan Plateau. The annual time series are shown since 1995 in Lake Namco and Lake Silingco, and since 1992 in Lake Zharinamco and Lake Ngangzco. The blue curve is the data from Hydroweb and the black is the data from GREALM and the grey is from DAHITI.

Figure 5. Comparisons of water level in three lakes located in the northern Tibetan Plateau. The annual time series are shown since 1992 in Lake Ngoring and since 1995 in Lake Qinghai and Lake Ayakkum. The blue curve is the data from Hydroweb and the black is the data from GREALM and the grey is from DAHITI.

Figure 6. Comparisons of water level in three lakes located in the Mongolian Plateau. The annual time series are shown since 1992 in Lake Hovsgol and since 2002 in Lake Uvs and Lake Hyargas. The blue curve is the data from Hydroweb and the black is the data from GREALM and the grey is from DAHITI.

Figure 7. The relationship between water level variation and climatic factors over six lakes in Central Asia. The climatic factors include precipitation and air temperature from 1992 to 2018. The left panel is the cumulative precipitation anomalies (blue line), and the right panel is the cumulative temperature anomalies (orange line) at basin scale compared with lake levels (gray line) shown on the right x-axis.

Figure 8. The relationship between water level variation and climatic factors over three lakes in the northern Tibetan Plateau. The precipitation and air temperature are from 1992 to 2018. The left panel is the cumulative precipitation anomalies (blue line), and the right panel is the cumulative temperature anomalies (orange line) at basin scale compared with lake levels (gray line) shown on the right x-axis.

Figure 9. The relationship between water level variation and climatic factors over four lakes in the southern Tibetan Plateau. The precipitation and air temperature are from 1992 to 2018. The left panel is the cumulative precipitation anomalies (blue line), and the right panel is the cumulative temperature anomalies (orange line) at basin scale compared with lake levels (gray line) shown on the right x-axis.

Figure 10. The relationship between water level variation and climatic factors over three lakes in the Mongolian Plateau. The precipitation and air temperature are from 1992 to 2018.

The left panel is the cumulative precipitation anomalies (blue line), and the right panel is the cumulative temperature anomalies (orange line) at basin scale compared with lake levels (gray line) shown on the right x-axis.

Figure 11. The significant regime shift in time series of precipitation (blue line) and temperature (orange line) over five lakes in Central Asia. Vertical lines represent regime shift years and Horizontal dash lines represent the mean value of each regime. For air temperature, the regime shift occurred in 1997 over whole lake zones. For precipitation, regime shift years were in 1997 and 2007 in Lake Balkhash, Lake Zaysan and Lake Issykkul. Lake Sarykamysh experienced the precipitation shifts in 1994 and 2001.

Figure 12. The significant regime shift in time series of precipitation (blue line) and temperature (orange line) over three the lakes in the northern part of the Tibetan Plateau. Vertical lines represent regime shift years and Horizontal dash lines represent the mean value of each regime. For air temperature, the regime shift occurred in 1997 over whole lake zones, but also in 2004 in Lake Qinghai and Lake Ngoring. For precipitation, regime shift year was in 2004 in Lake Qinghai and Lake Ngoring, and in 2000 in Lake Ayakkum.

Figure 13. The significant regime shift in time series of precipitation (blue line) and temperature (orange line) over four the lakes in the southern part of the Tibetan Plateau. Vertical lines represent regime shift years and Horizontal dash lines represent the mean value of each regime. For air temperature, the regime shift occurred in 1997 over whole lake zones. For precipitation, regime shift year was in 1998 in Lake Namco and Lake Siling, and in 1996 in Lake Zharinamco and Lake Ngangco. Lake Namco and Lake Zharimaco also experience a precipitation shift in 2005.

Figure 14. The significant regime shift in time series of precipitation (blue line) and temperature (orange line) over three the lakes in the Mongolian Plateau. Vertical lines represent regime shift years and Horizontal dash lines represent the mean value of each

regime. For air temperature, the regime shift occurred in 1996 over whole lake zones, but also in 2008 in Lake Hovsgol and Lake Uvs. For precipitation, regime shift year was in 1994 and 2003.

Figures

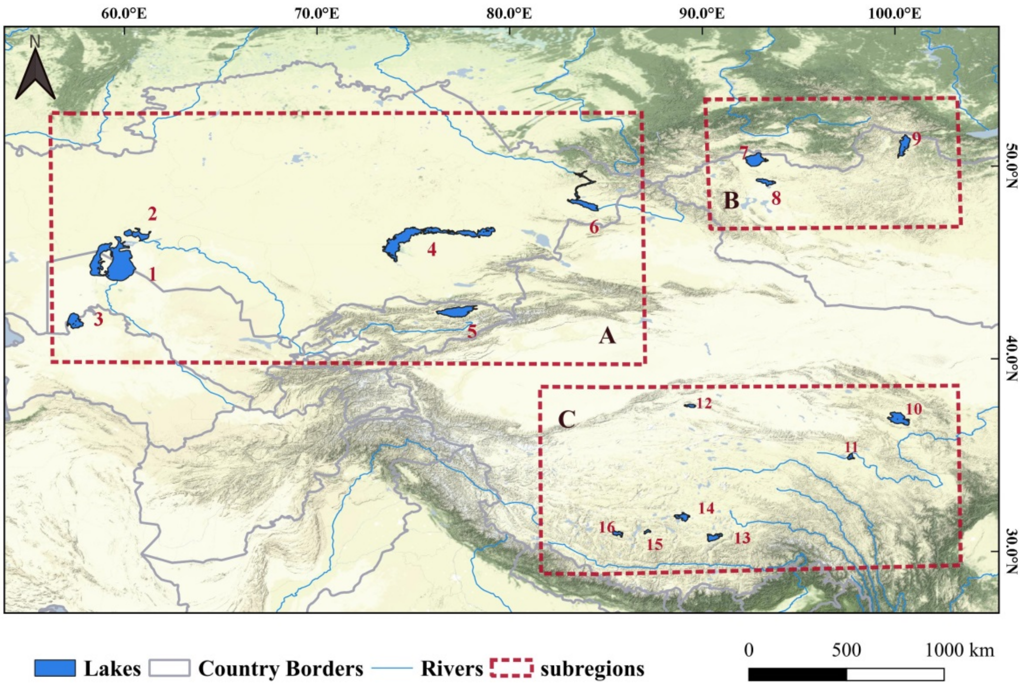

Figure 1. The locations of lakes selected in this study. The rectangles represent the spatial extent of general endorheic regions in A) Central Asia, B) the western Mongolian Plateau, and C) the Tibetan Plateau. The lakes in Central Asia include 1) the south Aral Sea, 2) the north Aral Sea, 3) Sarykamysh, 4) Balkhash, 5) Issyk-Kul, and 6) Zaysan; the lakes in the Mongolian Plateau are 7) Uvs, 8) Hyargas, and 9) Hovsgol; and the lakes in the Tibetan Plateau are 10) Qinghai, 11) Ngoring, 12) Ayakkum, 13) Namco, 14) Silingco, 15) Ngangco, and 16) Zharinamco.

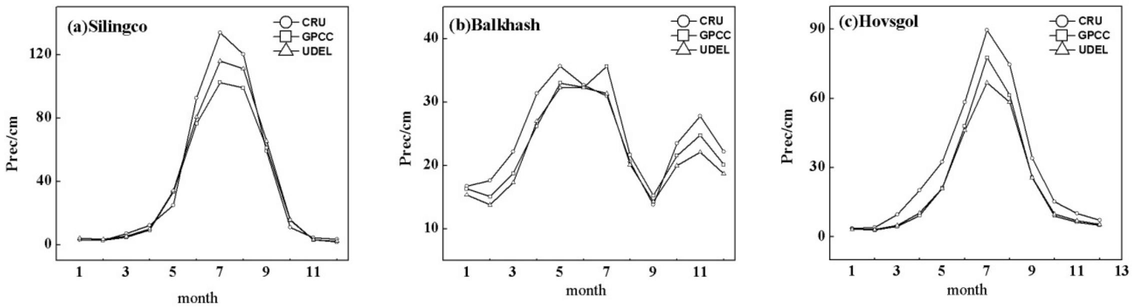

Figure 2. The seasonal cycle of precipitation from different gridded datasets over three lakes from three endorheic lake zones during the period of 1990-2016. Lake Silingco was selected from the Tibetan Plateau and Lake Balkhash was from Central Asia, and Lake Hovsgol was from the Mongolian Plateau.

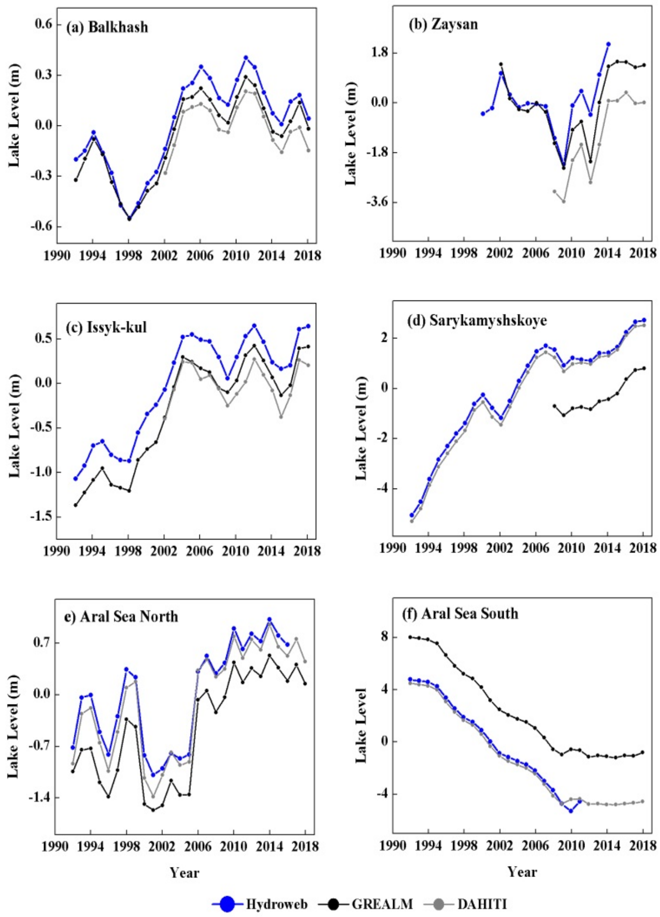

Figure 3. Comparisons of water level from three altimetry datasets for five lakes in Central Asia. The plots represent the annual values of water levels between 1992 and 2018. The water level here is referred to the relative values (y-axis value). The blue curve is the data from Hydroweb and the black is the data from GREALM and the grey is from DAHITI.

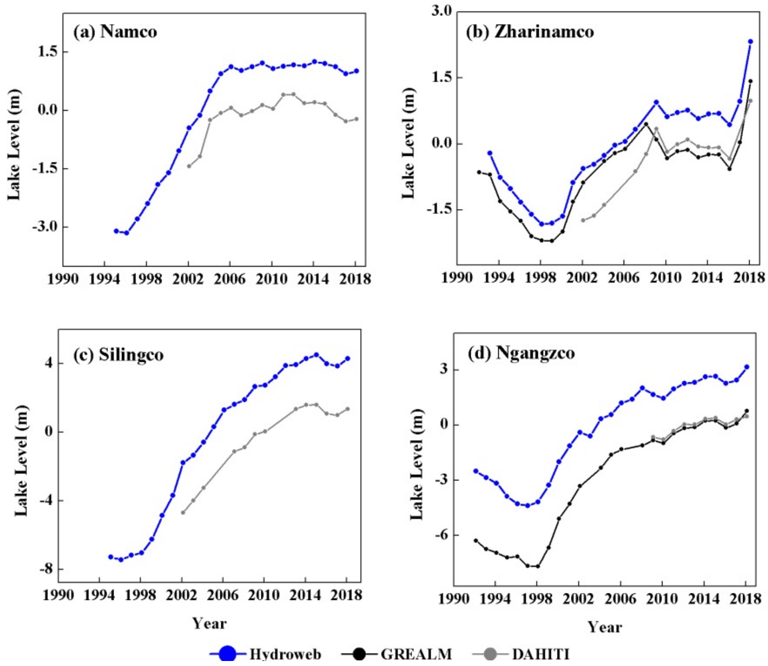

Figure 4. Comparisons of water level in four lakes located in the southern Tibetan Plateau. The annual time series are shown since 1995 in Lake Namco and Lake Silingco, and since 1992 in Lake Zharinamco and Lake Ngangzco. The blue curve is the data from Hydroweb and the black is the data from GREALM and the grey is from DAHITI.

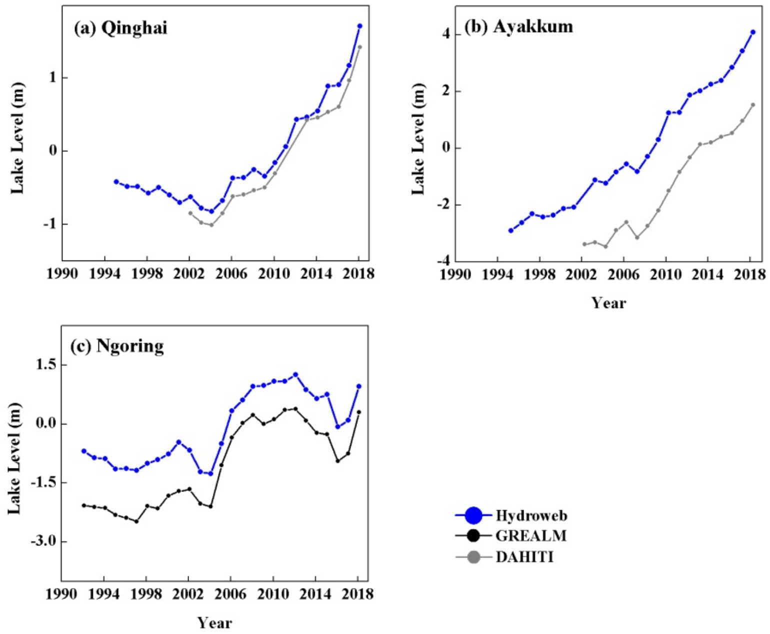

Figure 5. Comparisons of water level in three lakes located in the northern Tibetan Plateau. The annual time series are shown since 1992 in Lake Ngoring and since 1995 in Lake Qinghai and Lake Ayakkum. The blue curve is the data from Hydroweb and the black is the data from GREALM and the grey is from DAHITI.

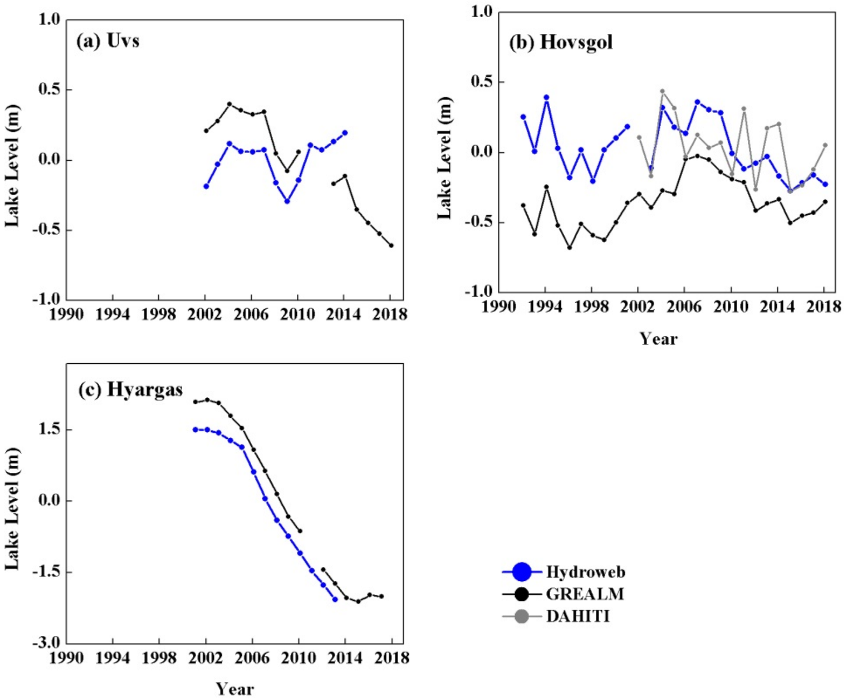

Figure 6. Comparisons of water level in three lakes located in the Mongolian Plateau. The annual time series are shown since 1992 in Lake Hovsgol and since 2002 in Lake Uvs and Lake Hyargas. The blue curve is the data from Hydroweb and the black is the data from GREALM and the grey is from DAHITI.

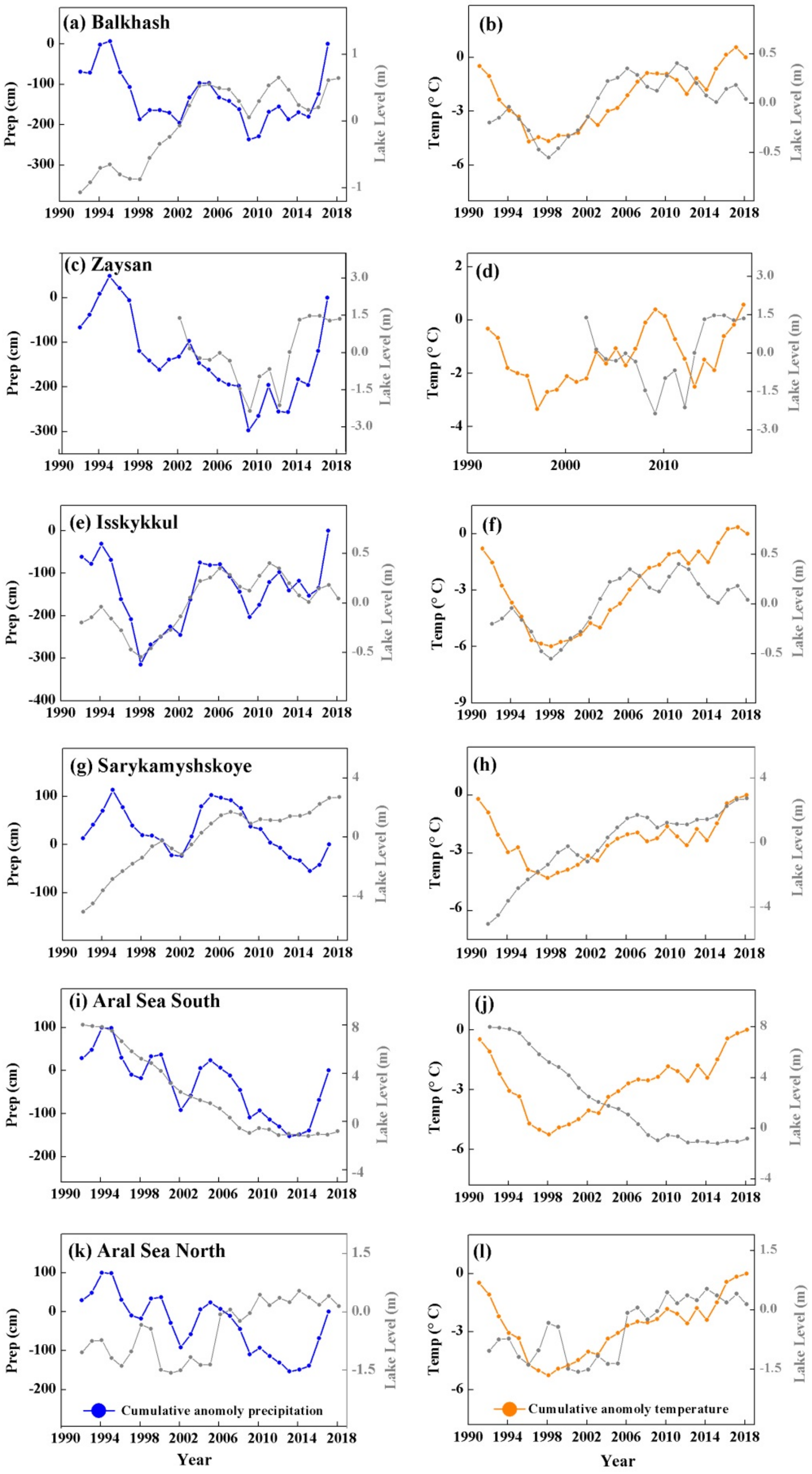

Figure 7. The relationship between water level variation and climatic factors over six lakes in Central Asia. The climatic factors include precipitation and air temperature from 1992 to 2018. The left panel is the cumulative precipitation anomalies (blue line), and the right panel

is the cumulative temperature anomalies (orange line) at basin scale compared with lake levels (gray line) shown on the right x-axis.

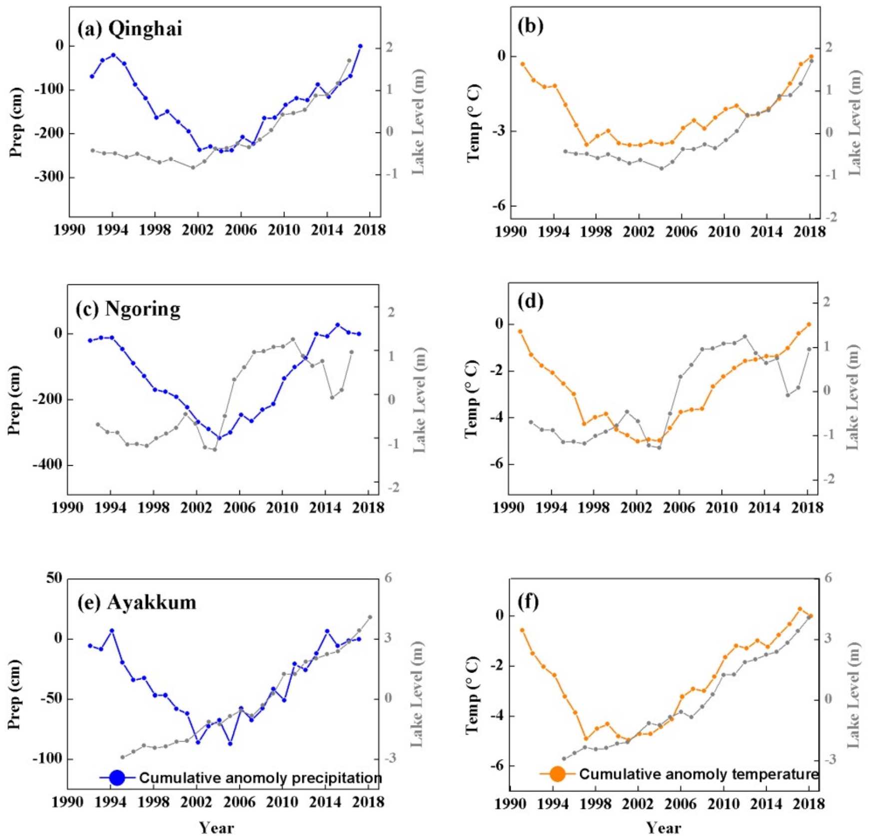

Figure 8. The relationship between water level variation and climatic factors over three lakes in the northern Tibetan Plateau. The precipitation and air temperature are from 1992 to 2018. The left panel is the cumulative precipitation anomalies (blue line), and the right panel is the cumulative temperature anomalies (orange line) at basin scale compared with lake levels (gray line) shown on the right x-axis.

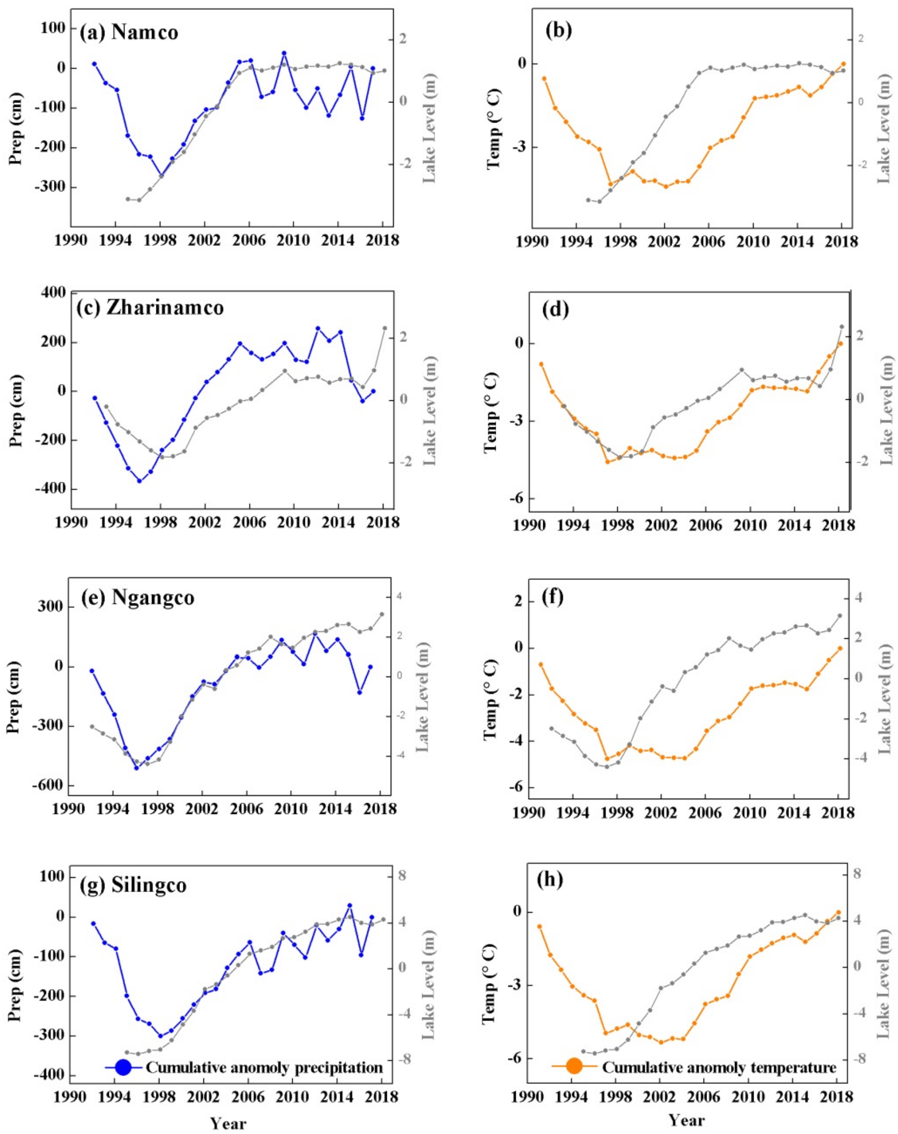

Figure 9. The relationship between water level variation and climatic factors over four lakes in the southern Tibetan Plateau. The precipitation and air temperature are from 1992 to 2018. The left panel is the cumulative precipitation anomalies (blue line), and the right panel is the cumulative temperature anomalies (orange line) at basin scale compared with lake levels (gray line) shown on the right x-axis.

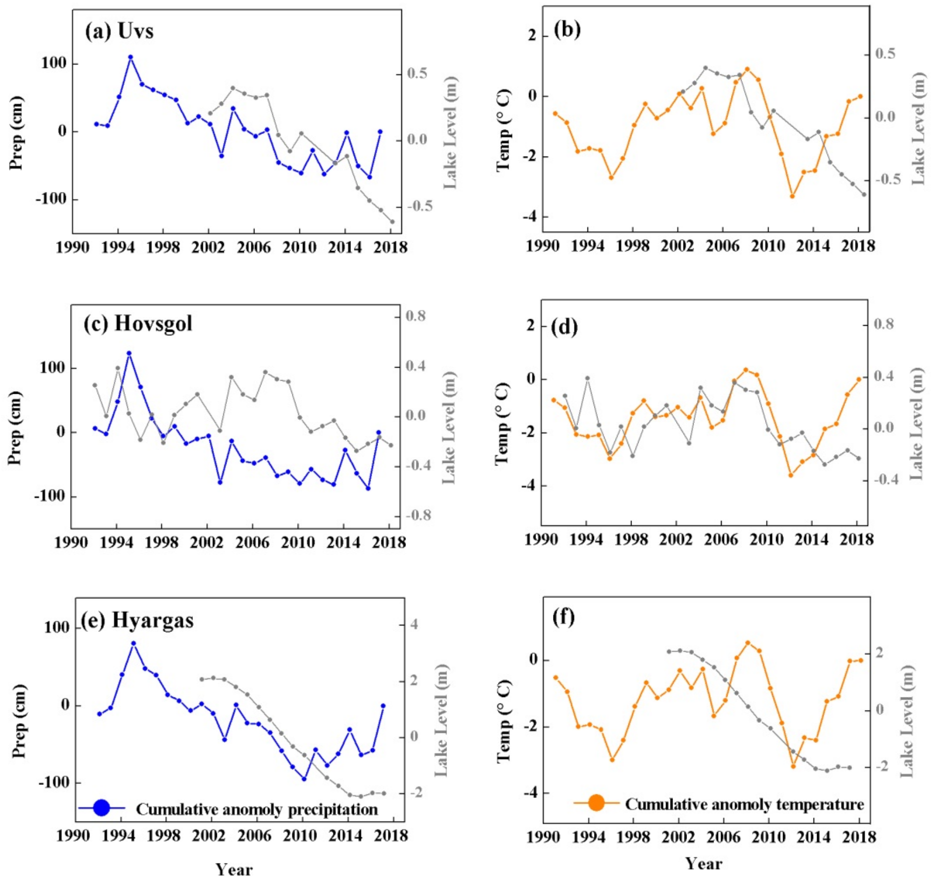

Figure 10. The relationship between water level variation and climatic factors over three lakes in the Mongolian Plateau. The precipitation and air temperature are from 1992 to 2018. The left panel is the cumulative precipitation anomalies (blue line), and the right panel is the cumulative temperature anomalies (orange line) at basin scale compared with lake levels (gray line) shown on the right x-axis.

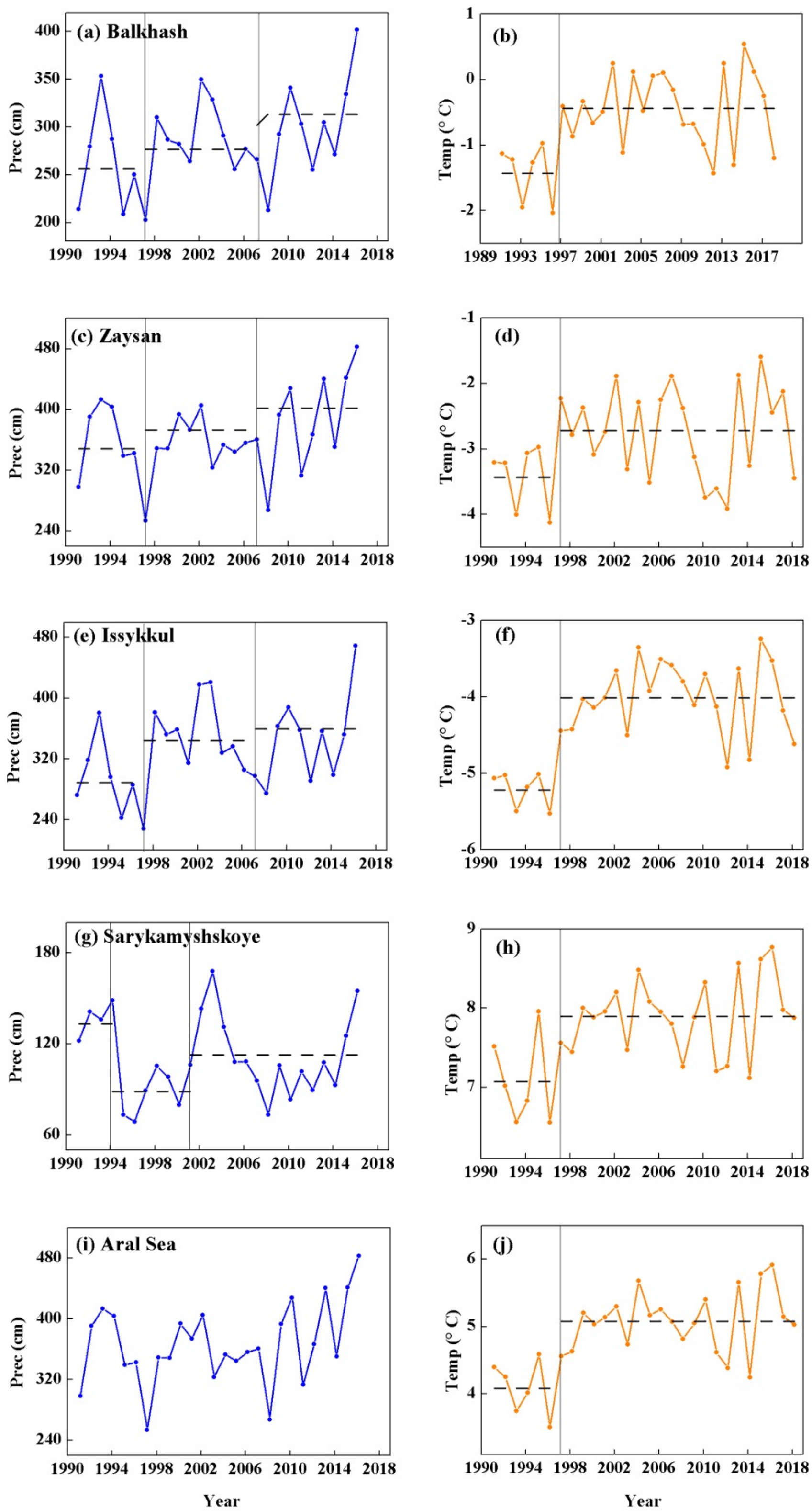

Figure 11. The significant regime shift in time series of precipitation (blue line) and temperature (orange line) over five lakes in Central Asia. Vertical lines represent regime shift

years and Horizontal dash lines represent the mean value of each regime. For air temperature, the regime shift occurred in 1997 over whole lake zones. For precipitation, regime shift years were in 1997 and 2007 in Lake Balkhash, Lake Zaysan and Lake Issykkul. Lake Sarykamysh experienced the precipitation shifts in 1994 and 2001.

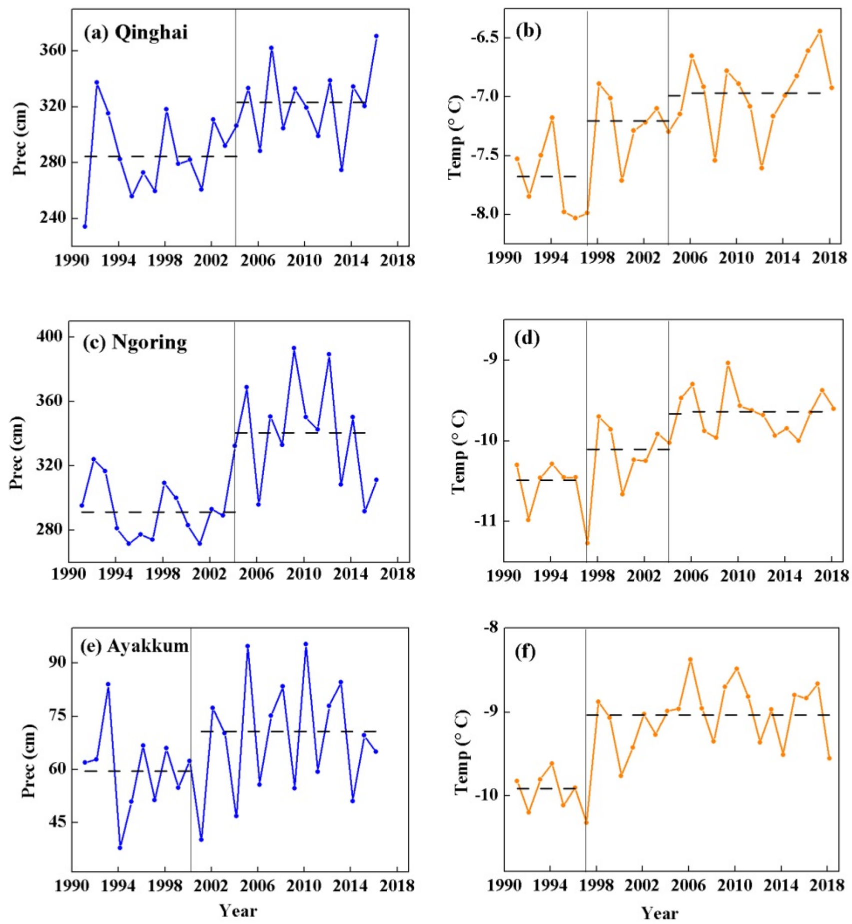

Figure 12. The significant regime shift in time series of precipitation (blue line) and temperature (orange line) over three the lakes in the northern part of the Tibetan Plateau. Vertical lines represent regime shift years and Horizontal dash lines represent the mean value of each regime. For air temperature, the regime shift occurred in 1997 over whole lake zones, but also in 2004 in Lake Qinghai and Lake Ngoring. For precipitation, regime shift year was in 2004 in Lake Qinghai and Lake Ngoring, and in 2000 in Lake Ayakkum.

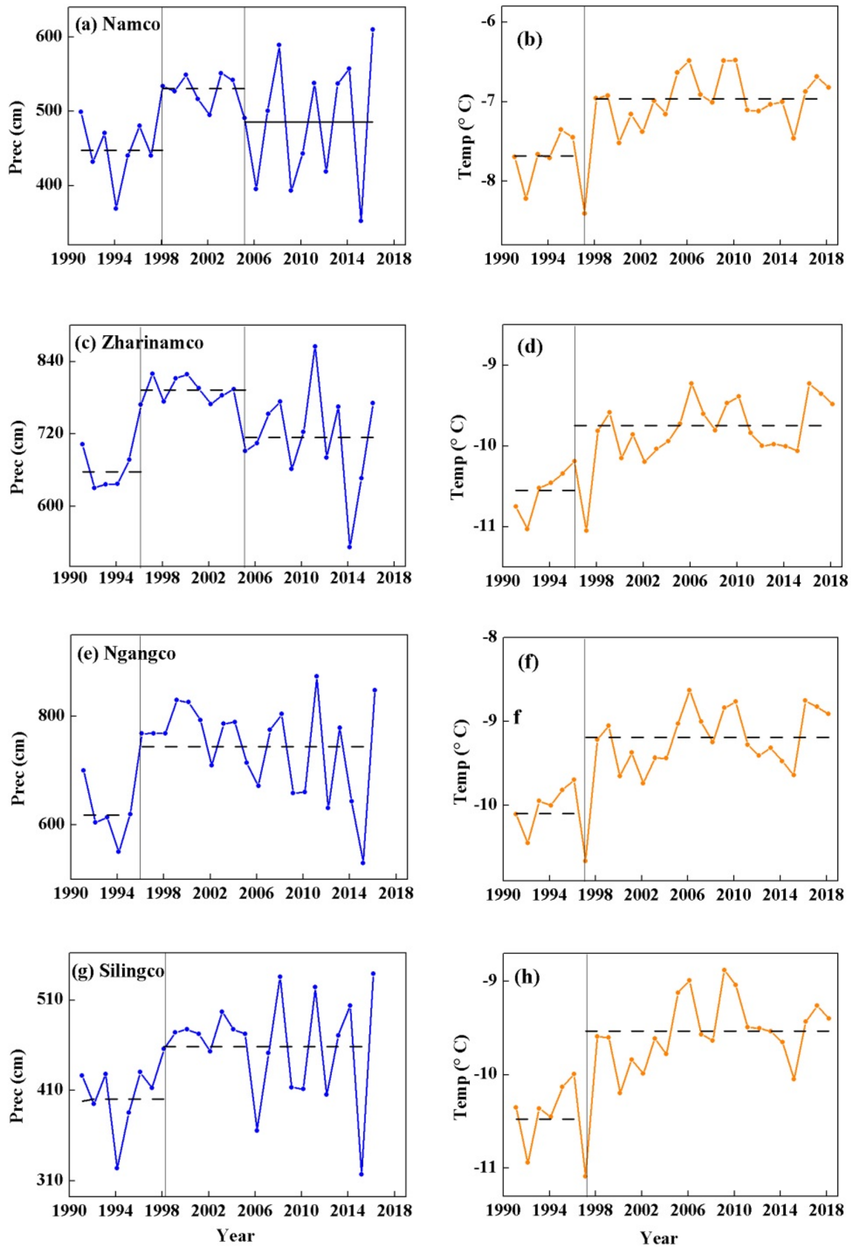

Figure 13. The significant regime shift in time series of precipitation (blue line) and temperature (orange line) over four the lakes in the southern part of the Tibetan Plateau. Vertical lines represent regime shift years and Horizontal dash lines represent the mean value of each regime. For air temperature, the regime shift occurred in 1997 over whole lake zones. For precipitation, regime shift year was in 1998 in Lake Namco and Lake Siling, and in 1996 in Lake Zharinamco and Lake Ngangco. Lake Namco and Lake Zharimaco also experience a precipitation shift in 2005.

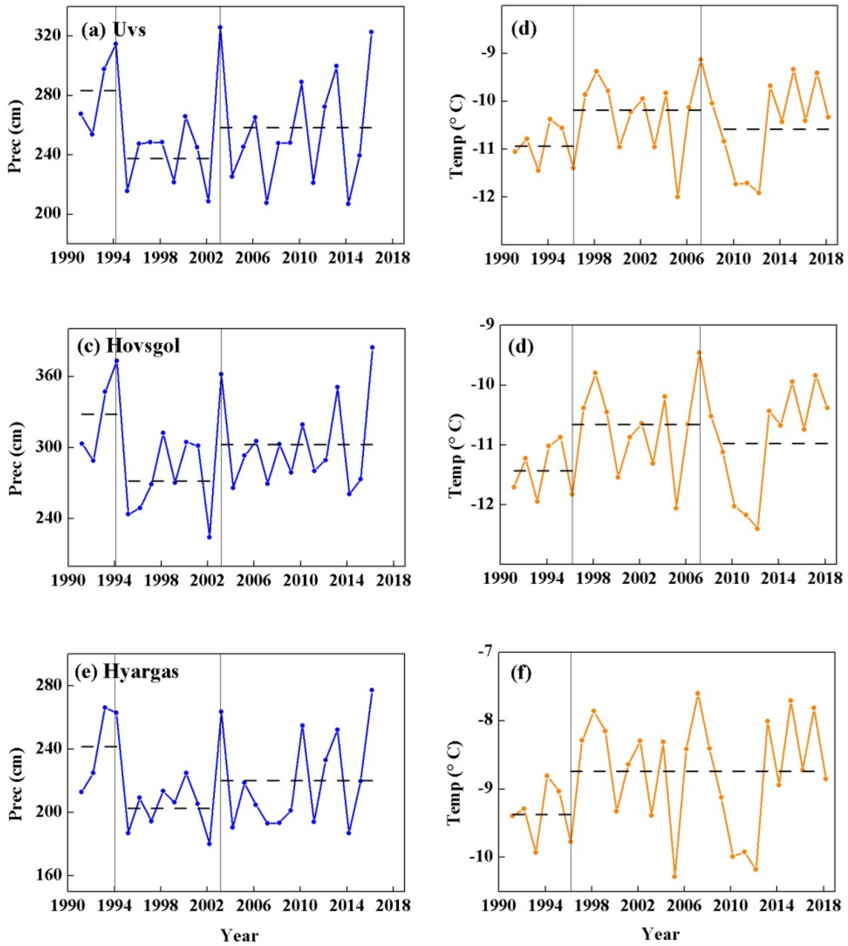

Figure 14. The significant regime shift in time series of precipitation (blue line) and temperature (orange line) over three the lakes in the Mongolian Plateau. Vertical lines represent regime shift years and Horizontal dash lines represent the mean value of each regime. For air temperature, the regime shift occurred in 1996 over whole lake zones, but also in 2008 in Lake Hovsgol and Lake Uvs. For precipitation, regime shift year was in 1994 and 2003.