DE GRUYTER Open Geosciences 2020; 12: 1200–1211

Research Article

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Spatiotemporal variation and climatic response of water level of major lakes in China, Mongolia, and Russia

https://doi.org/10.1515/geo-2020-0142
received May 10, 2020; accepted September 23, 2020

Abstract: Lakes are important indicators of climate change. The change in lake water level objectively reflects the availability of regional water resources. Analyzing the changes in water level and climate response of major lakes in countries along the "Belt and Road" is essential for sustainable water use and ecological protection. Based on the water level datasets of 39 large lakes (>400 km^2) in China, Mongolia, and Russia (CMR) from 2002 to 2016, this study analyzed the spatiotemporal characteristics of water levels in major lakes of CMR, and their responses to climatic factors containing temperature, precipitation, and evapotranspiration. The results showed that (1) the water level of main lakes in CMR slightly increased with change rates ranged from −0.36 to 0.48 m/a, and the trends varied in lakes, (2) the water level of most lakes was sensitive to temperature with sensitivity value ranged from −2.14 m/°C to 5.59 m/°C, (3) changes of annual cumulative precipitation and evapotranspiration contributed most to the change of lake water level, but key factors affecting water level varied in lakes. Human activity is an important driving factor for the change in water levels and its impacts need further study.

Keywords: lake water level, spatiotemporal variation, climatic response, China, Mongolia, and Russia, Belt and Road

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1 Introduction

In the context of global change, with increasing temperature and shrinking glaciers, the global water resources and its distribution have undergone significant changes in recent years. Lakes consist of an important part of the terrestrial aquifer, accounting for 95% of the liquid freshwater resources on earth and the spatial distribution of which reflect the storage and utilization of land surface water resources to some extent [1,2]. The fluctuations or changes of lakes demonstrate the impacts of climate change, surface processes, and human activities on water cycles, material migration, and ecosystems [3]. The water level is regarded as the most important and basic parameter in lake hydrological analysis [4–6], playing an important role in the social and economy, and its reduction may result in significant ecological consequences [7,8]. Since the water level can sensitively and accurately measure the lake dynamics [9], it is of importance to analyze the fluctuations of water level and its response to climate change. Researches on water level changes of certain single lakes have been conducted by some scholars for years [10–12].

In recent years, study areas have been extended to regional scales of hotspots such as the Qinghai-Tibet Plateau [13–15], Central Asia [16–18], and even global scales [19]. For instance, Kleinherenbrink et al. [20] and Hwang et al. [15] separately analyzed the water level changes of different lakes in the Qinghai-Tibet Plateau using water level data monitored by a satellite radar altimeter. Mao et al. [18] observed that the water levels of 11 typical lakes in Central Asia peaked in different months, showing obvious seasonal changes. In addition to studying the changing characteristics of lake water levels, more research focused on the key factors affecting the water level [8,13,21]. The changes in water level were jointly affected by climate change and anthropogenic activities [22]. For example, Han et al. [23] found that the variation of precipitation and the operation of the Three Gorge Reservoir mainly affected the variation of water level in the Dongting Lake region. However, Chang et al. [24] revealed that the water level of Qinghai lake depended more on climatic factors than on anthropogenic factors. Using the Cryosat-2 SARIn model data from 2010 to 2015, Jiang et al. [21] revealed that the driving factors for water level change in the Qinghai-Tibet Plateau were variable and the autumn/winter temperature played an important role in the lake water level change. Therefore, the key influencing factors of lakes varied in regions due to spatial heterogeneity. In addition, with the expansion of the research area, the impact mechanism of lake water level changes is more complicated. Wang et al. [13] analyzed the water level changes of 56 lakes in China during 2003–2009, showing that the water level change rates were between −0.51 m/a and 0.62 m/a, varied in regions for being affected by the different temporal and spatial characteristics of climatic factors. For example, the water level of most lakes in the Qinghai-Tibet Plateau showed an increase in trends because the melting glaciers and permafrost under the warming climate increased the supply of lake water. However, in northern China, due to the decrease in precipitation and the increase of temperature and evapotranspiration, the water level mainly declined. On a global scale, Tan et al. [19] systematically analyzed the spatial-temporal characteristics of the water levels changes of 204 global major lakes, indicating that precipitation had a significant and direct impact on water levels, while the impact of temperature was more complex.

Studies above showed that the water level is sensitive to climate change, and the response intensity as well as the characteristics varied in regions. Different regions in global are facing serious water scarcity challenges currently. It is extremely important to explore the impact of regional climate change on water level by combining with policies such as the “Belt and Road Initiative (BRI).” BRI not only supplies opportunities for socio-economic development but also challenges to the water resources protection of all participating countries. After China’s implementation of the BRI policy, China–Mongolia and China–Russia have more cooperation and exchanges in various fields. Since the ecological background of the arid regions along the BRI is relatively fragile, the temporal and spatial distribution characteristics, development, and utilization methods and efficiency of water resources in CMR, a key role in regional ecological security, are highly concerned. To ensure water resources security in the development of CMR, it is vital to study the variation characteristics of water levels of major lakes in CMR under climate change, which helps understand the status and changes of water resources and ecological civilization as well as the construction of ecological safety barriers along with the BRI countries and regions. Therefore, the objectives of this study are to (1) analyze the spatial-temporal variation characteristics of water levels of 39 large lakes in CMR from 2002 to 2016, (2) explore the responses of water level to climatic factors including temperature, precipitation, and evapotranspiration, and (3) analyze the key factors affecting the change of water level.

2 Materials and methods

2.1 Study area

The study area is the three countries (CMR) of Eurasia, with a wide range of distribution and a complex and diverse natural environment. The characteristics of water resource distribution varied in CMR. Among CMR, China covers a large territory, with complicated topography and various climate. In China, annual precipitation generally decreases from the southeast coast to the northwest inland. China is rich in water resources but its distribution is uneven and per capita, water availability is low [25]. There are more than 2,000 lakes in China, with coverage area exceeding 60,000 km^2, and most are distributed in the Qinghai-Tibet Plateau and the eastern plains of China. Mongolia is characterized by a high altitude with an average elevation of 1,580 m above sea level. Most regions in Mongolia have a continental temperate steppe climate with obvious seasonal variation. Mongolia is a typical arid and semi-arid landlocked country with very few water resources, and the annual precipitation is about 120 to 250 mm, with 70% occurring during July and August. Mongolia mostly depends on the lake water of the entire country and most lakes are distributed in the northwest region [26]. Most of Russia is located in the north temperate zone, with a mainly temperate continental climate. The annual precipitation is 150 to 1,000 mm in Russia. Freshwater resources are rich in Russia, accounting for about a quarter of the global. There are more than 2.7 million lakes in Russia, but the spatial distribution of water resources in these lakes is uneven [27], with 89% stored in Russia’s three major lakes (Baikal, Lake Ladoga, and Lake Onega) [28].

2.2 Data source

The lake water level data were derived from the global water level change dataset of a multisource radar altimeter [29], published by the Global Change Science Research Data Publishing System. The daily global water level change dataset contains a series of water level for 118 lakes with areas greater than 400 km^2 in 2002–2016, which was extracted from Geophysical Data Record data and MODIS image data based on three kinds of spaceborne radar altimeters (ENVISAT/RA-2, Cryosat-2/SIRAL, and Jason-2), using lake boundary extracting, water level calculation, water level anomaly elimination, Gaussian filter denoising, elevation system conversion, etc. More details of the extracting methods were demonstrated by Liao et al. [29]. In this study, 39 lakes were selected: China (27 lakes), Mongolia (four lakes), and Russia (eight lakes), and the basic information of geographic location and climate information of each lake was presented in Table 1. Climate data from 2002 to 2016 were obtained from the climatic research unit (CRU), including long-term datasets of monthly temperature, precipitation, and potential evapotranspiration with 0.5° × 0.5° resolution.

2.3 Method

The Sen + Mann–Kendall test, trend analysis, and multiple linear regression analysis were used to analyze the change rates of water level and three key climatic factors (temperature, precipitation, and potential evapotranspiration), and the response of water level change to these climatic factors. Lastly, we calculated the relative contribution of each climatic factor to water level change.

(1) Sen + Mann–Kendall test for water level change

The rank-based M–K test is the most widely used nonparametric method for trend detection. We used the Sen + Mann–Kendall test to detect the change of lake water level in CMR. The Sen trendiness calculation formula is as follows:

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right),\ j > i,\ i = 1, 2, 3, \ldots, N, \quad (1)$$

where x_i and x_j are water levels in chronological order. When β is greater than 0, it indicates that the water level presents an upward trend and when β is less than 0, it indicates that the water level decreases.

The standardized test statistic, Z, can be calculated according to Hirsch et al. [30], which illustrated that $|Z| > 1.96$ indicating a significant upward/downward trend (at a significance level of $\alpha = 0.05$).

(2) Linear trend analysis of lake water level and key climatic factors

$$\text{Tre} = \frac{n \times \sum_{i=1}^{n} i \times C_i - \left(\sum_{i=1}^{n} i\right)\left(\sum_{i=1}^{n} C_i\right)}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2}, \quad (2)$$

where n represents the number of years, $i = 1$ for 2002, $i = 2$ for 2003, etc. C_i is the annual value of and key climatic factors, *i.e.* annual lake water level, annual average temperature, annual cumulative precipitation, and annual cumulative evapotranspiration in year i. Tre is the change rate of a linear regression equation, indicating that the factor is an increasing trend in the n-year if Tre is more than 0, otherwise, it decreases. The greater the Tre is, the more obvious the trend becomes. The change rates three climatic factors (recorded as T_{L}, T_{tem}, T_{pre}, and T_{pet}, respectively) were considered statistically significant if $p < 0.05$ via F test.

(3) The response of water level to climatic factors change

A multivariate linear regression analysis was conducted to quantify the correlation of lake water level and three climatic factors during 2002–2016, as shown in equation (6):

$$L = S_{\text{tem}} \times T + S_{\text{pre}} \times P + S_{\text{pet}} \times \text{Pet} + \mu\ , \quad (3)$$

where L, T, P, and Pet represent the annual water level, annual average temperature, annual cumulative precipitation, and annual cumulative evapotranspiration, respectively. S_{tem}, S_{pre} and S_{pet} are the regression coefficients, representing the sensitivity of water level to annual average temperature, annual cumulative precipitation, and cumulative evapotranspiration, respectively. In addition, μ is a random error, indicating the influence of various random factors on the model and also reflecting the impacts of other factors not included in the model such as human activity and glacial melting.

(4) Calculation of the relative contribution of each factor on water level change

The relative contribution of changes in climate factors to the trend of water level (RC_{L}) was calculated. Taking temperature as an example, the relative contribution rate of temperature (RC_{tem}) was calculated the using equation (7):

$$\text{RC}_{\text{tem}} = \frac{S_{\text{tem}} \times T_{\text{tem}}}{|S_{\text{tem}} \times T_{\text{tem}}| + |S_{\text{pre}} \times T_{\text{pre}}| + |S_{\text{pet}} \times T_{\text{pet}}|} \times 100\% \quad (4)$$

the parameters are the same as in equations (2) and (3). In the same way, the relative contribution rate of precipitation and evapotranspiration was calculated and recorded as RC_{pre} and RC_{pet}, respectively.

Table 1: Geographic location and climate information of 39 lakes in China, Mongolia, and Russia

Number	Lake name	Country	Longitude (°)	Latitude (°)	Surface area (km^2)	Mean annual temperature (°C)	Average annual precipitation (mm)	Average annual evapotranspiration (mm)
1	Poyang lake	China	116.29	29.08	3206.98	18.35	1549.24	35.59
2	Dongting lake	China	112.75	29.08	2579.2	18.18	1312.03	32.08
3	Nam Co	China	90.65	30.71	1,920	−0.45	534.32	24.69
4	Zhari Namco	China	85.62	30.93	990.26	−1.28	787.94	29.06
5	Ngangtse Co	China	87.06	30.98	445.48	−1.23	786.75	28.76
6	Gering Co	China	88.44	31.06	477.98	−0.18	717.48	28.04
7	Taro Co lake	China	84.12	31.14	486.62	0.32	718.65	31.36
8	Tai lake	China	120.08	31.19	2537.17	16.62	1227.89	31.49
9	Tangra yumco	China	86.71	31.24	825	−0.56	783.42	29.95
10	Chao lake	China	117.56	31.50	786.01	16.68	1173.36	34.16
11	Ngangla Ringco	China	83.10	31.57	542.89	−3.24	444.93	27.69
12	Siling Co	China	89.16	31.74	2129.02	0.86	619.01	24.79
13	Gaoyou lake	China	119.26	32.80	639.21	15.70	1035.34	32.81
14	Hongze lake	China	118.56	33.26	1663.32	15.50	975.84	33.44
15	Banggong Co	China	79.70	33.60	627.19	−1.84	158.19	29.45
16	Ulan UL lake	China	90.61	34.73	566.96	−5.62	227.33	23.79
17	Eling lake	China	97.69	34.90	629.75	−2.26	338.05	27.39
18	Gyaring lake	China	97.27	34.92	526.1	−2.80	317.71	27.03
19	Qinghai lake	China	100.19	36.92	4254.9	0.58	340.09	28.82
20	Ayakkum lake	China	89.51	37.55	797.01	−3.31	80.87	29.88
21	Har lake	China	97.59	38.29	600	−6.64	143.32	25.29
22	Bosten lake	China	87.08	41.99	1057.02	9.97	103.05	42.66
23	Sayramu lake	China	81.17	44.60	462.63	0.80	367.60	27.16
24	Ebinur lake	China	82.96	44.87	673.46	9.35	189.51	34.37
25	Ulungur lake	China	87.28	47.26	895	7.31	184.06	34.17
26	Hulun Nuur	China	117.40	48.96	2,400	1.45	252.36	27.21
27	Xingkai lake	China	132.40	45.00	4,400	5.22	616.45	24.27
28	Har Us Nuur	Mongolia	92.25	47.96	1,400	4.60	60.39	28.46
29	Khyargas Nuur	Mongolia	93.31	49.20	1,420	−1.09	212.31	21.95
30	Uvs Nuur	Mongolia	92.75	50.31	3,350	0.54	300.18	21.35
31	Lake Khovsgol	Mongolia	100.48	51.08	3,367	−5.06	386.91	18.51
32	Lake Baikal	Russia	108.40	53.68	31,500	−1.76	340.51	19.46
33	Lake Il'Men'	Russia	31.32	58.27	550	6.14	604.86	18.14
34	Rybinsk Reservoir	Russia	38.27	58.51	2,800	4.72	616.96	17.97
35	Lake Peipus	Russia	27.55	58.55	3,429	6.02	653.95	18.54
36	Lake Beloye	Russia	37.64	60.18	650	4.16	650.09	17.15
37	Lake Ladoga	Russia	31.48	60.83	16,400	4.61	656.66	15.71
38	Lake Onega	Russia	35.91	61.39	9,890	4.20	667.53	15.60
39	Lake Taymyr	Russia	102.52	74.59	5,000	−14.14	242.78	9.57

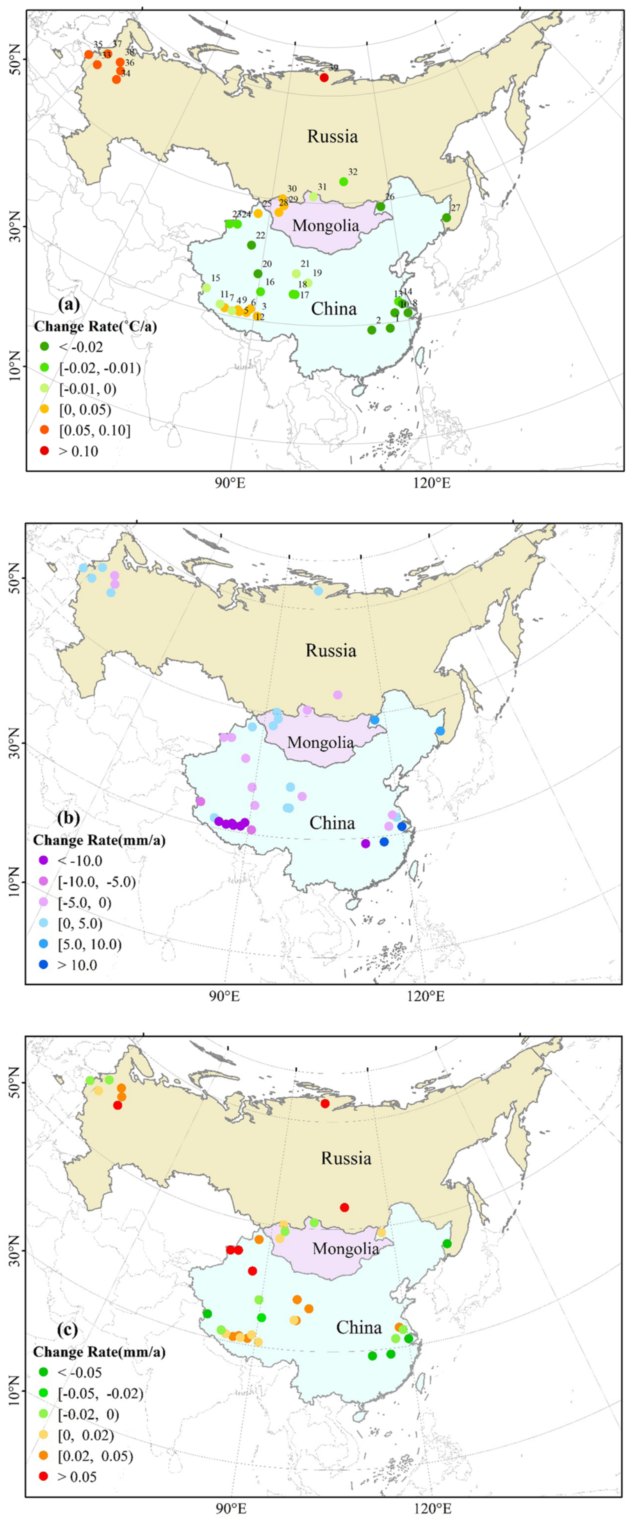

Figure 1: The spatial distribution of basin climate change trend for major lakes in China, Mongolia, and Russia. (a) Annual average temperature; (b) annual cumulative precipitation; (c) annual cumulative potential evapotranspiration.

3 Results

3.1 Climate change in lakes of CMR

Climate change is an important factor affecting the water cycle and will inevitably lead to changes in river runoff and lake water level. In the context of global climate change, the temporal and spatial trends of the climatic factors of the lake in CMR showed apparent differences (Figure 1). Based on linear trend analysis, the change rate of annual average temperature, annual precipitation, and annual evapotranspiration in each lake is listed in Table S1.

The temperature of the major lakes in CMR during 2002–2016 generally showed a slight upward trend with change rate ranged from −0.04°C/a to 0.21°C/a (Figure 1a). The annual average temperature in China's lake decreased weakly with an overall average change rate of −0.01°C/a. Among them, seven lakes with rising annual average temperatures were mainly distributed in the southern and northwestern regions of the Qinghai-Tibet Plateau. The remaining 19 lakes with a downward trend (−0.03 ± 0.01°C/a) were mainly distributed in the northern part of the Qinghai-Tibet Plateau, the middle and lower reaches of the Yangtze River, and the inland areas of the northwest. In Mongolia, the annual average temperature of four lakes was on a not obvious decline. Except for a slight downward trend in the lake Khovsgol, the annual average temperature in other lake was on the rise. Similar to Mongolia, the annual average temperature of most lakes in Russia was rising (0.08 ± 0.02°C/a), and the temperature change rate of Taimer Lake was significant ($p < 0.01$), indicating its upward trend was the most obvious.

The annual cumulative precipitation of the major lake showed a decreasing trend on the whole in CMR with an average change rate of −1.25 ± 7.17 mm/a, but the trends varied in lakes (Figure 1b). The precipitation rate of lakes in China ranged from −14.32 to 19.12 mm/a, and most lakes showed a decreasing trend, mainly distributed in the Qinghai-Tibet Plateau and the northwestern inland areas. Compared with other lakes in the middle and lower reaches of the Yangtze River, the annual precipitation in Poyang lake has increased and the intensity of precipitation is high in Tai lake. In addition, the annual precipitation in some lakes in the northern and northwestern Tibetan Plateau showed a weak increase. In Mongolia, the precipitation changes in four lakes were relatively small. Except for the weak decline trend of the lake Khovsgol in the northern region, the precipitation of the other three lakes has increased with insignificant change. In Russia, the precipitation in the lakes generally increased with an average change rate of 1.19 mm/a, and lake Onega and lake Baikal, two of the three largest lakes in Russia had declining rainfall trends.

Compared with the temperature and precipitation changes, the evapotranspiration change trends in the main lakes of the three countries were relatively weak, and the overall trend was upward with a rate of 0.01 mm/a. Except for the obvious downward trend of evapotranspiration in Xingkai lake, the evapotranspiration of most lakes had not changed significantly. As shown in Table S1, the annual evapotranspiration of 17/27 lakes slightly increased in China, and these lakes are mostly distributed in the Qinghai-Tibet Plateau and Northwest China. The evapotranspiration of the remaining nine lakes in China has weakened, which is mainly distributed in the middle and lower reaches of the Yangtze River. The evapotranspiration of four lakes in Mongolia was not obvious, indicating an upward trend overall, but it decreased in lake Khyargas. Similarly, except for Peipus lake, the evapotranspiration mainly showed a slight increase in lakes with an average change rate of 0.03 ± 0.03 mm/a in Russia.

3.2 Spatiotemporal variation characteristics of lake water level

The results of the Sen + Mann–Kendall test showed that the water level of 22 lakes increased, and 48.72% showed a significant increase ($|Z| > 1.96$) (Table 2). Lakes with a significant increase in water level are mostly distributed in Qinghai-Tibet Plateau in China and northwest Russia. In addition, the water level of 23.08% lakes significantly decreased ($|Z| > 1.96$), and these lakes were mainly located in the arid inlands of China and Mongolia.

The linear trend analysis showed similar results with those of Sen + Mann–Kendall test. In general, water levels of all lakes in CMR were on the rise with an average increasing rate of 0.04 ± 0.13 m/a (Figure 2). The water level of 24 lakes showed an increasing trend, and the remaining 15 lakes showed a decreasing trend. The average change rate of lake water level in China was −0.01 ± 0.02 m/a, but the water level varied greatly among years with a standard variation of 0.13 m. There were nine lakes in China with a slight downward trend, which was mainly distributed in the southwestern part of the Qinghai-Tibet Plateau and the middle and lower reaches of the Yangtze River. The interannual water level of lakes in central and northern Qinghai-Tibet Plateau increased, of which the variation was more than 2 m/a, demonstrating great fluctuation of water level among lakes. The remaining lakes with a slightly decreasing level were located in the middle and lower reaches of the Yangtze River and northwestern China. On the contrary, the average water level of lakes in Mongolia showed a descending trend, with a rate of −0.09 m/a. Except for the weaker upward trend in the water level of Har Us Nuur, the other three lakes all showed a downward trend, among which the water level of lake Khyargas dropped significantly at a rate of 0.36 m/a. In general, the water level of lakes was dominated by a weak upward trend in Russia, with change rates ranged from −0.01 to 0.03 m/a. However, there are three lakes that showed a decreased trend of water level, and the most obvious decline was observed in lake Baikal.

3.3 Response of water level to climatic factors

The sensitivity of water level to climatic factors indicated that the response of water level to annual average temperature, cumulative precipitation, and cumulative evaporation changes on water level varied greatly in different lakes (Table 3).

Temperature and precipitation are the main factors affecting the changes in the water level of most lakes. The water levels of most lakes in CMR were sensitive to the annual average temperature. As a whole, there were 19

Table 2: Results of Sen + Mann-Kendall test for lake water level

Change trend	Trend types	Number of lakes	Percentage (%)
$\beta < 0$, $\|Z\| > 1.96$	Significant decrease	9	23.08
$\beta < 0$, $\|Z\| \le 1.96$	Slight decrease	8	20.51
$\beta \ge 0$, $\|Z\| > 1.96$	Significant increase	19	48.72
$\beta \ge 0$, $\|Z\| \le 1.96$	Slight increase	3	7.69

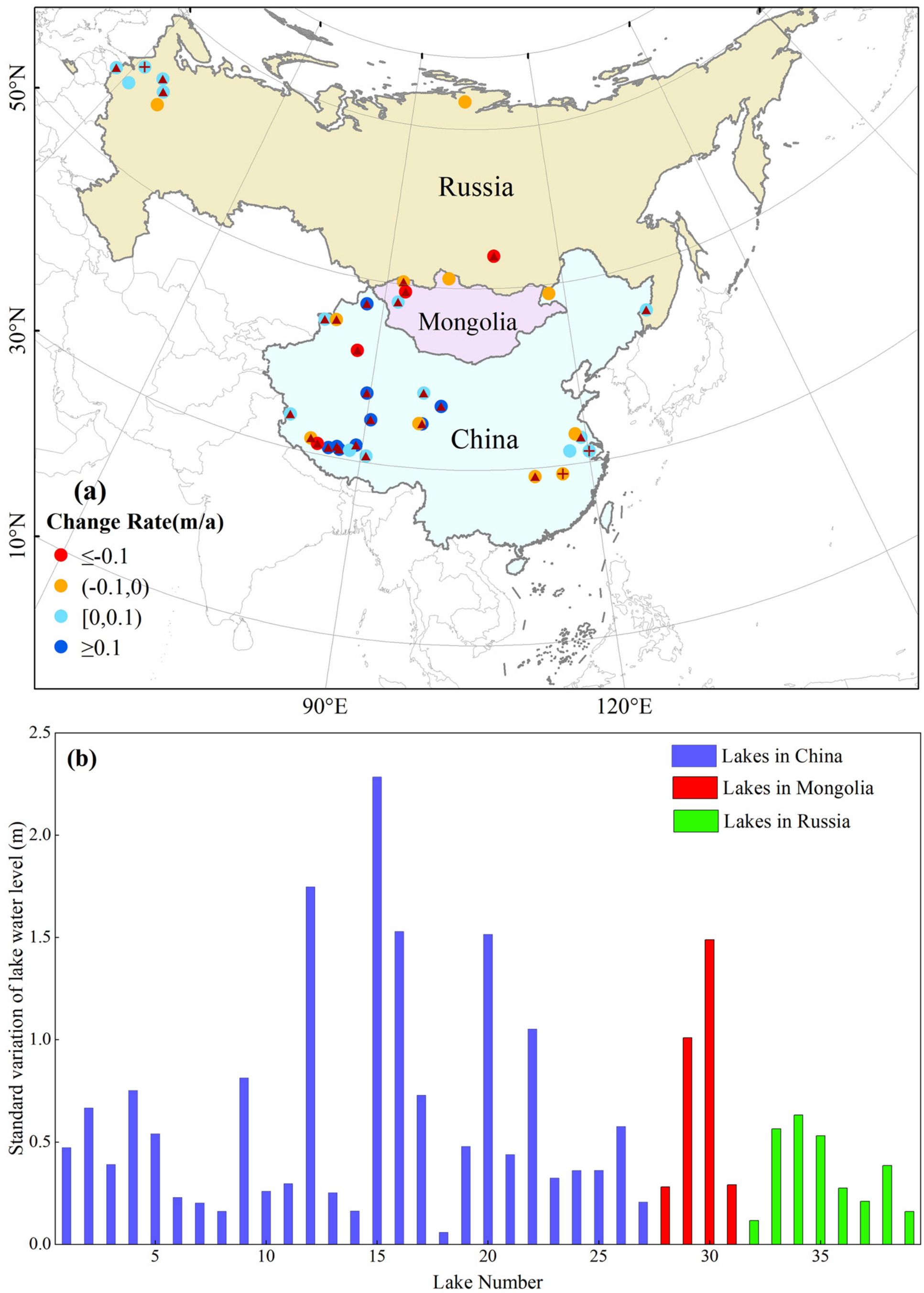

Figure 2: The lake variation of major lakes in China, Mongolia, and Russia from 2002 to 2016. (a) The change rate of water level; (b) the standard variation of water level.

lakes whose sensitivity of water level to the annual average temperature was negative, indicating that the water levels decreased as the temperature increased. In China, the temperature of 15 lakes in China is negatively correlated with the water level changes. Most of these lakes were distributed in arid northwestern China and southeastern China, and several lakes were located in Qinghai-Tibet Plateau. The remaining 12 lakes, of which the water level was positively correlated with the temperature, were mainly distributed in the Qinghai-Tibet Plateau. Among these lakes, the response of the water level of Siling Co and Banggong Co to annual average temperature was great, with the sensitivity value of 5.59 and 4.56 m/°C. In Mongolia, the sensitivity of the water level of two lakes, the lake Khyargas and Uvs Nuur, to temperature was negative, while the water level of lake Har Us Nuur and lake Khovsgol increased with increasing temperature, among which the water level of Har Us Nuur responded strongly to temperature. Among the major lakes in Russia, the water levels of the Rybinsk reservoir, lake Ladoga, and lake Taimer were negatively correlated with temperature. Increasing temperature in three lakes enhanced the evaporation of lake water surface and brought negative impacts on water level changes. In addition, the water levels of the remaining six lakes in Russia were positively correlated with temperature, and the water level of lake Baikal was most sensitive to temperature.

Overall, the water levels of 24 lakes in CMR were positively correlated with the annual cumulative precipitation, indicating that the water level increased with the rising precipitation. In China, the water level of most lakes in the Qinghai-Tibet Plateau was negatively sensitive to the annual cumulative precipitation, while positive correlations were showed between precipitation and water level of 15 lakes distributed in the middle and lower reaches of the Yangtze River and northwestern inland areas in China. In Mongolia, the sensitivity of water level to annual cumulative precipitation was negative except lake Kusugur. In Russia, the water level of most lakes was positively correlated with precipitation. However, the sensitivity values of water levels to precipitation in CMR mostly are below 0.1 m/(10 mm), indicating that the response of water levels to precipitation was slight.

Evapotranspiration is one of the direct factors affecting water level changes. The sensitivity of water level to annual cumulative evapotranspiration varied in three countries. In China, the water levels of most lakes are negatively correlated with evapotranspiration, and most of them are located in the central and southern areas of the Qinghai-Tibet Plateau, the northwestern region, and the middle and lower reaches of the Yangtze River. Among these lakes, the water level of Bangong Co responded strongly to evapotranspiration, and the sensitivity value was up to −3.42 m/mm. Similarly, the water levels of Har Us Nuur and Uvs Nuur in Mongolia were negatively correlated with evapotranspiration. Moreover, the water level of Harwusu lake was more sensitive to evapotranspiration than temperature. In Russia, except for lake Ladoga, lake Beloye, and lake Peipus, the water levels of remaining lakes were negatively correlated with evapotranspiration and four of them responded more sensitively to evapotranspiration than temperature.

4 Discussion

4.1 Relative contribution of each climatic factor to lake water level

The sensitivity of water level of 39 major lakes in CMR to three climatic factors, i.e. annual average temperature, cumulative precipitation, and cumulative evapotranspiration varied in lakes from 2002 to 2016. To explore the impact of climate change on the lake water level, we analyzed the relative contribution of climatic factors to water level (Figure 3). Overall, the change in annual cumulative precipitation contributed most to the change in water levels. The relative contribution of precipitation to water levels in China was largest, with the average relative contribution rate of 21.06%, indicating that the change of water level of most lakes in China was mostly affected by the change of precipitation. For example, the increasing precipitation contributed 75.88% to the rise of the water level of Tai lake. The average relative contribution rate of annual cumulative evapotranspiration to water level changes was 4.39%, which was larger than that of annual average temperature (1.94%). This demonstrates that precipitation and evapotranspiration have obvious direct effects on water levels [17]. Meanwhile, the changes of annual cumulative precipitation and evapotranspiration contributed most to the change of lake water level in Mongolia and Russia; however, the average relative contributions of precipitation and evapotranspiration were both negative. Moreover, the contribution of evapotranspiration to water level was larger than that of precipitation in some lakes, indicating the spatial heterogeneity of climatic influence on the lake water level.

4.2 Analysis of factors affecting water level

The variations of water level changes and their sensitivity to climatic changes indicate that the impact mechanism of water level changes is complex, and the key factors affecting lake water levels are also different. Precipitation was one of the direct factors affecting water level changes, especially for lakes in inland arid areas where the precipitation is the main source of water supply. For these lakes, reduced precipitation leads to water level decline and *vice versa*. For example, the precipitation of Bosten lake, Ebinur lake, and Taro co in China, lake Khovsgol in Mongolia, and Baikal lake in Russia have all decreased to different degrees, that is, the water supply has

Table 3: The sensitivity of water level to climatic factors from 2002 to 2016 in China, Mongolia and Russia

Lake number	S_{tem} (m/°C)	S_{pre} (m/(10 mm))	S_{pet} (m/mm)	R^2	P value	Lake number	S_{tem} (m/°C)	S_{pre} (m/(10 mm))	Spet (m/mm)	R^2	P value
1	0.462	0.020	0.174	0.51	0.06	21	−0.422	0.061	0.654	0.39	0.20
2	−0.058	0.021	0.316	0.27	0.34	22	0.413	0.092	−0.574	0.35	0.21
3	1.023	−0.006	−0.413	0.37	0.19	23	−0.029	−0.035	−0.055	0.32	0.26
4	0.868	−0.015	0.075	0.27	0.45	24	−0.132	0.047	0.063	0.19	0.67
5	−1.545	−0.018	0.253	0.77	0.09	25	−0.152	0.036	0.135	0.06	0.88
6	−0.206	0.008	−0.167	0.98	0.03	26	0.044	0.054	0.120	0.57	0.03
7	0.905	0.000	−0.507	0.50	0.65	27	0.230	0.001	−0.181	0.12	0.71
8	−0.108	0.009	0.032	0.50	0.06	28	0.526	−0.400	−1.015	0.63	0.02
9	−0.269	−0.011	0.521	0.16	0.66	29	−0.085	−0.017	0.274	0.03	0.96
10	0.218	0.009	0.066	0.23	0.44	30	−0.089	−0.016	−0.017	0.11	0.76
11	−0.027	−0.006	0.483	0.66	0.03	31	0.031	0.014	0.081	0.37	0.18
12	5.594	−0.057	−2.259	0.41	0.22	32	0.492	0.007	−0.667	0.35	0.21
13	−0.249	0.004	−0.032	0.27	0.35	33	0.218	0.018	−0.334	0.43	0.12
14	0.166	0.002	−0.055	0.34	0.22	34	−0.054	−0.002	−0.417	0.53	0.05
15	4.559	−0.234	−3.417	0.64	0.05	35	0.009	0.021	0.058	0.32	0.25
16	2.956	−0.106	−2.324	0.23	0.54	36	0.224	0.020	0.055	0.42	0.13
17	0.209	0.084	0.397	0.23	0.43	37	−0.040	0.014	0.048	0.07	0.86
18	−0.031	0.034	0.223	0.68	0.44	38	0.088	0.006	−0.036	0.24	0.41
19	−0.326	−0.041	0.237	0.22	0.47	39	−0.009	0.018	−0.041	0.10	0.70
20	−2.139	−0.124	1.589	0.29	0.47						

decreased, leading to a decline of lake water level. The water level of Ulungur lake in China and Har Us Nuur in Mongolia increased with rising precipitation. In addition, in most lakes, the water level responds more strongly to temperature than precipitation, and for some lakes, such as Nam Co and Chao lake, the relative contribution of temperature was larger than that of precipitation, indicating that the influence of temperature on water level was more obvious than precipitation for some lakes. The impact of temperature on the water level is mainly reflected in two aspects: first, an increase in temperature will increase evaporation, which will lead to a decline in water levels. Second, in the glacially covered lakes, the increasing temperature promotes the melting of glaciers, and the amount of water supply will increase, so the water level increases [31]. Overall, when the increase in evapotranspiration caused by temperature rise is greater than the increase in precipitation and the supply of ice-melt water, the water level drops. Previous studies have presented that global warming accelerated the melting of the glaciers in Qinghai-Tibet Plateau and the amount of water flows, which is regarded as a substantial water supply resource for surrounding lakes and a key factor of water level rising [32]. In our study, the water level of most lakes in Qinghai-Tibet Plateau was on the rise. This is mainly due to the rising temperature and the strengthened runoff recharge from the melting glaciers, though the precipitation in some lakes had declined. Among these lakes, the apparent rise in water levels of Siling Co and Ulan UL lake indicated that the impact of global warming on glacial meltwater plays a leading role in water levels. Besides, Kehrwald et al. [33] showed that the glaciers on the Qinghai-Tibet Plateau have melted rapidly since the Himalayan glaciers period, and some have almost disappeared in recent years, resulting in a decrease in water supply and a decline in lake water level. However, the study of Phan et al. [34] found that the changes of more than half of the Tibetan lakes (900 lakes examined) were not related to glaciers in the basin. In addition, Li et al. [35] revealed that the impact of melting glaciers on lake changes was limited. These contrary results revealed the complexity of the impact of climate on the lake water level of Qinghai-Tibet Plateau and further research is needed.

Natural factors such as climate change are the main causes of changes in lakes, which determine the trend of large-scale water level changes. However, with the development of the social economy, human activities, including lake construction, water diversion, urban development, dam, and reservoir establishments have increasing impacts on lakes, even exceeding the natural factors in certain areas [19,31,36]. Li et al. [37] found that the water level of lake Khyargas in Mongolia showed an apparent

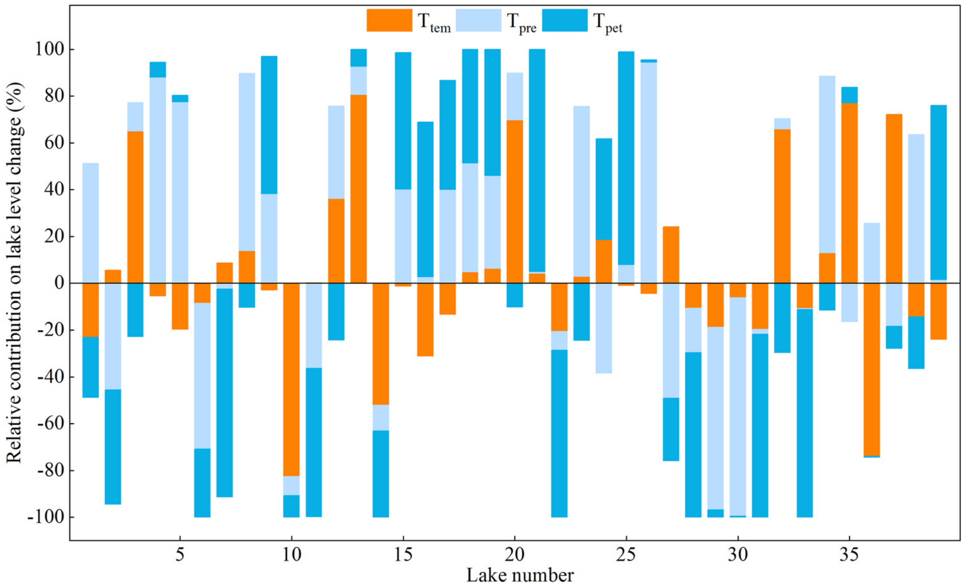

Figure 3: Relative contribution rate of each climatic factors to water level change from 2002 to 2016 in CMR.

downward trend after the construction of the Tasir hydropower station in the upper reaches of the lake in 2004. The main reason was that the supply of lake water was reduced and the reduction trend accelerated after the water was stored by the station. A typical example in China is the Three Gorges Reservoir, which remarkably influenced the water level of the downstream lakes after its construction. For instance, Han et al. [38] and Mei et al. [39], respectively, studied the impact of the Three Gorges Reservoir on the water levels of Dongting Lake and Poyang lake, indicating that the reservoir significantly changed the water level of these two lakes, especially in floods and dry seasons. Another example was the Hulun Nuur in China. Our results show that the precipitation in Hulun Nuur increased in recent years; however, its water level has dropped significantly. This is because except for the strong evaporation caused by climate warming, human activities such as agricultural water use and overgrazing were the most likely causes of water level drops [10]. Thus, human activities are the driving factors of lake changes and have a huge impact on lake changes in a short period of time. However, how to distinguish and quantify the extent of climate change and human activities impact these lakes is still one of the difficulties in the current study on lake evolution. In this study, the impact of human activities on the water level of lakes is not considered owing to a limited data resource, which may cause uncertainty of our results. It is necessary to further consider the impact of human activities on lakes and fully reveal the driving mechanism of water level changes.

5 Conclusions

Based on the global typical water level change dataset and climate data, this study explored the spatial-temporal variation characteristics and climatic responses of water levels in CMR. The results showed that from 2002 to 2016, the water levels of the 39 major lakes in CMR showed a slight upward trend with change rates ranged from –0.36 to 0.48 m/a. The annual precipitation in most lakes decreased, with an average rate of –1.25 mm/a; however, the annual average temperature and the annual evapotranspiration showed a slight increase during the study period. The water levels of most lakes in CMR were mostly sensitive to temperature. In addition, the change of precipitation and evapotranspiration contributed most to the change the water level, but the key influencing factors varied in lakes. Human activities play an important role in the changes in water level and a more comprehensive study of the driving mechanism of the change of water level is needed. The results of this study can provide a scientific basis for the development and utilization of water resources and ecological protection of CMR.

Acknowledgments: This work was supported by the Technological Basic Research Program of China [Grant No. 2017FY101301], the National Natural Science Foundation of China [Grant No. 41671107], National Key Research and Development Program of China [Grant No. 2016YFC050350404], Youth Innovation Promotion Association, CAS [Grant No. 2016049], Program for "Kezhen" Excellent Talents in IGSNRR, CAS, [Grant No.

2017RC101], and Key Research Program of Frontier Sciences, CAS [Grant No. QYZDB-SSW-DQC005].

Author contributions: Methodology and data analysis, Qinghua Tan, writing – original draft preparation, Qinghua Tan, and Yujie Liu.

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