APPLICATIONS PAPER

Assessing China's Lake Changes and Associated Driving Forces During 1985–2015

Cong Xie, Xin Huang, and Jiayi Li

Abstract

China's lakes have experienced dramatic changes in recent decades, but quantitative information on such changes remains unclear. Here we present a national-scale investigation of lake changes in China during 1985 to 2015 and further explore the associated driving factors. We found an apparent increase in the total area of the lakes (increased by 4616.7 ± 296.3 km^2). The increasing trend in lake area has been particularly pronounced in the Tibetan Plateau Lake-zone (TPL) and Xinjiang primarily due to increased precipitation and glacier/snow melting under global warming, although significant downward trends ($P < 0.05$) in lake area occurred in eastern and northeastern China and Inner Mongolia, dominantly driven by anthropogenic activities. There are significant negative relationships between relative lake area and irrigated area, built-up land, and number of water projects in the East and the Northeast China Plain ($P < 0.05$). This study provides a crucial basis for continuous investigation and protection of China's lakes.

Introduction

Lakes are widely distributed on Earth, constituting vitally important components of global hydrological, nutrient, and carbon cycles (Lehner and Döll, 2004). They are dynamic and complex aquatic ecosystems, holding indispensable ecological values and providing essential resources for life (Herdendorf, 1982). Under direct exposure to various geophysical environments, lakes worldwide are highly sensitive to climate change, therefore serving as useful indicators to assess environmental changes (Smith *et al.,*, 2005). Changes in the abundance and area of lakes have broad implications for regional hydrological and biogeochemical cycles, and water resources conservation. Therefore, monitoring the spatial distribution and temporal changes of lakes is crucial for a wide range of socioeconomic, political, and scientific interests.

During the past few decades, drastic changes have occurred in many lakes around the world under the influence of both climate change and human activity (Carpenter *et al.,*, 1992; Lyon and Greene, 1992; Verpoorter *et al.*, 2014). These changes revealed the diverse responses of lake systems to the effects of climate and human activity, suggesting an increasing vulnerability of these lake resources across broad geographic areas. Under the recent global warming, lakes in populated regions are particularly vulnerable to the influence of various human activities, such as human water regulation, diversion, and consumption (Fang *et al.,*, 2005; Ma *et al.,*, 2010). For instance, over the past half century, the distribution and abundance of lakes in China have been significantly altered by excessive anthropogenic activities, e.g., agricultural irrigation, water diversion projects, and land use changes. As human population increases, the intensified anthropogenic forcing has driven complex physical and ecological changes in China's lakes, drawing considerable attention to water shortages, groundwater depletion, and ecosystem degradation (Jiang *et al.*, 2008; Xu *et al.*, 2016; Zhang *et al.*, 2017). Given the increasing vulnerability of these lake resources to climatic and anthropogenic impacts, understanding the spatiotemporal patterns of lake changes and the associated natural and human drivers under global climate warming are issues of increasing concern.

To investigate the continuous changes in lakes, targeted regional studies have been conducted to document the dynamic lake systems across China, e.g., Tibetan Plateau, Mongolian Plateau, and Yangtze Basin (Gao *et al.*, 2014; Tao *et al.*, 2015; Xie *et al.*, 2017; Zhang *et al.*, 2017a; Zhang *et al.*, 2017c). Despite the substantial efforts that have been made in identifying lake changes within individual lake regions, there have been few studies that have quantified the spatiotemporal changes of the nationwide lakes and the possible diverse responses of lake systems to different regional climates and various anthropogenic activities. Ma *et al.* (2010a) conducted a comparative study at the national level between 1960s to 1980s and 2005 to 2006, suggesting that the lake changes may have been predominantly attributed to climate variations in North China and human activities in South China. Yang and Lu (2014) employed Landsat satellite images acquired in the period of 2005 to 2008 to develop a national inventory of lakes and reservoirs, and estimated the changes in the lake and reservoir capacity across mainland China. However, the temporal frequencies employed in these studies may be insufficient for the continuous monitoring of spatiotemporal changes in the nationwide lakes. To date, no previous studies have investigated the current distribution status of the lakes and their long-term evolution patterns for the entire of China. In addition, we currently have limited knowledge of the quantitative relationships between lake changes and climatic/anthropogenic factors, as well as the effects of land use and land cover (LULC) changes on the lakes across the whole of China. Therefore, the major objectives of our study are to (1) document the current distributions of all the lakes across China in 2015; (2) map the spatiotemporal changing patterns of the nationwide lakes from 1985 to 2015; and (3) provide quantitative understanding on relationship between climatic/human factors and lake changes.

Cong Xie is with the State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing (LIESMARS), Wuhan University, 430079,Wuhan, China.

Xin Huang is with the School of Remote Sensing and Information Engineering, Wuhan University,430079, Wuhan, China, 430079; and State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing (LIESMARS), Wuhan University, 430079,Wuhan, China (xhuang@whu.edu.cn).

Jiayi Li is with the School of Remote Sensing and Information Engineering, Wuhan University,430079, Wuhan, China, 430079.

Photogrammetric Engineering & Remote Sensing
Vol. 84, No. 10, October 2018, pp. 53–xxx.
0099-1112/18/53–xxx

doi: 10.14358/PERS.84.10.xxx

Study Area

China has a great wealth of lake resources over a great spatial extent (75° to135° E, 18° to 53° N) and altitudinal range from the Turpan Desert (156 m below sea level) to the Tibetan Plateau, across a large climatic range from the tropical to subarctic/alpine (Wang and Dou, 1998). The formation, distribution, and changes of these lakes are closely associated with the great diversity of climatic, geographic, and socioeconomic conditions in China. The diverse natural and human factors among different regions have driven profound and complex changes in the lake systems in China. Therefore, China's lakes are commonly divided into five zones when considering the regional climates, geomorphological conditions, and political boundaries (Jiang *et al.,*, 2017; Ma *et al.,* 2010; Wang and Dou, 1998). The five lake zones are (Figure 1): Northeast Plain and Mountain Lake-zone (NPML), Inner Mongolia-Xin Jiang Lake-zone (IMXL), Tibetan Plateau Lake-zone (TPL), Eastern Plain Lake-zone (EPL), and Yunnan-Guizhou Plateau Lake-zone (YGPL).

Data and Methods

Development of China's Multitemporal Lake Database

The surface water extent of all the lakes across China was extracted from the recent global surface water datasets, which were produced based on Google Earth Engine® (GEE) platform using three million Landsat satellite images between 1984 and 2015 (Pekel *et al.,*, 2016). These datasets map the extent and change of surface water on monthly time scale over the past three decades, and show a satisfactory performance in terms of the accuracy of water extraction, with the overall errors of omission less than 5% and errors of commission less than 1%. The monthly water history collection, containing the entire history of water detection for each month in the past 32 years, can be accessed and used in the GEE platform (*https://earthengine.google.com/*).

The surface areas of all the lakes in China for the seven episodes (i.e., 1985, 1990, 1995, 2000, 2005, 2010, and 2015) were delineated from the monthly global surface water datasets through visual interpretation and manual digitalization. The water maps acquired in at least three years (primarily within ±1 years of the mapping years) were used for each study period due to the limited availability of cloud-free data for a given year covering the entire China (Ma *et al.,*, 2010; Yang and Lu, 2014). To reduce the effect of seasonal variability on lake water area, the surface water maps within in the wet season for each lake-zone of China. Specially, the data from September to November were chosen for the TPL zone (Zhang *et al.*, 2017a; Zhang *et al.*, 2017b), the maps from June to September were collected for the IMXL and NPML zones (Liu *et al.,*, 2013; Tao *et al.*, 2015), and the images from June to October were selected for the EPL and YGPL zones (Xie *et al.*, 2017). The selected water maps were first converted into polygons with contiguous water pixels, and these polygons of water bodies were then visually classified into two classes: natural lakes and other water bodies (e.g., artificial ponds, reservoirs, and rivers). Subsequently, the detected lake polygons were carefully modified by means of quality assurance and quality control (QA/QC) procedures, including: (1) manual correction for each lake boundary by visual inspection against Google Earth high-resolution images; (2) topology checking for mapped lakes, e.g., removal of duplicate or overlapped polygons, and combination of the dissected polygons due to a bridge or other barriers; and (3) cross-validation and comparison of the mapped lakes for the seven episodes referring to published literature and public datasets. The manual editing procedures need a large amount of human labor, but are essential to guarantee the accuracy of lake mapping (Ma *et al.,*, 2010, Nie *et al.,*, 2017, Yang and Lu, 2014). Following the QA/QC procedures, the surface areas, altitudinal values, and administrative divisions of the mapped lakes (≥1 km^2) were calculated using ArcGIS 10.3® software. In this study, we focused

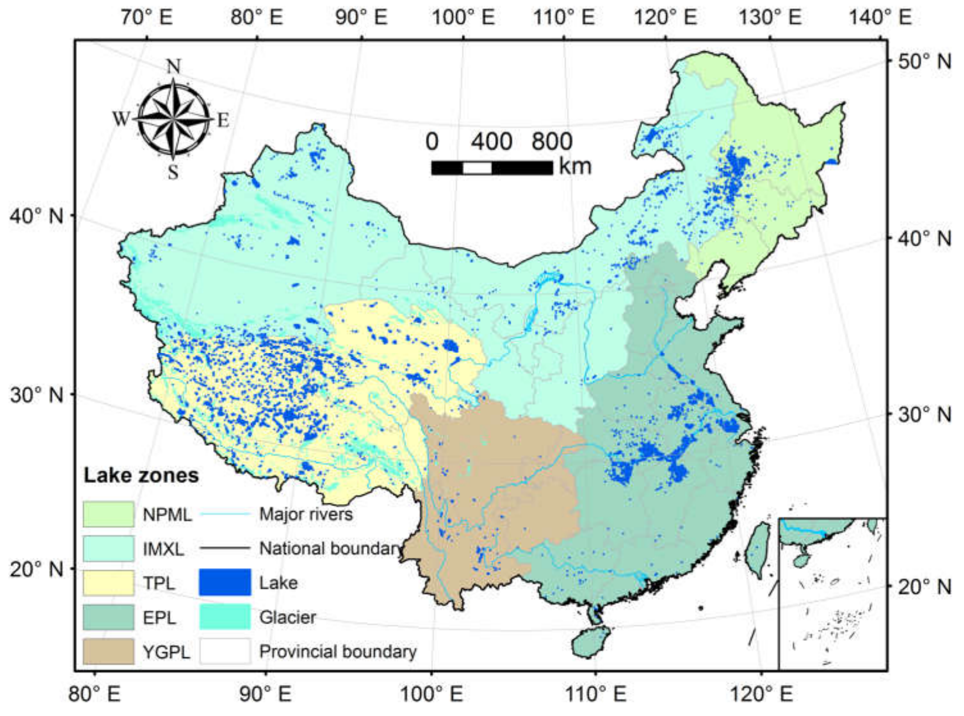

Figure 1. Distribution of lakes and the associated five lake zones in China, including Northeast Plain and Mountain Lake-zone (NPML), Inner Mongolia-Xin Jiang Lake-zone (IMXL), Tibetan Plateau Lake-zone (TPL), Eastern Plain Lake-zone (EPL), and Yunnan-Guizhou Plateau Lake-zone (YGPL). The inset in the lower right corner shows the Nansha Islands of China.

on the lakes greater than 1 km^2 in size, which has been commonly used as the minimum lake unit in China (Fang *et al.,* 2005; Liu *et al.*, 2013; Ma *et al.,*, 2010). The uncertainty of the lake area mapping was mainly associated with the spatial resolution of surface water datasets (i.e., 30 m), which can be assessed by the linear errors (±0.5 pixels) and the shoreline length (Nie *et al.,*, 2017; Salerno *et al.,*, 2012; Wang *et al.,* 2015). In addition, the relative lake area change was used to estimate the overall trend of area changes in relatively large lakes (surface area ≥10 km^2) (Tao *et al.*, 2015; Zhang *et al.,* 2017a), which can be calculated as:

$$\text{Relative lake area } (\%) = \frac{1}{n}\sum\left(A_i / A_i^s\right)\times 100 \qquad (1)$$

where n is the number of lakes, A_i represents the averaged surface area of i^{th} lake in one of the seven periods (i.e., 1985, 1990, 1995, 2000, 2005, 2010, and 2015), and A_i^s denotes the surface area of the i^{th} lake in the reference period (the average lake area between 1985 and 2015 is used as the reference).

Relationships Between Lake Changes and Climatic/human Factors

Climatic data were used to document the general trends in air temperature and precipitation over the entire China during the past three decades. The monthly temperature and precipitation data from 1985 to 2015 were collected from over 700 meteorological stations (China Meteorological Administration; *http://data.cma.cn/*). Mean annual temperature (MAT) and mean annual precipitation (MAP) for the five lake zones were calculated using the monthly climate data. The MAT anomaly and AMP anomaly were calculated as the difference between the temperature or precipitation in a given year and the long-term average temperature or precipitation over the study period, respectively. Human population, irrigation area, grazing data (number of sheep and goats), mining data (coal production), built-up area, and water projects construction (number of floodgates) for the five lake zones during the period of 1985 to 2015 were documented from statistical year books of China's major provinces, municipalities, and autonomous regions (*http://data.stats.gov.cn/*). These factors were used as indicators of human activities. The glaciated area over China was derived from the Second Chinese Glacier Inventory, which was compiled using 218 Landsat TM/ETM+ images mainly from 2006 to 2010 (Guo *et al.,*, 2015). An overview of multi-source datasets used in this study is shown in Table 1.

To explore the possible driving factors, the relationships between lake changes and the regional climate and human activities were investigated. The annual mean temperature (AMT) and precipitation (AMP) were calculated as measures of regional climate. Moreover, irrigation area, human population, grazing, coal mining, urban area, and number of floodgates were used as indicators of human activities. Correlation analysis (Spearman's correlation coefficient) was performed using SPSS Statistics 19 software to understand the association between the relative lake area and corresponding climate/human factors in the five lake zones. The *t*-test results with $p < 0.01$ and $p < 0.05$ are reported as strongly significant and significant, respectively.

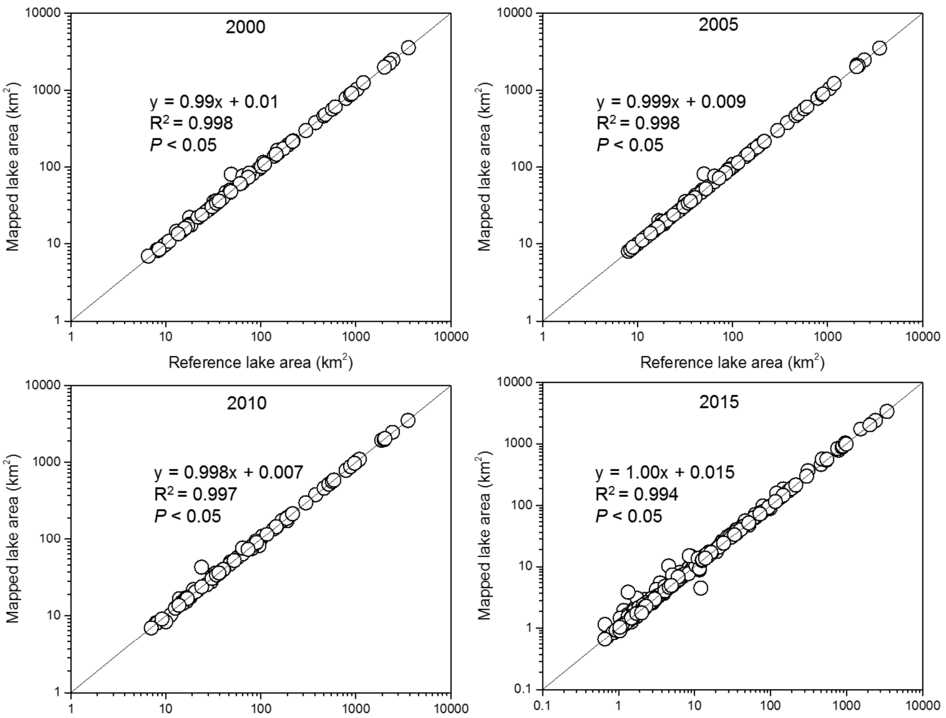

Figure 2. Comparisons of the mapped lake area in this study and the reference lake area delineated from Google Earth high-resolution images for the four episodes (i.e., 2000, 2005, 2010, and 2015).

Results and Discussion

Accuracy Validation and Comparison with Other Datasets

To assess the accuracy of the mapped lake area in this study, we collected the reference lake dataset by manual digitalization using the very high-resolution images available in Google Earth. Since high-resolution imaging satellites (e.g., GeoEye and Ikonos) started acquiring data after the late 1990s, the reference lake areas for 2000, 2005, 2010, and 2015 were available to validate the developed lake dataset. The 300 randomly sampled lake regions (water area ≥1 km^2) that represent the various lake classes and sizes were selected from our lake dataset. The comparisons between our mapped lake area and the reference lake area for the four episodes are shown in Figure 2, which exhibited high linear confidence of fit ($R^2 \geq 0.994$, $P < 0.05$). In addition,

Table 1. Overview of the multi-source datasets applied in this study.

Data category	Data source	Time span	Application in this study	Reference
Surface water	Global surface water datasets	1984–2015	Delineation of China's multi-temporal lakes	(Pekel *et al.,*, 2016)
Glacier area	Second Chinese Glacier Inventory	2006–2010	Extraction of glacier area over China	(Guo *et al.,*, 2015)
Climate	China Meteorological Administration	1985–2015	Measures of regional climate	-
Human activity	Statistical year books	1985–2015	Indicators of human activity	-

the developed lake datasets were further compared to another two datasets, including the national-level lake dataset produced by using Landsat TM/ETM+ images from 2005 to 2008 (Yang and Lu, 2014) and the regional-level lake dataset for the Tibetan Plateau between 1976 and 2013 (Zhang *et al.*, 2017a). The number and areas of the mapped lakes in this study were compared to the nationwide lake results for the episode of 2005 (Figure 3). In general, the datasets obtained in this study show relatively consistent results as compared to the datasets from the literature. Moreover, the lake datasets created by Zhang *et al.*(2017a) over the Tibetan Plateau using Landsat images between 1976 and 2013 were also used to validate the mapped lake results in this study. A relatively high agreement (0.86 ≤ R^2 ≤0.99, P <0.05) for the lake areas of the Tibetan Plateau (Zhang *et al.*, 2017a) and the lake results in this study for 1985, 1990, 1995, 2000, 2005, and 2010 can be seen in Figure 4. It should be noted that the slight discrepancy between the two datasets can be attributed to the different acquisition times of the source Landsat images. The validation and comparisons imply that the lake datasets developed in this study can provide a reliable basis for continuous monitoring of lake changes in China.

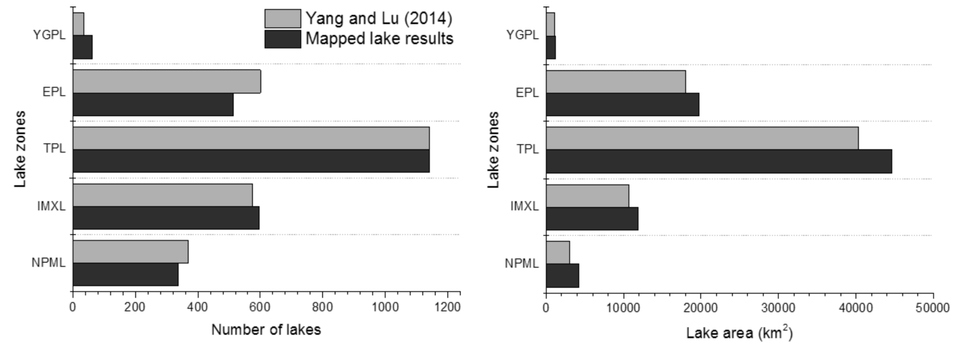

Figure 3. Comparisons between the number and areas of the national-level lakes (Yang and Lu 2014) and the lake results produced in this study for the episode of 2005.

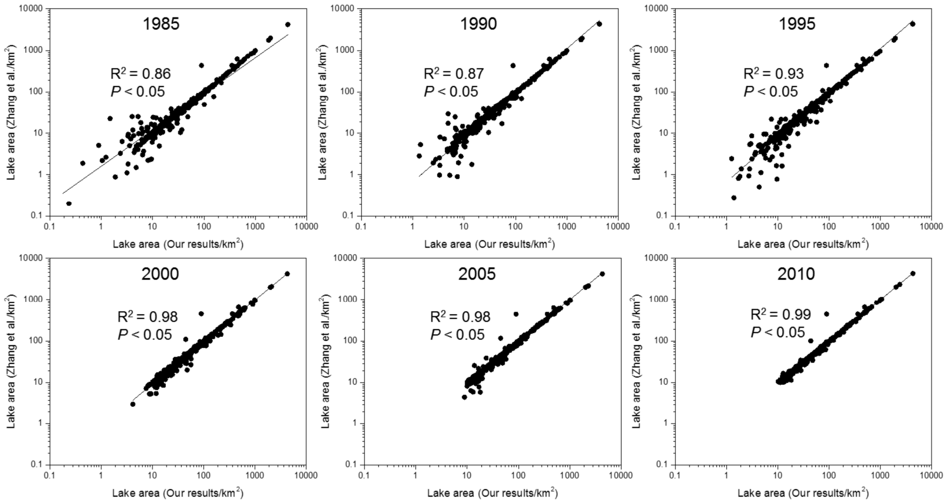

Figure 4. Comparisons between the lake datasets of the Tibetan Plateau (Zhang *et al.* 2017) and the lake datasets produced in this study for 1985, 1990, 1995, 2000, 2005, and 2010.

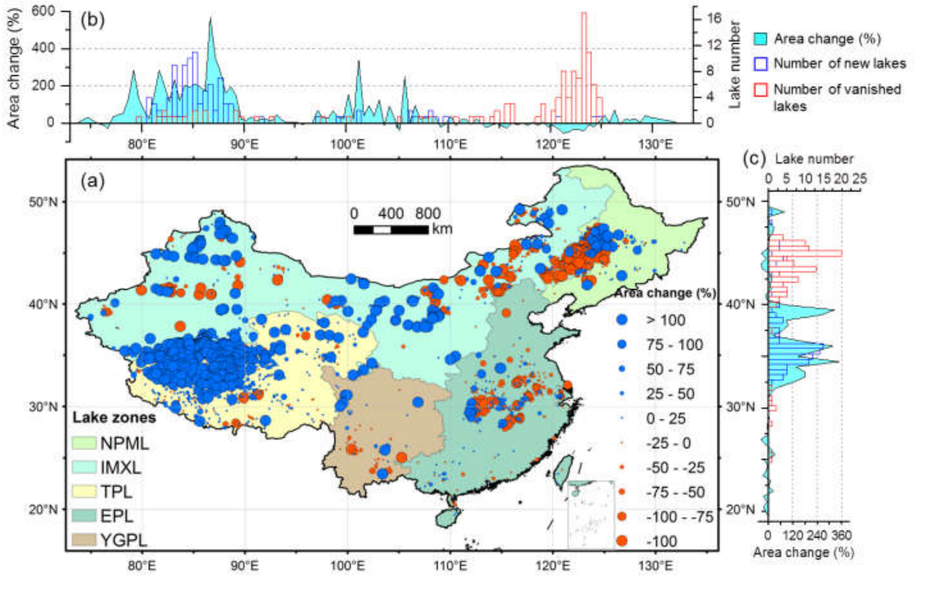

Figure 5. (a) Distribution of area changes in lakes (≥1 km²) between 1990 and 2015. The longitude (b) and latitude (c) summaries (an interval of 0.5°) of area changes in lakes, number of newly formed lakes, and number of vanished lakes are shown on the top and right, respectively.

Changes in the Area and Number of Lakes Over the Past Few Decades

The area and number of all the lakes in China between 1990 and 2015 are listed in Table 2. To facilitate the analysis of the changes in different-sized lakes, the lakes were divided into four groups: 1 to 10 km^2; 10 to 100 km^2; 100 to 1000 km^2; and >1000 km^2 (Ma *et al.*, 2010; Wang and Dou, 1998). A total of 2,924 lakes were detected across the entire country in 1990, of which the four groups occupied 79.8%, 15.8%, 4.0%, and 0.4%, respectively. Over the past 25 years, the total area of lakes has increased by 4616.7 ±296.3 km^2 (6.0 ±0.4%) while the number of lakes has experienced a net reduction of 5 (from 2,924 to 2,919), referring to 109 vanished lakes and 104 newly formed lakes (Table 2). Geographically, most of the vanished lakes are concentrated in Northeast China (120° to 125° E, 40° to 47° N), with 50 (45.9% in proportion) in the NPML and 49 (45.0% in proportion) in Inner Mongolia (Figure 5,

Table 2. Changes in number and surface area of lakes between 1990 and 2015. The uncertainties of lake surface areas are reported in the parentheses.

	1990		**2015**		**lake changes**	
lake class	**number of lakes**	**total area (km²)**	**number of lakes**	**total area (km²)**	**change in total area (km²)**	**change in total area (%)**
NPML						
1–10	422	1074.2(±10.4)	381	800.5(±10.4)	–273.7(±14.7)	–25.5(±1.4)
10–100	55	1460.2(±18.3)	49	1262.7(±19.7)	–197.5(±26.8)	–13.5(±1.8)
100–1000	6	1352(±25.9)	5	1214.4(±31.7)	–137.6(±40.9)	–10.2(±3.0)
>1000	1	1042.8(±6.7)	1	1043(±6.7)	0.2(±9.5)	0(±0.9)
All lakes	484	4929.1(±34.1)	436	4320.6(±39.3)	–608.5(±52)	–12.3(±1.1)
IMXL						
1–10	595	1479.6(±7.2)	594	1492.2(±12.7)	12.6(±14.6)	0.9(±1.0)
10–100	72	1820.3(±22.1)	78	2041.1(±18.2)	220.9(±28.6)	12.1(±1.6)
100–1000	12	4582.4(±41.6)	11	5242.3(±50.5)	659.9(±65.4)	14.4(±1.4)
>1000	2	3300.6(±24.1)	2	3111.5(±29.7)	–189.1(±38.2)	–5.7(±1.2)
All lakes	681	11182.8(±53.4)	685	11887.1(±62.7)	704.3(±82.3)	6.3(±0.7)
TPL						
1–10	797	1994.3(±9.2)	774	2355.8(±14.4)	361.5(±17.1)	18.1(±0.9)
10–100	230	8349.5(±25.9)	285	10018.1(±18.9)	1668.6(±32.0)	20(±0.4)
100–1000	73	19792.8(±58.7)	86	21405.9(±39.5)	1613.1(±70.7)	8.2(±0.4)
>1000	3	8160.7(±26.3)	5	10865.8(±22.0)	2705.1(±34.2)	33.1(±0.4)
All lakes	1103	38297.3(±69.9)	1150	44645.6(±51.1)	6348.3(±86.6)	16.6(±0.2)
EPL						
1–10	460	1343.4(±11.3)	466	1268.1(±17.7)	–75.3(±21.0)	–5.6(±1.6)
10–100	95	3041.4(±26)	86	2787.4(±27.1)	–254(±37.6)	–8.4(±1.2)
100–1000	23	6902.9(±107.3)	20	6441.8(±112.2)	–461.1(±155.3)	–6.7(±2.2)
>1000	4	10263.4(±128)	4	9268.5(±168.6)	–994.9(±211.6)	–9.7(±2.1)
All lakes	582	21551.1(±169.4)	576	19765.8(±205.1)	–1785.3(±266.0)	–8.3(±1.2)
YGPL						
1–10	60	110.3(±2.0)	58	109.1(±3.7)	–1.3(±4.2)	–1.1(±3.8)
10–100	11	354.1(±2.9)	11	316.9(±2.8)	–37.2(±4.0)	–10.5(±1.1)
100–1000	3	759.6(±5.0)	3	756(±4.5)	–3.6(±6.7)	–0.5(±0.9)
>1000	0	0	0	0	0	-
All lakes	74	1224(±6.1)	72	1182(±6.5)	–42(±8.9)	–3.4(±0.7)
China						
1–10	2334	6001.8(±19.4)	2273	6025.6(±28.3)	23.9(±34.3)	0.4(±0.6)
10–100	463	15025.5(±46.6)	509	16426.3(±42.6)	1400.9(±63.2)	9.3(±0.4)
100–1000	117	33389.6(±131.9)	125	35060.4(±133.1)	1670.8(±187.4)	5.0(±0.6)
>1000	10	22767.5(±133.0)	12	24288.8(±172.7)	1521.3(±218.0)	6.7(±1.0)
All lakes	2924	77184.4(±194.0)	2919	81801.1(±224.0)	4616.7(±296.3)	6.0(±0.4)

Table 3. The abundance distribution and area changes of the lakes (including vanished, shrunk, enlarged, and newborn lakes) in the five lake zones between 1990 and 2015.

	vanished lakes		shrunk lakes		enlarged lakes		newborn lakes	
	number	area (km²)	number	area (km²)	number	area (km²)	number	area (km²)
NMPL	50	128.5	281	675.2	153	192.2	2	3.0
IMXL	49	177.6	322	877.9	310	1637.3	53	122.5
TPL	2	3.1	134	613.8	947	6842.5	49	122.8
EPL	6	20.3	363	2059.5	209	294.4	0	0.0
YGPL	2	2.1	41	54.4	31	14.5	0	0.0
Total	109	331.6	1141	4280.7	1650	8980.8	104	248.3

Table 3). The newborn lakes mainly appeared in Xinjiang (53) and TPL (49), and to a smaller extent in West China (80° to 90° E, 33° to 40° N). Correspondingly, the TPL and IMXL zones also witnessed a large proportion of lake expansion, accounting for 57.4% and 18.8% of the 1912 enlarged lakes in China. In contrast, the shrunk lakes (1,141 in total) are observed primarily in the EPL (a proportion of 31.8%, particularly in the middle and lower Yangtze Basin), followed by the IMXL (28.2%) and NPML (24.6%) zones. The lakes in the EPL have experienced the most-serious decline (1,785.3 ±266.0 km²) while the largest increase of lake area (6,348.3 ±86.6 km²) has occurred in the TPL.

Temporal Evolution Patterns of Lakes from 1985 to 2105

To understand the temporal changes in the lakes, all the large lakes (≥10 km²) were investigated for the seven episodes, i.e., 1985, 1990, 1995, 2000, 2005, 2010, and 2015. Over the past three decades, the long-term evolution of the lakes in the NPML, EPL, and YGPL zones (Figure 6a, d, and e) has shown a significant decrease in surface area ($0.48 \le R^2 \le 0.91$, $p < 0.05$). In contrast, a notable increasing trend was found in the surface area of lakes in the IMXL ($R^2=0.66$, $p < 0.05$, Figure 6b) and TPL ($R^2=0.82$, $p < 0.05$; Figure 6c) zones, with an apparent increase in the period of 1995 to 2000. In the IMXL, an opposite trend of lake area changes appeared in Inner Mongolia

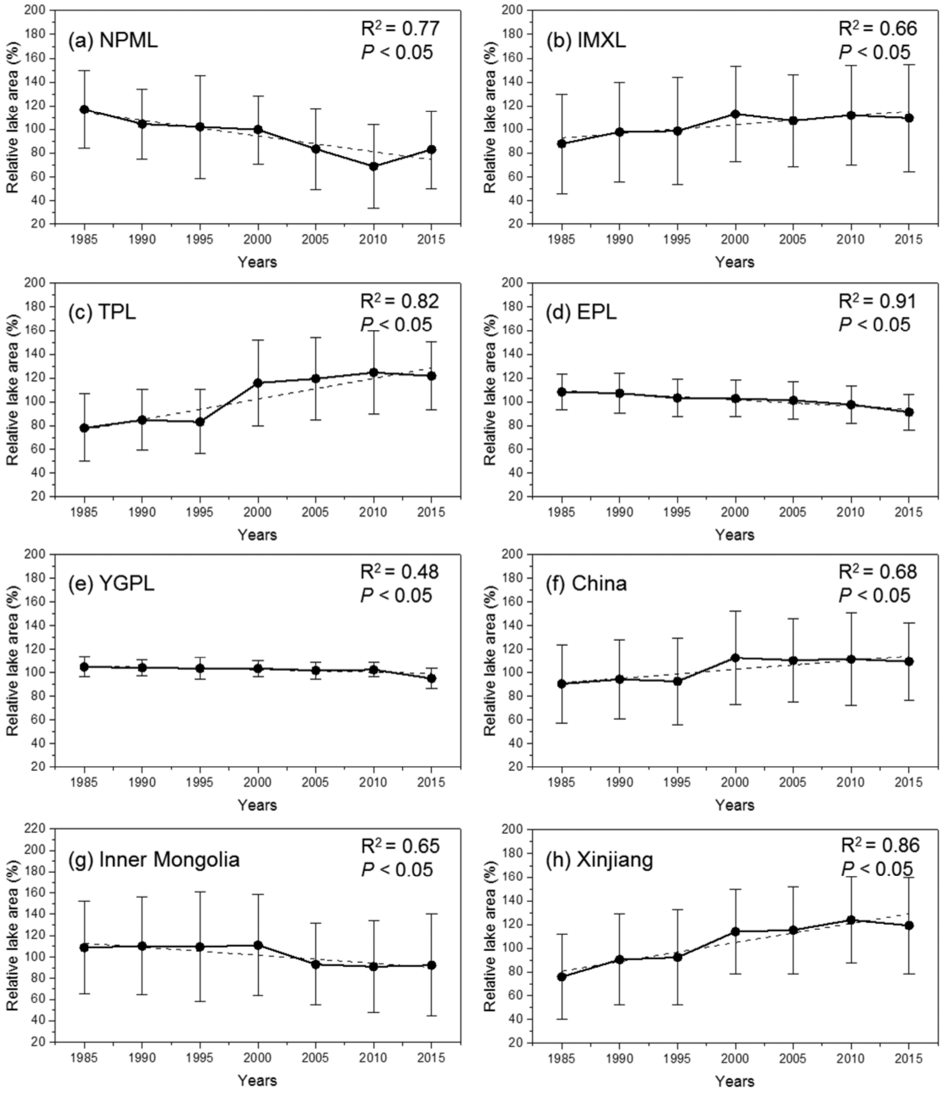

Figure 6. Temporal changes in the relative lake area in the (a) NPML, (b) IMXL, (c) TPL, (d) EPL, (e) YGPL, and (f) entire China from 1985 to 2015. The lake changes in the two adjacent regions in the IMXL, i.e., Inner Mongolia and Xinjiang, are also shown in (g) and (h), respectively. The mean lake area between 1985 and 2015 is used as the reference. Error bars indicate the standard error of changes in the large lakes (≥10 km^2). The goodness-of-fit of the least squares regression was assessed using the coefficient of determination R^2.

(downward trend, $R^2 = 0.65$, $p < 0.05$, Figure 6g) and Xinjiang (upward trend, $R^2 = 0.86$, $p < 0.05$, Figure 6h). The distinctly different patterns of lake area changes were also detected on the Tibetan Plateau and the Mongolian Plateau during the last four decades, with a significant inflection point of lake changes at 1997/1998 (Zhang *et al.*,, 2017a). The changing pattern (i.e., rapid expanding or shrinking) of lake area exhibited a strong spatial heterogeneity in a given lake-zone, which could result in a large variance of relative surface area of different lakes. The fluctuation in lake area could be related to the combined influence of climate change and human activities. Overall, the relative water area of the lakes across the entire China exhibited a prominent increase ($R^2 = 0.68$, $p < 0.05$, Figure 6f) during the period of 1985 to 2015.

Relationships Between Lake Changes and Driving Factors

To explore the possible driving forces of lake changes, correlation analysis was performed between the overall changes in the relative water area of lakes (≥10 km^2) and the climatic and human factors in the five lake zones from 1985 to 2015 (Table 4). Over the past 30 years, a consistent increase in human population and irrigated area (Figure 7c and d) has been observed in the NPML and EPL zones, showing a significant negative correlation ($P < 0.05$) with the area changes of lakes in both regions. As the major grain production bases in China, the NPML and EPL zones have experienced a rapid increase in the area of irrigated cropland (increased by 319.0% and 22.4%, respectively) from 1985 to 2015 (Figure 7d), resulting in the overexploitation of both surface water and groundwater resources for agricultural irrigation. For example, underground aquifers are the primary source of water for irrigation in the North China Plain, and the excessive irrigation has led to a rapid reduction in the groundwater depth from about 10 m below the ground in the 1970s to about 30 m in 2001 (Zhang *et al.*,, 2003). Therefore, irrigation water consumption is an important factor for the lake area decrease in these regions. Along with rapid population growth, the EPL has also witnessed unprecedented urban sprawl in recent decades, with a huge increase in built-up area from 5.2×10^3 km^2 in

Table 4. Correlation analysis on the relationship between overall changes in relative water area of lakes (≥10 km²) and climatic and human factors in the five lake zones from 1985 to 2015. Significant relationship was notated by asterisk signs (*P<0.05, **P<0.01).

						IMXL	
		NPML	EPL	YGPL	TPL	Xinjiang	Inner Mongolia
Method	Variable	r	r	r	r	r	r
Correlation analysis	AMT	-0.45	-0.65	-0.68	0.98**	0.66	-0.31
	AMP	0.07	-0.35	0.00	0.81*	0.92**	0.24
	Irrigation	-0.86*	-0.98**	-0.85*	0.79	0.70	-0.82*
	Coal production	-0.66	-0.80*	-0.85*	0.60	0.63	-0.84*
	Grazing	-0.85*	-0.27	-0.63	-0.13	0.73	-0.94**
	Built-up area	-0.90**	-0.92**	-0.81*	0.18	0.20	-0.70
	Floodgate	-0.88**	-0.89**	-0.96**	0.75	0.53	-0.41

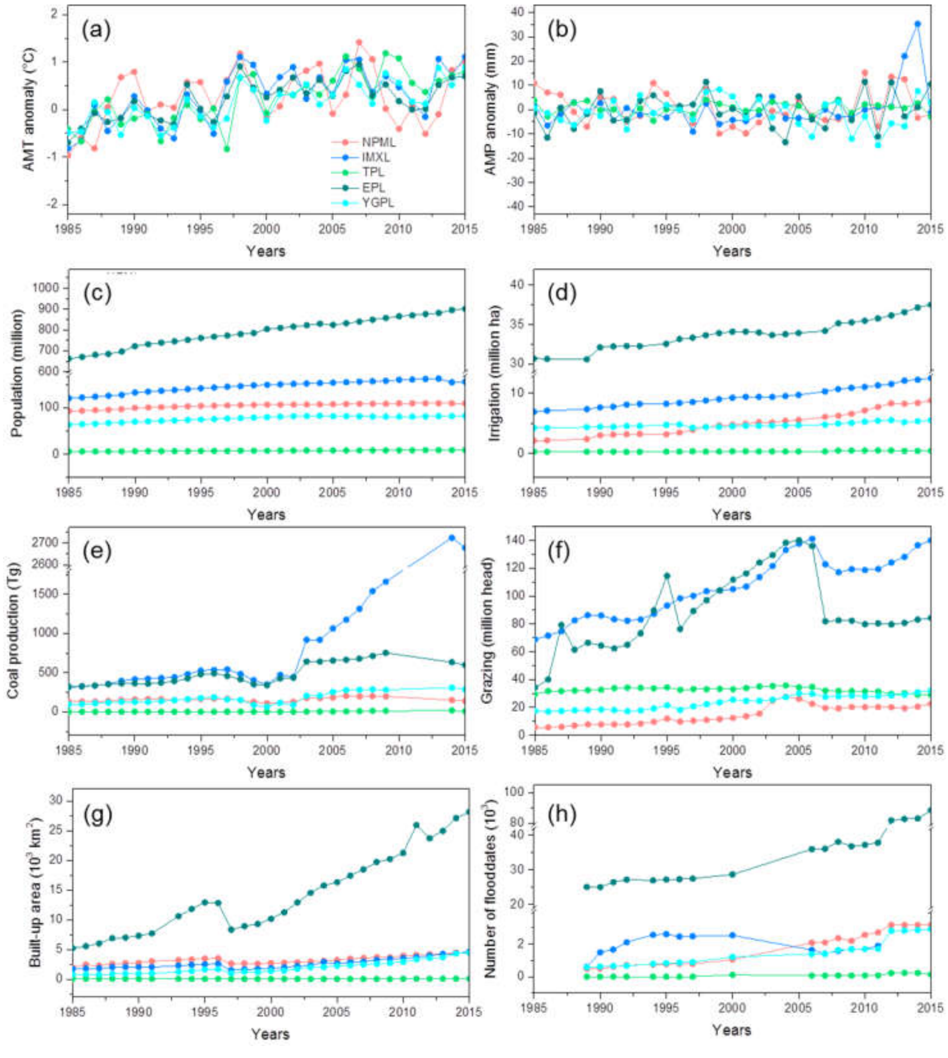

Figure 7. Changes in climate and human activities in the five lake zones (i.e., NPML, IMXL, TPL, EPL, and YGPL) during the past decades: (a) Annual mean temperature (AMT) anomaly, (b) annual mean precipitation (AMP) anomaly, (c) human population, (d) irrigated area, (e) coal production, (f) number of sheep and goats, (g) built-up area, and (h) number of floodgates.

1985 to 28.1 × 10^3 km² in 2015 (Figure 7g), which is significantly negatively correlated (P <0.01) with the area changes in lakes. The loss of lake area in the EPL, especially in the middle and lower Yangtze floodplain, can thus be largely attributed to intensive land reclamation for cultivation and human settlement (Ma *et al.*, 2010, Xie *et al.*, 2017). Additionally, strong inverse correlations are found between the number of floodgates and the relative water area of lakes in the NPML, EPL, and YGPL zones (P <0.01). The excessive construction of floodgates or dams on river systems has greatly altered the natural flow regimes of rivers through the artificial water regulation, and subsequently reduced the water discharged into lakes. For instance, more than 5,700 dams and 5,000 floodgates have been constructed in the Huai River Basin, with a drainage area of 2.7×10^5 km^2 in the eastern China, and most rivers are now regulated by water projects, resulting in dramatic changes in the hydrological regimes and increased pollution discharge (Zhang *et al.*, 2010). Consequently, the extensive water project construction has played an important role in affecting the lake changes in these areas.

In contrast, significant positive correlations are traced between climatic factors (e.g., annual mean precipitation and temperature) and the lake changes in the TPL ($P < 0.05$). Over the past few decades, an increase of precipitation has been observed in the Inner Tibetan Plateau based on a high-resolution regional climate simulation (Gao *et al.*, 2015), and the cumulative net precipitation (precipitation minus evapotranspiration) has also shown an apparent increasing trend since 1998 (Zhang *et al.*, 2017a). The increased precipitation (snowfall and rainfall) is an important source of water for the lakes on the Tibetan Plateau, and has contributed to the increase in water level, particularly for the salt lakes in closed basins (Zhang *et al.*, 2011). For example, Qinghai Lake, China's largest lake within a closed basin, experienced a continuous increase in surface area (increased by 153.9 km^2) from 2006 to 2015, which was primarily associated with precipitation and evaporation (Cui *et al.*, 2017; Li *et al.*, 2007). Similarly, the air temperature records from the available meteorological stations in the TPL have indicated an obvious increase in temperature ($P < 0.05$, Figure 7a), which is highly correlated with the lake area change patterns ($P < 0.01$). The climate on the Tibetan Plateau has been experiencing drastic changes during the past three decades, with a rapid warming trend (0.3°C per decade) at the altitudes above 4,000 m, which is twice the rate of observed global warming (Xu *et al.*,, 2009). The climate warming has exerted a great influence on the cryosphere and hydrological cycle, including accelerated glacier/snow melting and permafrost degradation (Li *et al.*, 2014, Neckel *et al.*, 2014), which has contributed to the rapid enlargement of lakes (Zhang *et al.*, 2017a).

According to the Second Chinese Glacier Inventory, the glacier/snow covers of the Tibetan Plateau decreased by 9.5 to 26% between the 1970s and 2010 (Guo *et al.*, 2015). Selin Co, the largest salt water lake in Tibet, expanded rapidly from 1975 to 2008, with an area increase of 420 km^2/10a on average, which was mainly due to the increase in melt water from the mountainous glaciers/snow under the background of global warming (Duo *et al.*,, 2010).

North China, especially Xinjiang and Inner Mongolia, is characterized by an arid and semiarid climate with low annual precipitation and high annual total solar radiation (Xie and Wang, 2007; Yang *et al.*, 2003). Air temperature and precipitation have displayed an increasing tendency since the 1980s in the northwestern China, suggesting a climatic shift to a warm humid pattern in this region (Shi *et al.*, 2003). A significant positive relationship can be observed between the annual mean precipitation and lake area changes ($P < 0.01$) in Xinjiang, which is located in the hinterland of the arid areas in Northwest China. Moreover, anthropogenic activities, such as increased water consumption by agricultural irrigation, have also played a role in influencing the lake changes in Xinjiang. For example, the Tarim River Basin, located in the southern Xinjiang, experienced rapid population growth (increased by 183.3%) and accelerated expansion of cultivated land (increased by 70%) from 1949 to 2000, posing great threat to the natural riparian ecosystems (Chen *et al.*, 2011; Zhang *et al.*, 2010). In addition, the decreasing trend of the total lake area in Inner Mongolia is significantly associated with intensive human activities, including agricultural irrigation, coal mining, and grazing ($P < 0.05$). Over the past 30 years, the area of irrigated cropland in Inner Mongolia has increased by 218.6% (from 9.7×10^3 km^2 to 30.9×10^3 km^2), resulting in the overexploitation of groundwater and river water in this region. The expansion of cultivation and the increasing number of livestock (including sheep, goat, and cattle) have also led to the degradation of the typical steppe ecosystem distributed throughout Inner Mongolia, affecting the soil function and water conservation of grasslands (Sasaki *et al.*, 2008; Schönbach *et al.*, 2011). For example, the total area of degraded steppe due to overgrazing expanded by 498.3 km^2 or 6.9% from 1985 to 1999 in Xilin River Basin (Tong *et al.*, 2004). Moreover, the coal production in Inner Mongolia showed an abrupt increase after the year 2000, accompanied by the rapid decline in lake area. Coal industry is highly water intensive, which needs large volumes of water for mining activities (consuming 2.54 m^3 of water to mine every ton of coal), and also impacts the local water balance, leading to groundwater level declining, water and soil loss, and land desertification (Pan *et al.*, 2012; Zhang *et al.*, 2013). Along with the rapid progress of industrialization in China, the water demand in the coal industry could dramatically increase, posing serious threats to the local environment and water system in the ecologically fragile regions (Pan *et al.*, 2012).

Limitations and Future Work

In this study, we investigated the spatiotemporal changes in the lakes across the entire China and the climatic/anthropogenic drivers from 1985 to 2015. To provide a quantitative understanding of driving factors, correlation analysis between climatic/human factors and lake changes was performed. However, the correlation analysis may induce some potential uncertainties in estimating the relationship between lake changes and driving factors. First, correlation analysis was performed at the aggregated scale over the five lake zones, which could be subject to modifiable areal unit problem (MAUP) or ecological fallacy (Fotheringham and Wong, 2015). Ideally, correlation analysis between area change of each lake and the associated human/climate factors can provide more details in the analysis of driving factors. Due to the limited data availability of human factors (i.e., irrigation area and coal production) for an individual lake, the correlation analysis was conducted over the five typical lake-zones based on the climatic, geographic, and socioeconomic conditions across China.

Moreover, since the diverse climatic/human factors have driven profound influence on the lakes across China, the direct causal-effect between lake changes and driving factors could be difficult to be indicated by correlation analysis. Although most of the driving factors used in this study were collected following the previous studies (Ma *et al.*, 2010; Tao *et al.*,, 2015), more climatic/human variables are needed to explain the dynamic patterns of China's lakes. The dynamic lake systems in China have been suffering from dramatic changes under various natural and anthropogenic impacts. Simple correlation analysis may be not capable of modeling the complex relationship between lake changes and driving factors. Additionally, to avoid the lag impacts of temperature or precipitation on lake area, more subtle monitoring of lake changes at a one-year interval using accumulated precipitation and average temperature could be performed. Therefore, the detailed investigations of spatiotemporal pattern (intra-year or inter-year scale) of lake changes and the exact driving forces by using more complete remote sensing observations and natural and socio-economic data are still required in the targeted research. At present, the quantitative information about the long-term evolution patterns of the nationwide lakes and the associated driving forces still remains unclear. In this study, the quantitative evaluation of the dramatic lake changes in the entire China and the possible driving factors provides a crucial basis for continuous investigation and protection of the dynamic lake systems.

Conclusions

In this study, we conducted a national-scale investigation of the current distribution and long-term evolution patterns of all the lakes across the entire China from 1985 to 2015. Furthermore, we also explored the relationships between the lake changes and possible climatic/anthropogenic factors. Our results indicate that dramatic changes have occurred to the lakes in China over the past three decades, involving a significant number of disappeared lakes in Northeast China but also newly emergent lakes on the Tibetan Plateau. Specifically, the TPL and Xinjiang have experienced extensive lake expansion over the last few decades, due to increased precipitation and glacier/snow melting under climate warming. In contrast, a marked decreasing trend in lake area has occurred in the eastern and northeastern China and Inner Mongolia, which is mainly associated with intensive human activities (e.g., increasing population, excessive irrigation, overgrazing, coal mining, urban expansion, and water projects construction). The comprehensive documentation of the dramatic lake changes in the whole of China and the possible driving factors may serve as baseline data to understand the dynamic lake system of China in a changing climate.

Acknowledgments

The research was supported by the National Natural Science Foundation of China under Grants 41522110 and 41771360, the Hubei Provincial Natural Science Foundation of China under Grant 2017CFA029, and the National Key Research and Development Program of China under Grant 2016YFB0501403.

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