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Extreme Climate Anomalies Enhancing Cyanobacterial Blooms in Eutrophic Lake Taihu, China

Boqiang Qin[1,2], Jianming Deng[1], Kun Shi[1], Jia Wang[3], Justin Brookes[4], Jian Zhou[1], Yunlin Zhang[1], Guangwei Zhu[1], Hans W. Paerl[5,6], and Li Wu[7]

[1]State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, China, [2]School of Geography & Ocean Science, Nanjing University, Nanjing, China, [3]Great Lakes Environmental Research Laboratory, NOAA, Ann Arbor, MI, USA, [4]Water Research Centre, School of Biological Science, University of Adelaide, Adelaide, SA, Australia, [5]The University of North Carolina at Chapel Hill, Institute of Marine Sciences, Morehead City, NC, USA, [6]College of Environment, Hohai University, Nanjing, China, [7]Key Laboratory of Earth Surface Processes and Regional Response in the Yangtze-Huaihe River Basin, School of Geography and Tourism, Anhui Normal University, Wuhu, China

Key Points:
- High rainfall in 2016 and warm winter in 2016/2017 in Lake Taihu was caused by a strong 2015/2016 El Niño and Atlantic Multi-decadal Oscillation and Pacific Decadal Oscillation
- Warm winter in combination with high precipitation greatly promote phytoplankton proliferation and intense blooms in 2017 in Lake Taihu
- Intense blooms led to high pH and dissolved oxygen depletion and further mobilized phosphorus from the sediment to promote blooms

Supporting Information:
Supporting Information may be found in the online version of this article.

Correspondence to:
B. Qin,
qinbq@niglas.ac.cn

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Author Contributions:
Conceptualization: Boqiang Qin, Jianming Deng
Data curation: Boqiang Qin, Jianming Deng, Kun Shi, Jia Wang, Justin Brookes, Jian Zhou, Yunlin Zhang, Guangwei Zhu
Formal analysis: Boqiang Qin, Jianming Deng, Jia Wang
Funding acquisition: Boqiang Qin
Methodology: Boqiang Qin, Jianming Deng, Jia Wang
Writing – original draft: Boqiang Qin, Jianming Deng
Writing – review & editing: Kun Shi, Jia Wang, Hans W. Paerl, Li Wu

Abstract

Climate warming in combination with nutrient enrichment can greatly promote phytoplankton proliferation and blooms in eutrophic waters. Lake Taihu, China, is a large, shallow and eutrophic system. Since 2007, this lake has experienced extensive nutrient input reductions aimed at controlling cyanobacterial blooms. However, intense cyanobacterial blooms have persisted through 2017 with a record-setting bloom occurring in May 2017. Causal analysis suggested that this bloom was sygenerically driven by high external loading from flooding in 2016 in the Taihu catchment and a notable warmer winter during 2016/2017. High precipitation during 2016 was associated with a strong 2015/2016 El Niño in combination with the joint effects of Atlantic Multi-decadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO), while persistent warmth during 2016/2017 was strongly related to warm phases of AMO and PDO. The 2017 blooms elevated water column pH and led to dissolved oxygen depletion near the sediment, both of which mobilized phosphorus from the sediment to overlying water, further promoting cyanobacterial blooms. Our finding indicates that regional climate anomalies exacerbated eutrophication via a positive feedback mechanism, by intensifying internal nutrient cycling and aggravating cyanobacterial blooms. In light of global expansion of eutrophication and blooms, especially in large, shallow and eutrophic lakes, these regional effects of climate anomalies are nested within larger scale global warming predicted to continue in the foreseeable future.

Plain Language Summary

Climate warming in combination with eutrophication can greatly promote algal blooms (algal scum aggregate at water surface) in eutrophic waters. But we know little of resultant response of algal bloom occurrence. Utilizing Lake Taihu, China, we examined how a large, shallow eutrophic system responds to extreme climate anomalies such as winter warmth and heavy rainfall. Intense algal blooms have persisted through 2017, after a decadal intensive effluent control. Causal analysis suggested that this bloom was synergistically driven by high external loading from flooding in 2016 and a notable warmer winter during 2016/2017, which were associated with a strong 2015/2016 El Niño, and joint effects of Atlantic Multi-decadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO), whilst persistent warmth during 2016/2017 was strongly related to warm phases of AMO and PDO. Intense blooms led to water column pH increase and dissolved oxygen depletion near the bottom, both of which mobilized phosphorus from the sediment to overlying water and promoting algal blooms. Our finding indicates that regional climate anomalies exacerbated eutrophication via a positive feedback mechanism, by intensifying internal nutrient cycling and aggravating algal blooms.

1. Introduction

Eutrophication and harmful algal blooms (HABs) are a world-wide proliferating environmental issue (S. Wang et al., 2018). Anthropogenic nutrient enrichment and climate change are two major drivers, determining the magnitude, extent and persistence of cyanobacterial blooms (Paerl et al., 2020). While nutrient over-enrichment is the chief cause of eutrophication and nuisance cyanobacterial blooms (Brookes & Carey, 2011), climate warming frequently enhances the dominance of cyanobacteria and further accelerates eutrophication (Rigosi et al., 2014). Global warming and altered precipitation patterns are projected to aggravate eutrophication at continental scale in the future (Sinha et al., 2017), and is a key management challenge facing eutrophic waters.

Lake eutrophication and harmful algal blooms are severe in China, particularly in the lakes from the middle and lower reaches of the Yangtze River (MLRYR) (Guan et al., 2020; Qin et al., 2013). The number of lakes from MLRYR accounts for ca. 60% of total number of freshwater lakes in China (Wang & dou, 1998), and all lakes are characterized by shallow depth. Lake eutrophication in this area are mainly induced synergistically by anthropogenic nutrient emission and climate warming (Guan et al., 2020; Qin et al., 2010). In addition, this area experience a monsoonal climate with humid and hot summer, and dry and cold winter, while the climate anomalies of this region are often intimately linked to the variability of global scale atmospheric-oceanic interactions (Li et al., 2019). Long-term observations suggested the warming trend since the beginning of last century in China is estimated higher than the global mean of temperature increase (Z. Yan et al., 2020), implying the influence of climate change tends to be more significant (Yang et al., 2016).

Lake Taihu is a large, shallow, and eutrophic lake situated in the delta of the Yangtze River which is one of the most industrialized and urbanized areas in China. This lake has experienced an extensive restoration since the drinking water crisis in 2007. However, a record-setting cyanobacterial bloom occurred in May 2017 and intense bloom persisted throughout 2017 in Lake Taihu (Qin et al., 2019), which cannot be explained simply by a climate warming or nutrient enrichment. As the external loading in 2017 was not the highest, we hypothesize that the severe cyanobacterial bloom in 2017 is resulted from a combination effects of intense internal nutrient loading with climate anomalies caused by global scale, inter-annual, decadal or multi-decadal external climate forcings such as El Niño events, Atlantic multidecadal oscillation (AMO), Pacific decadal oscillation (PDO), North Atlantic Oscillation (NAO) and Arctic Oscillation (AO). There are few studies have addressed such combination effects on the phytoplankton proliferation in inland waters. We tested this hypothesis by documenting: (a) what were the main drivers of severe blooms which occurred in 2017 in Lake Taihu, and (b) whether bloom persistence in 2017 were associated with a combination of internal nutrient loading and climate anomalies during 2016/2017.

2. Materials and Methods

2.1. Lake Taihu

Lake Taihu, is China's third largest freshwater lake (2,338 km^2), located in a large, heavily-urbanized (>40 million inhabitants) catchment (~36,500 km^2) in the Yangtze River Delta region (Figure 1). Prevailing southeasterly monsoonal winds during summertime concentrate nutrients discharged from northwestern watershed and cyanobacterial blooms in the northwestern region of lake. Since the 1990s, this shallow (max depth <3 m) eutrophic lake has experienced accelerated eutrophication accompanied by toxic cyanobacterial blooms (*Microcystis* spp.), especially in the highly eutrophic northern bays or northwestern coastal zone areas that are subjected to prevailing southeasterly, onshore winds in the summer, and receive the most external pollutants from the watershed (Qin et al., 2007). In May 2007, a massive bloom overwhelmed the lake's drinking water plants, leaving millions of local residents of Wuxi City without potable water for nearly a week (Guo, 2007). Since the drinking water crisis, Taihu has been the site of intensive restoration efforts. A series of countermeasures, including effluent diversion, flushing and dredging, were implemented, but little improvement of water quality has achieved (Qin et al., 2019).

2.2. Cyanobacterial Bloom Monitoring

Because of the high spatial heterogeneity of cyanobacterial blooms in Lake Taihu, we used remote sensing imagery to map the spatial distribution of the bloom. Due to the inherent problems in atmospheric correction and bio-optical inversion algorithms for inland waters, variable aerosols, cloud cover, and wind speed (turbulent entrainment to make algal bloom migration downward), and other nonliving constituents (e.g., tripton, colored dissolved organic matter [CDOM], suspended sediments and shallow bottom) can significantly affect the remote sensing signal, especially for the case of Lake Taihu. These deviations have been minimized by selecting the bands between red and near-IR and algorithm, and the statistical reliability of long-term monitoring data was evaluated by Hu et al. (2010). Such deviation was evaluated against the

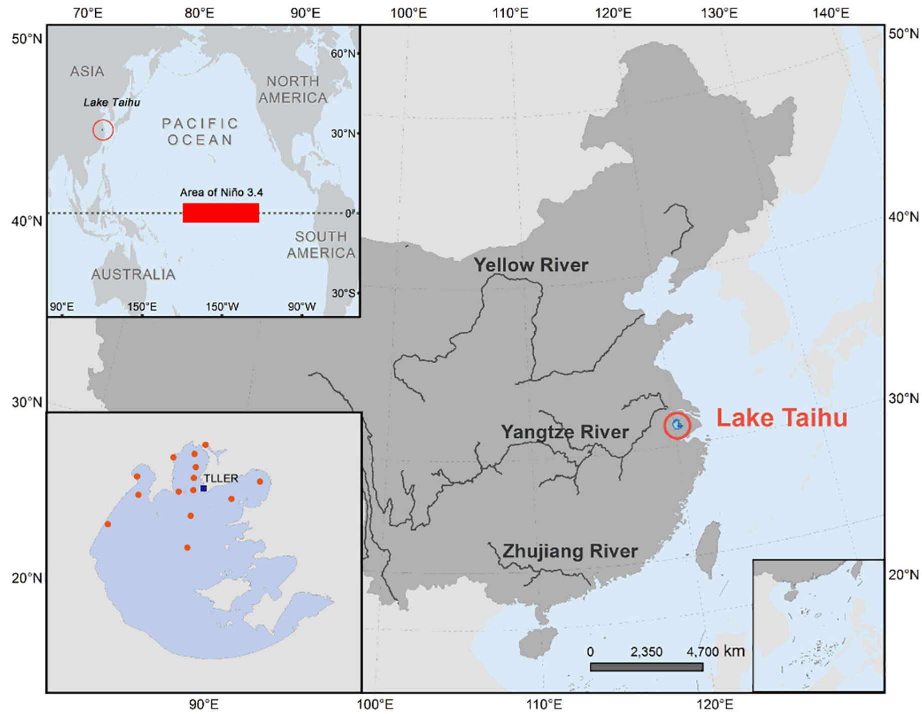

Figure 1. Location of Lake Taihu (main part of map), monthly sampling sites in the northern lake (red dot, low left corner) and location of Taihu Laboratory for Lake Ecosystem Research (TLLER), Chinese Academy of Science, and location of Lake Taihu and defined area of Nino 3.4 at equatorial Pacific (upper left corner).

concurrent in-situ measurements, and the results showed that relative error (RE) ranged from 0.4% to 64.5% with a mean absolute percent error (MAPE) of 27.1%, and root-mean-square error (RMSE) values between the measured and predicted values were 15.01 μ g/L (Shi et al., 2017).

Bloom area was retrieved from satellite imagery by utilizing Moderate Resolution Imaging Spectroradiometer (MODIS) reflectance data corrected for Rayleigh scattering to establish a cyanobacterial floating algae index (FAI) (Hu et al., 2010). Index FAI >-0.004 was defined as the threshold value for determining a cyanobacterial bloom. MODIS images with 250 m spatial resolution data were downloaded from the NASA EOS data gateway, which has been available since 2003. The bloom occurrence frequency was defined as the number of images with bloom as a percentage of total number of images. The bloom start dates for each year were calculated as the date when daily chlorophyll *a* concentration (Chl*a*) MODIS-derived reached the background median concentrations +5% (Shi et al., 2019).

2.3. Observations of Phytoplankton Biomass and Water Quality Parameters as Well as Riverine External Loading

Phytoplankton biomass, indicated as Chl*a* concentration, was monitored monthly along with total nitrogen (TN), total phosphorus (TP), concentrations and pH. There are 14 monthly sampling sites located in the northern lake where cyanobacterial blooms frequently occur due to the summer prevailing southeastern wind (Figure 1). Monthly observations of Chl*a*, TN, TP concentrations, and pH have been conducted by the Taihu Laboratory for Lake Ecosystem Research (TLLER) since 1991. Water samples from the surface, middle and bottom at each site were mixed to represent an integrated water column sample. Dissolved oxygen (DO) concentrations near the bottom were measured every 30 min with YSI-6600 sonde which was deployed at the end of pier (ca. 300 m from lakeshore) in TLLER. The measurements were started in 2008 and terminated near the end of 2016 due to equipment failure. Although we have only one site with near-bottom DO observation for exploring the relationship between cyanobacterial bloom and DO depletion, this location is right in bloom prevailing zone (Wu et al., 2018).

Riverine input of nutrients in Lake Taihu is a dominant fraction of external loading (Zhai et al., 2020). Riverine loadings of nitrogen and phosphorus have been measured since 2006 by Taihu Basin Authority, Ministry of Water Resources of China, based on observations of flow rate and nutrient concentration of ca. 70 rivers in which 22 large rivers (accounting for ~80% of annual inflow and external nutrient loading) are monitored regularly. Selection of cross-section of river, flow rate measurement instrument and flow rate calculation follow the national standard (Ministry of Housing and Urban-Rural Development of China (MHURD), 2015), which can guarantee the observational deviation of flow rate <10%. Water samples were taken synchronously during flow rate measurement.

Chlorophyll *a* (Chl*a*) concentration was measured using spectrophotometry at wavelengths of 665 and 750 nm, following extraction with hot 90% ethanol (Lorenzen, 1967). TN and TP concentrations were determined by spectrophotometry after digestion with alkaline potassium persulfate (Ebina et al., 1983). Mean TN, TP, and Chl*a* concentrations were obtained by averaging over the northern lake.

2.4. Hydrology and Meteorology Parameters in Association With Teleconnective Climate Indices

External loading is strongly associated with rainfall and runoff (Daloglu et al., 2012; Williams & King, 2020), which are intra-annually distributed in three periods, that is, low precipitation period from January to April (before flood season), the rainy period from May to September (flood season), and the dry period from October to December (dry season). Phytoplankton growth rate is related to the thermal condition of lake (Paerl et al., 2011), especially the winter warmth in the subtropical lakes (J. M. Deng et al., 2014; Ma et al., 2016). Long-term observations of precipitation and air temperature in the Taihu Basin were collected at the Wuxi Meteorological Station (nearby Lake Taihu).

Local climate anomalies of Taihu basin are strongly influenced by a number of interannual or interdecadal and globally climatological forcings, including El Niño, PDO, AMO, NAO, and AO (Wang & Yang, 2017; Y. L. Zhu et al., 2011), etc. An El Niño episode is identified by a sea surface temperature (SST) anomaly of 0.5°C above baseline persisting for 5 months over the equatorial Pacific Ocean (5°N–5°S and 170°–120°W, known as Niño 3.4 index). The PDO is defined by the leading pattern (EOF) of sea surface temperature (SST) anomalies in the North Pacific basin (typically, polewards of 20°N). The AMO has been identified as a coherent mode of natural variability occurring in the North Atlantic Ocean. It is based on the average anomalies of sea surface temperatures (SST) in the North Atlantic basin, typically over 0°–80°N. The NAO index is the difference in normalized sea level pressures between Ponta Delgadas (Azores) and Akureyri (Iceland). AO index is defined as the first leading mode from the EOF analysis of monthly mean height anomalies at 1,000-hPa, and normalized by the standard deviation of the monthly index. For statistical telecorrelation analysis, time series of El Niño and Southern Oscillation (ENSO), PDO, AMO, NAO, and AO indices were collected at https://psl.noaa.gov/data/climateindices/list/.

2.5. Statistical Analysis

Long-term trends of MODIS-derived blooms events (bloom areas, frequency, start dates) were evaluated by generalized additive models (GAMs) according to Harding et al. (2016). GAMs were also used in order to explore the relationships between climate forcings, nutrients, Chl*a* concentrations and bloom intensities, based on the daily, monthly or yearly observations. The significance level (p) of the statistical tests were examined at two levels: $p < 0.05$ and $p < 0.01$. Occurrence probability of yearly mean bloom area, frequency and start date were determined by fitting probability distribution whose density functions (kernel density estimates) were first developed by *density* function in R 3.6.1(R Core Team, 2019), and then cumulative probability were calculated based on the probability density functions.

3. Results

3.1. Variation of Cyanobacterial Blooms During 2006–2018

The bloom extent and frequency in Lake Taihu have increased recently (Figures 2a and 2b). The unprecedented intensive blooms occurred in 2017, evidenced by the largest annual mean area and highest frequency

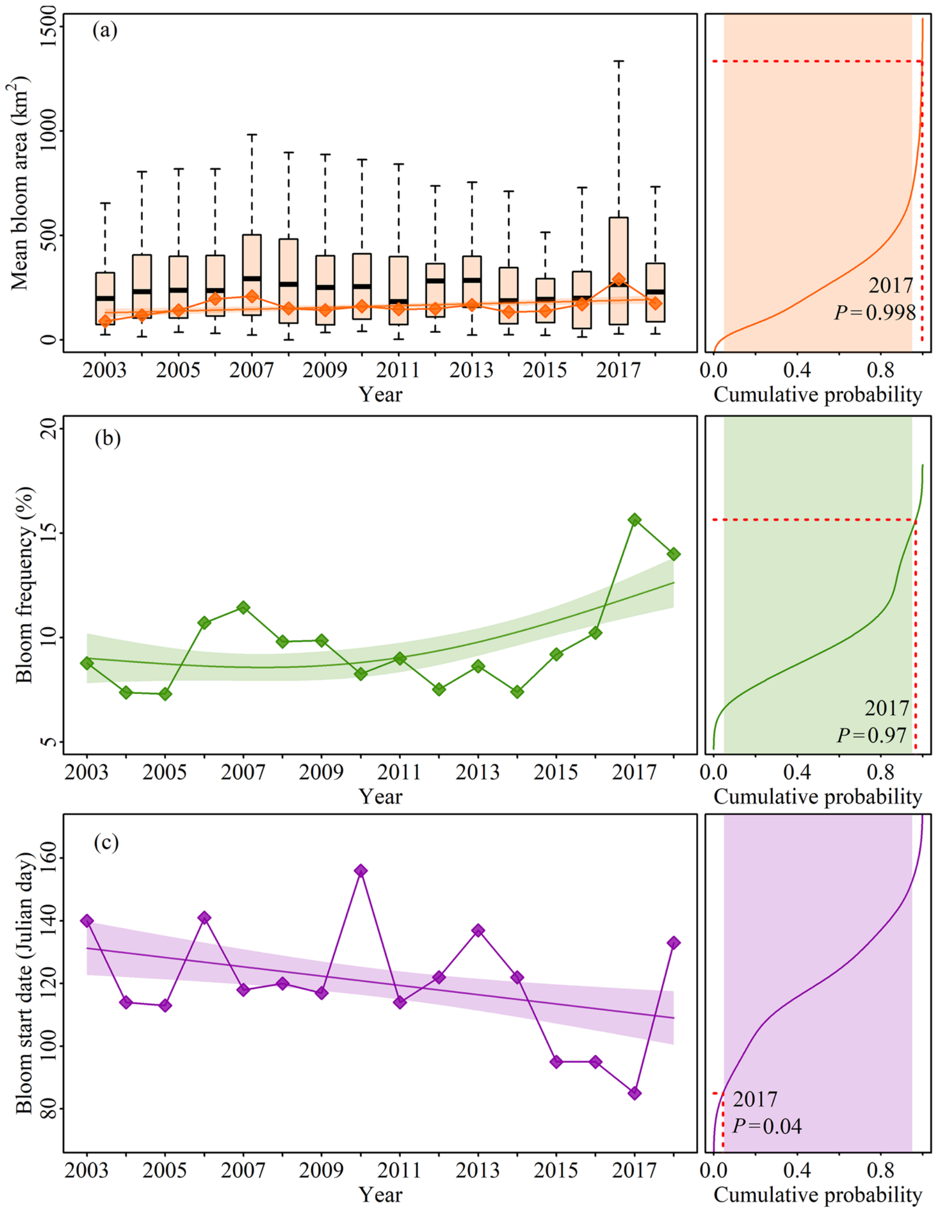

Figure 2. Bloom events in Lake Taihu from 2006 to 2018. (a) Mean surface areas of cyanobacterial blooms derived from Moderate Resolution Imaging Spectroradiometer satellite imagery; (b) Annual occurrence frequency (the number of bloom images in percentage of total detectable images); (c) Annual bloom start dates (Julian day). Solid lines in the left panels indicate long-term trends estimated by generalized additive models (GAMs, $N = 13$), and shading indicates the standard error of the estimates. The cumulative probability for bloom area, frequency and start date are presented in the right panels. The shadows indicated cumulative probability range from 0.05 to 0.95. The red dash lines are the 2017 value.

of blooms (Figures 2a and 2b). A record-setting bloom area was observed as large as 1,582 km^2 on May 16, 2017, covering nearly 70% of the lake surface. In addition, the bloom start date in 2017 was the earliest observed during the 2006–2018 period (Figure 2c). According to cumulative distribution curves (Figure 2, right panel), the probability of bloom area, frequency and start date in 2017 were 0.002, 0.04, and 0.04, respectively, indicating that the severe blooms in 2017 were extremely rare in this lake during 2006–2018. Large bloom areas persisted throughout the summer and autumn, rendering the mean algal blooms in 2017 to be the largest over 2006–2018.

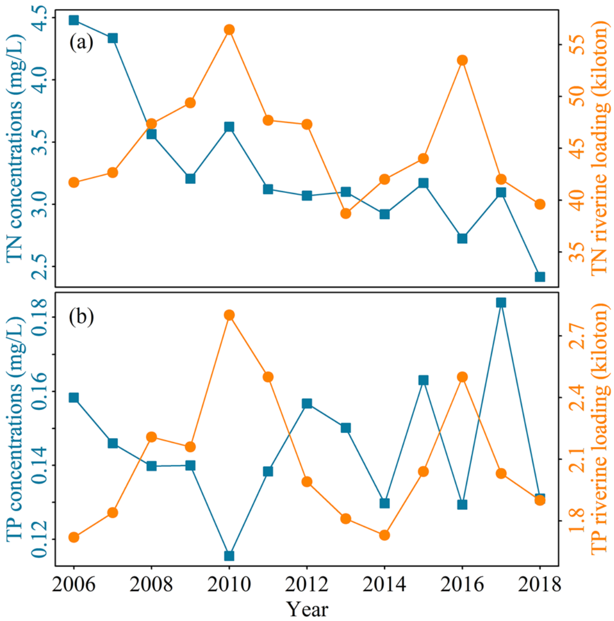

Figure 3. Annual mean total nitrogen (TN) and total phosphorus (TP) concentrations in the water column (blue line) and annual riverine external loading (orange line) to Lake Taihu from 2006 to 2018. (a) TN concentrations and riverine loading N; (b) TP concentrations and riverine loading TP.

3.2. Changes in Nutrient Concentrations and External Loading During 2006–2018

Based on monthly monitoring of Chla, total nitrogen (TN) and total phosphorus (TP) in the northern lake, Chla was not correlated with TN ($r^2 = 0.005$, $p > 0.05$) (Figure S1a) but significantly correlated with TP ($r^2 = 0.3$, $p < 0.01$) (Figure S1b). Averaged TN to TP mass ratios of each month over the period 1992–2018 indicated that TN:TP mass ratio decreased from ca. 50 in April to 12.4 in September (Figure S2), which further illustrated that phytoplankton production in Lake Taihu was P limited in spring and P and N colimited during summer and autumn (Guildford & Hecky, 2000; Xu et al., 2010). In addition, TN has declined significantly from 4.82 to 2.50 mg/L since 2006 ($p < 0.01$, Figure 3a), while TP has fluctuated without a trend during 2006–2010 and increased after 2010 with a peak in 2017 (Figure 3b). It is noteworthy that the highest and the second highest riverine loadings of both TN and TP were in 2010 and 2016, respectively (Figures 3a and 3b), while the yearly mean TP concentration peaked in 2017 at 0.20 mg/L (Figure 3b), which was much higher than mean concentration 0.14 mg/L over 2006–2018. This suggested that both TN and TP were not responsive to external loading due to the complex influence of in-lake biogeochemical processes such as denitrification, nutrient regeneration and mobilization from sediment (i.e., internal loading).

3.3. Rainfall and Temperature Anomalies in Association With Phytoplankton Biomass and Cyanobacterial Blooms in Lake Taihu

Anthropogenic climate change exerts bottom-up influence on phytoplankton community through changes in precipitation that affect riverine nutrient inputs, and increases in temperature that affect cyanobacterial growth rates. Long-term observations of rainfall have shown an increase of annual precipitation since the 1950s in the Taihu basin (Figure S3). A heavy flood occurred in 2016 (Figure S3), resulting in the water level in Lake Taihu reaching its second highest value since the 1950s. Meanwhile, long-term observations indicated that winter and spring surface air temperatures have risen since 1950s (Figure S3). The average winter air temperature of 2016/2017 has been the highest since 1950s (Figure S3), suggesting notable warming during 2016/2017 winter following the flood of 2016.

Correlation analyses suggest that mean TP concentrations during growing seasons (March–August) were positively related to annual rainfall of the previous year (GAM, $r_{adj}^2 = 0.19$, $p < 0.05$, Figure 4a), and winter/spring temperature anomalies were significantly correlated with annual mean bloom areas (GAM, $r_{adj}^2 = 0.47$, $p < 0.01$, Figure 4b).

4. Discussion

Our observations indicate that Lake Taihu had experienced unprecedented intense cyanobacterial blooms in 2017, illustrated by the large mean area, high frequency and early start date. Intense algal blooms occurred following high external nutrient loading that resulted from highly anomal precipitation and runoff in the previous year (2016) (Figure S4b) and a notable warm preceding winter (2016/2017) (Figure S4c).

4.1. Drivers of the Extraordinary Blooms in Lake Taihu in 2017

Cyanobacterial blooms in Lake Taihu are mainly driven by nutrient availability and water warmth (Qin et al., 2019). After a decadal intensive effluent reduction effort, annual mean TN decreased significantly (Figure 3a), while annual mean TP concentrations in Lake Taihu sustained at high level (Figure 3b),

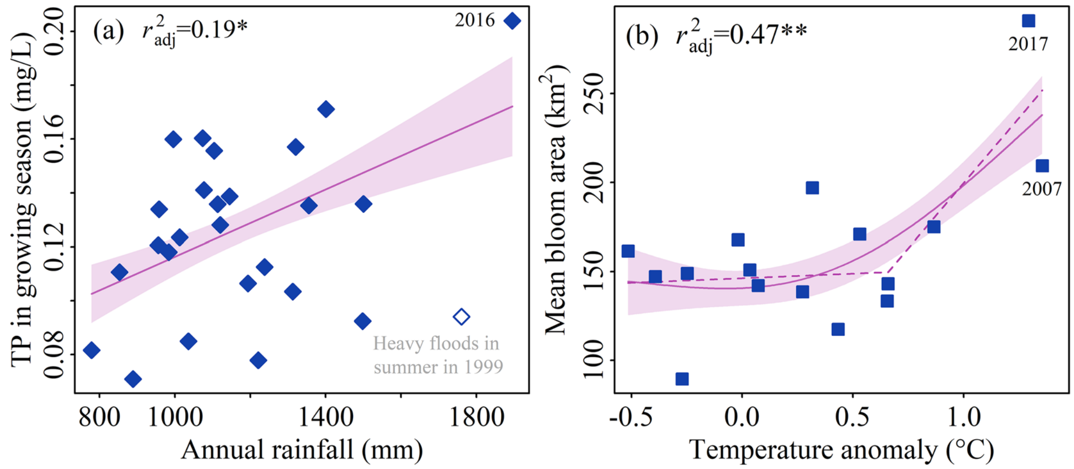

Figure 4. Correlation between annual rainfall of previous year and phosphorus availability of growing season (March–August) in Lake Taihu ($r^2 = 0.19$, $p < 0.05$) (a), and winter/spring temperature deviation from average versus annual mean bloom areas retrieved from satellite imagery ($r^2 = 0.47$, $p < 0.01$) (b). Some extreme responses of total phosphorus concentrations and bloom areas were marked by individuals years. Relationships were estimated by generalized additive models, and shading indicates the standard error of the estimates.

resulting the yearly mean TN:TP ratio continued decline (Qin, Zhang, et al., 2020). Water warmth limits the cyanobacterial growth in Lake Taihu during the winter because of the low water temperature (~5°C–6°C, Figure S5) which is close to the lower limitation for algal growth (Butterwick et al., 2004).

Extreme climatic conditions have increasingly exerted influences on the phytoplankton community and cyanobacterial blooms in Lake Taihu recently (Yang et al., 2016). Heavy rainfall can induce intense cyanobacterial blooms due to an increase in external loading (Yang et al., 2016). However, compared to precipitation in the previous year, the preceding winter temperature plays an important role in supporting the severe cyanobacterial blooms in 2017 (Figure 4). Correlation analysis demonstrated that winter temperature deviation from average significantly affected spring and summer bloom intensity (Figure 4b) (Ma et al., 2016). The very warm winter of 2016/2017 resulted in an extensive cyanobacterial bloom (718 km^2) on December 31, 2016 (Qin et al., 2019), which even for Taihu is a rare occasion. An increase in winter water temperature frequently led to an early initiation and proliferation of cyanobacterial blooms (Duan et al., 2009; Shi et al., 2019). Extremely warm winter months combined with the water diversion from Yangtze River has been blamed for a severe bloom that caused a drinking water crisis in spring 2007 in Wuxi (Qin et al., 2010).

As one of Pacific Rim nations, China's climate anomalies are strongly influenced by global-scale interannual variation of climate cycles such as ENSO which are modulated by the PDO (Heng et al., 2020; L. Wang et al., 2008), especially rainfall anomalies (Heng et al., 2020), associated with the Atlantic Multidecadal Oscillation (AMO) (Gao et al., 2015; Lyu & Yu, 2017), NAO and AO. These teleconnection patterns are often accompanied by a warm winter, excessive rainfall and flooding throughout Eastern Asia (L. Wang et al., 2008). Climate anomalies during 2016–2107 in the Taihu basin (Figure S4) were an outcome of combined effects imposed by ENSO, AMO, and PDO (Figure 5). High precipitation during 2016 (Figure S4b) was likely associated with the strong 2015/2016 El Niño (Figure 5f) which terminated in spring 2016 (WMO, 2017) but its influences extended more than three months later (Table S1), and positive (warm) phases of AMO (Figure 5a) and PDO (Figure 5b) (Supplementary Table S1), while the persistent warming during 2016/2017, including the notable warm winter 2016/2017 (Figure S4c), likely resulted from a number of global scale climate deviations in association with AMO, PDO, as well as NAO and AO (Figures 5a–5d) (Table S1). Surprisingly, both AMO and NAO can distantly affect the local climate of Taihu basin, especially the AMO which can affect both surface air temperature (SAT) and precipitation anomalies in the Taihu basin (Figures 5a and 5b, Table S1). Influence from AMO is more significant relative to PDO in the Taihu basin (Figure 5) (Table S1). Consequently, a combination of climate anomalies resulted from the strong 2015/2016 El Niño in association with joint effects of warm phases of AMO and PDO were responsible for the highly frequent and long persistent intense cyanobacterial blooms in 2017.

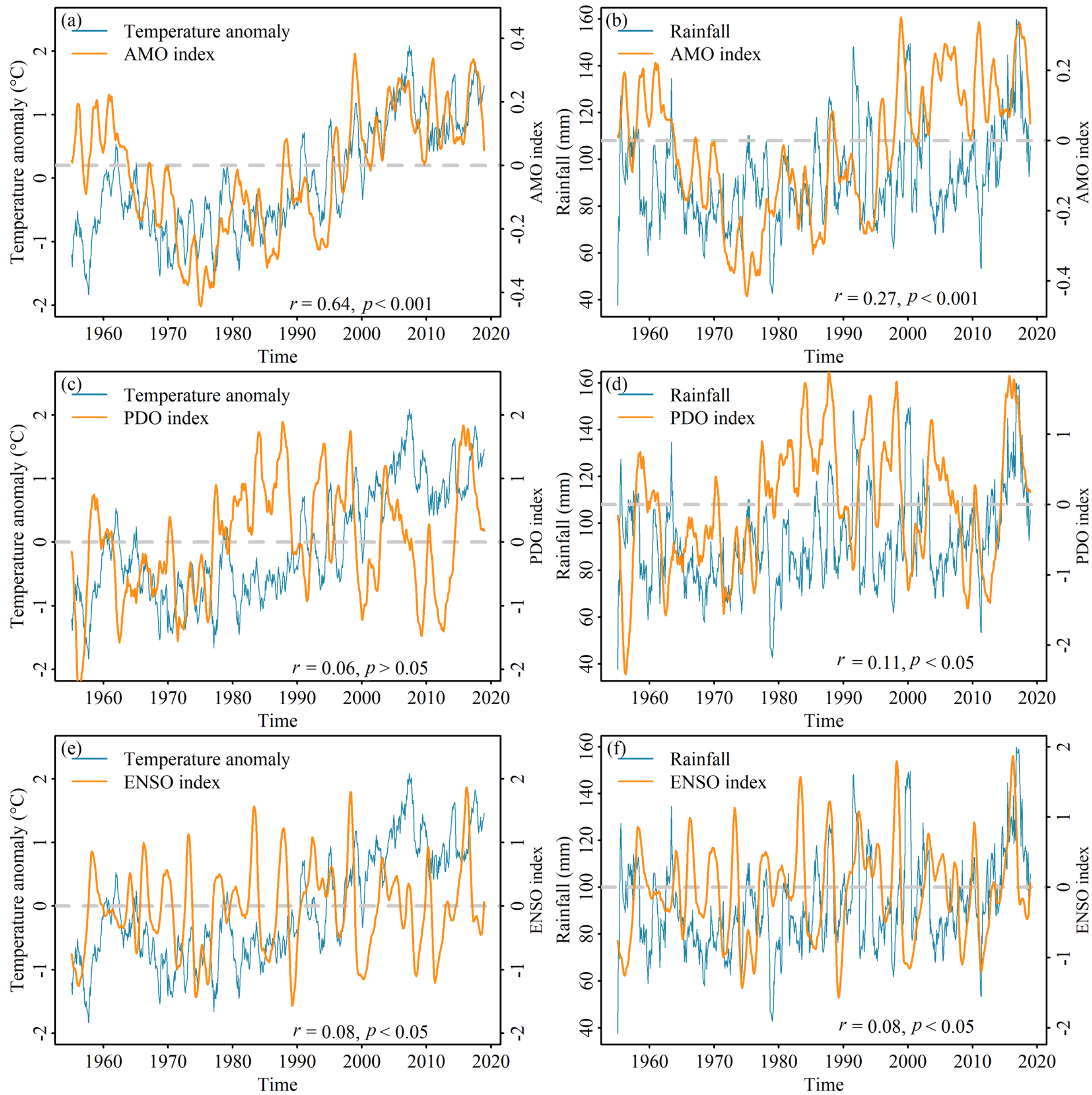

Figure 5. Pearson correlation between surface air temperature (SAT, Wuxi) with (a) Atlantic Multi-decadal Oscillation (AMO), (c) Pacific Decadal Oscillation (PDO), and (e) El Niño and Southern Oscillation (ENSO), and precipitation (Wuxi) with (b) AMO, (d) PDO, and (f) ENSO, based on 12 months moving average over period from 1955 to 2018.

4.2. Response of Lake Taihu Ecosystem to Extreme Climate Anomalies 2016/2017

Ecological responses of aquatic ecosystems to climate changes are increasingly evident (O'Reilly et al., 2015; van de Waal et al., 2010). However, few studies have addressed ecosystem responses to a combination of extreme climate anomalies, particularly during the 2-years, prolonged warm surface air temperature in the Taihu basin (Figure S4). Such combination of climate anomalies resulted in an increasing amplitude of ecosystem response. P concentrations peaked in 2017, while external P loading to Lake Taihu was low (Figure 3), which was likely associated with high internal loading. Because most external P inputs (60%–70% of riverine loading) is retained in the sediments (Qin et al., 2019), legacy P in sediment can be mobilized by positive feedback effects induced by the intense cyanobacterial blooms. The warm winter of 2016/2017 stimulated intense cyanobacterial blooms, which occurred early and persisted through the summer and autumn. Thus, extensive blooms in turn altered physical-chemical conditions, including elevated pH (Gao

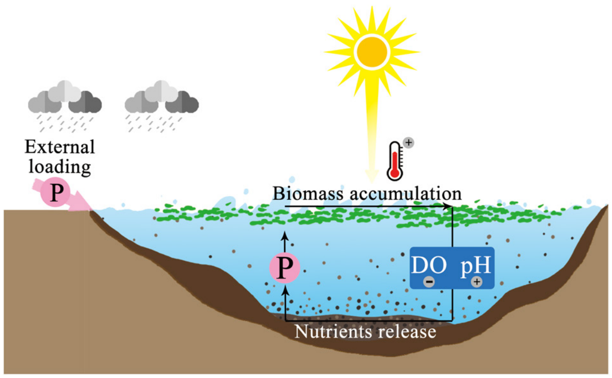

Figure 6. Conceptual diagram of a combination of climate (high precipitation and warm winter) anomalies induced internal phosphorus cycling through boosting cyanobacterial blooms to increase pH and decrease dissolved oxygen, which led to a positive feedback to ensure cyanobacterial bloom persistence.

et al., 2012; Krausfeldt et al., 2019) and decreased dissolved oxygen (DO) (X. Yan et al., 2017). Monthly water quality monitoring revealed that water column pH in the northern lake was significantly related to the Chl*a* concentration when pH > 8.0 (Figure S6, $p < 0.001$). High-frequency *in-situ* monitoring of near-bottom dissolved oxygen (DO) concentration at the TLLER pier suggested that the DO had decreased since 2008 (Figure S7), and hypoxia frequently took place during low wind velocity periods (Figure S8). Both high pH (Christophoridis & Fytianos, 2006; NiemistÖ et al., 2011) and low DO (Ding et al., 2018; L. Zhu et al., 2020) would promote nutrients mineralizing and degrading into dissolved forms in the sediments. Occasional sediment resuspension under windy conditions can liberate significant amounts of soluble P into overlying water (J. Deng et al., 2018). Coupling nutrient mobilization induced by high pH in the water column to DO decline at the lake bottom supports additional cyanobacterial blooms by enhancing internal nutrient cycling (Gao et al., 2014) in response to a combination of extreme climate anomalies (Figure 6). This scenario represents a positive feedback to ensure proliferation and persistence of cyanobacterial blooms in 2017 (Figure 6). This can also explain why TP in 2017 was 30.6% above predicted value based on temporal trend regression (TP = 0.003 × Year − 5.813, $r^2 = 0.54$, $p < 0.001$), while the Chla concentration deviated 79.4% over the prediction of temporal trend regression (Chla = 1.13 × Year − 2,236.2, $r^2 = 0.54$, $p < 0.001$).

4.3. Implication for Eutrophication and Bloom Management

Eutrophication and cyanobacterial blooms favor shallow lakes and estuaries (Qin, Zhou, et al., 2020). Global increases in excessive nutrient input due to extreme climate events driven by climate change will be likely intensified in magnitude and frequency in the future (Sinha et al., 2017), which will boost cyanobacterial blooms. This is one of the reasons why rehabilitation efforts on many large eutrophic waters have resulted in minimal improvement worldwide (Ho et al., 2019), including Lakes Okeechobee (USA) (Rosen et al., 2017), Winnebago (USA) (Miller & Beversdorf, 2017), Pontchartrain (USA) (Mishra & Mishra, 2010), Kasumigura (Japan) (Salem et al., 2017), Champlain (shallow northern part, USA/Canada) (Fortin et al., 2015), Winnipeg (Canada) (Ulrich et al., 2016), Erie (shallow western part, USA) (Bullerjahn et al., 2016), Peipsi (Eastonia) (Alikas et al., 2015), Lake Victoria (Africa) (Mbonde et al., 2015) and Chaohu (China) (Zhang et al., 2016). More intense cyanobacterial blooms will, in turn, further deteriorate water quality by decreasing clarity and transparency, reducing submersed macrophyte coverage, increasing hypoxic area. This scenario leads to impairment of aquatic ecosystem functions and services, including drinking water supplies, loss of fisheries and recreational/esthetic uses, etc.

The current warming trend has been documented on a global scale and is a known manifestation of the greenhouse effect, which is reflected in rising global temperatures since the 1950s (IPCC, 2013). In addition to global warming, both the amplitude and the frequency of regional interannual climate variations in association with global scale external forcings such as El Niño, PDO, and AMO have likely increased with widespread climatic (e.g., changes in precipitation and surface air temperature) consequences (Cai et al., 2015). Lake Taihu is a mirror for global accelerated eutrophication and cyanobacterial proliferation (Huisman et al., 2018), resulting from anthropogenic nutrient discharge and the combined regional warming and heavy precipitation exerted by a changing climate (Paerl et al., 2020). Extensive lake restoration initiated after the drinking water crisis in 2007 is likely challenged by these climatic changes. A combination of extreme climate anomalies cause magnified responses of highly productive aquatic ecosystem, which ultimately mobilizes phosphorous from the sediment and promotes algal blooms by forming a positive feedback to exacerbate the water quality. Such ecosystem responses may dampen the effect of external loading reduction and lengthen the restoration time. Considering the profound influences exerted by the extreme climate anomalies during 2016–2017, new targets for nutrient reduction control strategies are urgently needed, especially for shallow and eutrophic systems.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All original data corresponding to those figures and tables in text and supplementary materials are compiling and deposit in public accessible data set Zenodo (https://zenodo.org/record/5095397#.YO2172z65PY).

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