Two-Decade Reconstruction of Algal Blooms in China's Lake Taihu

HONGTAO DUAN,*,† RONGHUA MA,† XIAOFENG XU,*,‡ FANXIANG KONG,† SHOUXUAN ZHANG,† WEIJUAN KONG,§ JINGYAN HAO,† AND LINLIN SHANG†

State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, China, 210008, Ecosystem Dynamics and Global Ecology (EDGE) Laboratory, School of Forestry and Wildlife Sciences, Auburn University, Auburn, Al, 36849, and Department of Geography Information Sciences, Nanjing University, Nanjing, China

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The algal blooming in the inland lakes has become a critically important issue for its impacts not only on local natural and social environments, but also on global human community. However, the occurrences of blooming on larger spatial scale and longer time scale have rarely been studied. As the third largest freshwater lake in China, Lake Taihu has drawn increasing attention from both public and scientific communities concerning its degradation. Using available satellite images, we reconstructed the spatial and temporal patterns of algal blooms in Lake Taihu through the past two decades. The blooming characteristics over the past two decades were examined with the dynamic of initial blooming date being highlighted. The initial blooming dates were gradually becoming later and later from 1987 to 1997. Since 1998, however, the initial blooming date came earlier and earlier year by year, with approximately 11.42 days advancement per year. From 1987 to 2007, the annual duration of algal blooms lengthened year by year, in line with the substantial increases in the occurrences of algal blooms in spring and summer months. The algal blooms usually occur in northern bays and spread to center and south parts of Lake Taihu. The increases in previous winter's mean daily minimum temperature partially contributed to the earlier blooming onset. However, human activities, expressed as total gross domestic product (GDP) and population, outweighed the climatic contribution on the initial blooming date and blooming duration. This study may provide insights for the policy makers who try to curb the algal blooming and improve the water quality of inland freshwater lakes.

Introduction

Global environmental change is one critical issue facing human beings and has been recognized as a result of anthropogenic activities (*1*, *2*). The eutrophication in inland freshwater lakes is one of the most severe environmental problems (*3*), not only due to the significant ecological functions of inland lakes (*4*), but also due to the ecological services, including freshwater supply, fishery, and flood mitigation, on which nearby human society depends (*5*). Since the alteration of water quality primarily results from economic development and sewage treatment, the eutrophication in inland lakes has become one of the most widespread environmental and social problems for all countries around the world (*2*, *6*). For example, lakes such as Victoria in Africa, Okeechobee in the United States, Taihu in China, and the Baltic Sea in Europe could be headed in the direction of becoming perennial algal soups (*5*).

Lake Taihu, the third largest freshwater lake in China, is one of the main sources for nearby residents' drinking water, and one of the most severely polluted freshwater reservoirs in China where the algal blooms have been heavily studied (*5*, *7*, *8*) (see Figure 1). The recent bloom in summer 2007 affected the Wuxi City nearby significantly; more than 1 million people were short of drinking water (*5*). This event made Lake Taihu one of the hot topics not only in China (*9*, *10*), but also in global community (*5*, *11*). Although the Chinese government has begun to recognize the importance and urgency of studying and managing eutrophication in the Lake Taihu and has provided some funding to support this kind of research, a long-term and large-scale campaign against the eutrophication in Lake Taihu is still in its infancy (*2*, *5*).

The algal bloom has long been recognized as the result of importing nutrients, mainly as nitrogen and phosphorus (*5*, *12*–*14*). Furthermore, the major nutrient sources have been recognized as industrial activities, for example, sewerage, livestock drainage, soil nutrients and losses of fertilizers in drained agricultural lands (*15*). Taihu Basin is identified as one of the regions in China featured as high population density and the high gross domestic product (GDP) per capita (*16*). For example, in 2000, the GDP in this area accounted for 10.3% of national GDP; the local per capita GDP was 3 times of that nationwide with a 7 times average population density than nationwide average population density (*17*). Along with the advancing of our understanding and the development of new techniques, more and more studies have recognized the complex integration of many environmental factors on algal blooming, which have not been fully understood and need to be thoroughly investigated (*11*). Currently, eutrophication has been partially attributed to climatic influences such as the increasing temperature (*14*). Although the identification of these factors has been achieved, quantitative understanding and mechanical exploration of eutrophication are still lacking.

A number of studies on algal blooms have been conducted since the 1960s (*18*–*27*). However, most of them were traditionally performed by taking ship-borne water samples and analyzing the samples in a laboratory or by doing on-site measurements (*20*). Due to the coarse sampling frequencies and limited sampling points, it is difficult to comprehend the temporal and spatial pattern of blooms for one entire lake, which were usually featured by outbursts uneven in time and space scales (*28*). The blooms can increase the aquatic content of chlorophyll-a and yield critical impacts on the light reflection of the water surface, and aquatic vegetational albedo, which can be detected by satellite. Therefore, it is possible to retrieve the algal blooming on the basis of shifts in ecological information of aquatic system at large spatial scale and long time series (*28*). Actually, satellite-derived data has become a powerful tool and has been preliminarily utilized in understanding algal blooming (*8*, *28*).

* Address correspondence to either author: Phone: 86-25-86882161 (H. D.); 1-334-844-8068 (X. X.). Fax: 86-25-57714759 (H. D.); 1-844-1084 (X. X.). E-mail: htduan@niglas.ac.cn (H. D.); xuxiaof@auburn.edu (X. X.).

† Nanjing Institute of Geography and Limnology, CAS.

‡ Auburn University.

§ Nanjing University.

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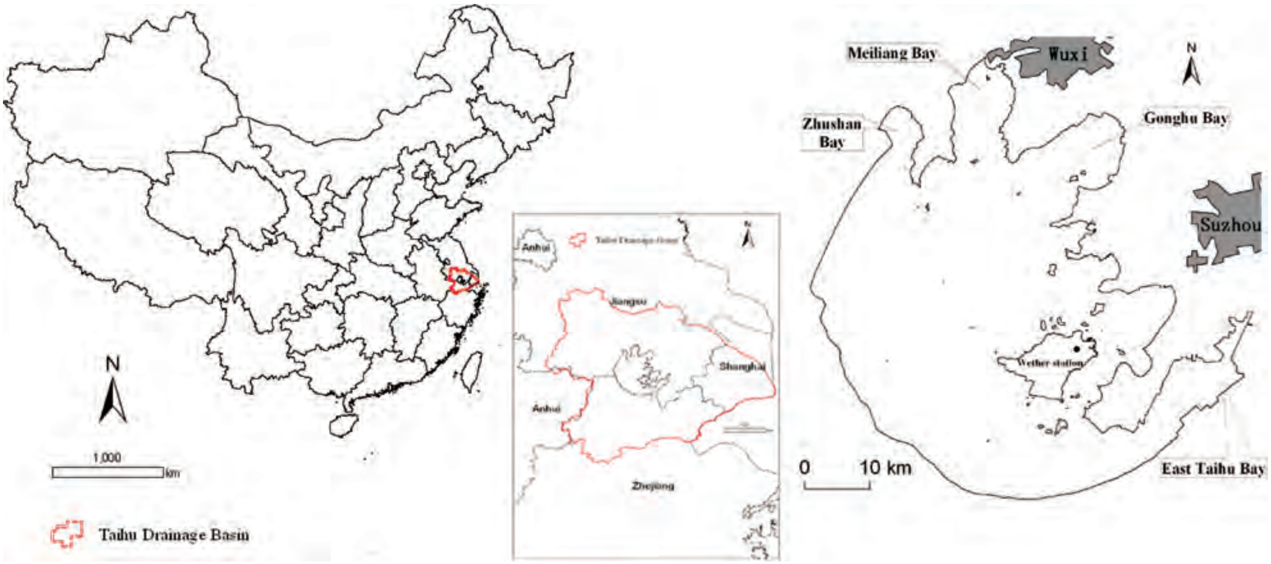

FIGURE 1. Location of Lake Taihu in China (a weather station from which the climate data are got is shown as a dot; two nearby cities, Wuxi and Suzhou, are also shown on the map).

It holds advantages over traditional measurements by providing spatial and temporal domain of their characteristics and distributions (*29*). In addition, satellite images can be used to retrieve a long time series of algal blooms information without in situ measurements (*28*). However, no study has been conducted simultaneously covering long time series and large spatial scale in Lake Taihu.

The objectives of this paper are (1) to verify the ability of satellite images in deriving the information of Lake Taihu algal blooming simultaneously covering large spatial scale and long time scales; (2) to reconstruct the temporal pattern of initial blooming dates in Lake Taihu in the past two decades; (3) to analyze the spatial sprawling of algal blooming; (4) to explore the possible underlying mechanisms for the advanced initial blooming date in Lake Taihu. This study is expected to contribute to water quality control and bloom prevention of inland freshwater lakes and to benefit some regional-scale studies.

Data Acquisition and Processing

In total, 394 remote sensing images over Lake Taihu were used to derive the spatiotemporal information of algal blooms. They include 178 scenes of Landsat TM/ETM and 216 scenes of MODIS images. The MODIS images that cover the period of 2002−2007 were downloaded from the NASA EOS Data Gateway (EDG), and Landsat data including nearly all cloud-free images over Lake Taihu since 1987 were provided by China Remote-Sensing Satellite Ground Station. The image data were first matched geographically according to corresponding 250 or 500 m pointer files by using ERDAS 9.1 software. For the other data geo-coding, satellite images were geometrically corrected based on 1:50000 topographic maps with ERDAS 9.1 software. The images were also resampled using the nearest neighbor method to preserve their radiometry.

Water molecules could strongly absorb radiation in red and near-infrared portions of the spectrum, where the absorption coefficient increases exponentially. Generally no reflectance signal from pure water surface is detectable at wavelengths beyond 750 nm (*30*). However, algal blooms in water will cause a detectable reflectance signal because of chlorophyll-a and phycocyanin in water (*31, 32*). Field spectra of three different kinds of water including clear water, water with algae (mainly *Microcystis aeruginosa*), and algal blooms in Lake Taihu were measured with FieldSpec 931 spectrometer (ASD Ltd., U.S.) (Supporting Information Figure S1). It shows a detectable reflectance signal at the wavelength of 900 nm from the algal blooms floating water surface (Supporting Information Figure S2); especially a concentrated algal bloom will form a clearly distinguishable signal which has been used in our study (Supporting Information Figure S3A and B). By visual comparison, it is easy to delineate the areas of algal blooms with the near-infrared bands by a threshold. Band 4 in near-infrared wavelengths is the best for retrieving the bloom information of four reflective TM bands between 400 and 900 nm by a threshold value, for example, band 4 > threshold value (Supporting Information Figure S3C). For MODIS, it can also be used to retrieve the blooms based on the infrared wavelengths (band 2 > threshold value) (Supporting Information Figure S3D). Although the threshold value based on visible images may have some uncertainties on determining the area of the blooms, it provides the possibility of mapping blooms in longer time scale and larger spatial scale without in situ data.

Due to the long revisiting period of 16 days and unavoidable cloudy conditions, Landsat data may lead to underestimations of the algal blooms' frequency or delay the detection of initial blooming date although the interannual variability could be captured using Landsat image. Compared with Landsat series, MODIS data with daily revisiting intervals are more accurate in capturing the initial blooming date and outburst events, but short of historical detection. Therefore, we also compared the Landsat and MODIS in retrieving algal information in the Lake Taihu. The spatial consistency between these two sensors is shown in Supporting Information Figure S2 and the temporal consistency is shown in Figure 4. This is consistent with a previous study has been verified in the Baltic Sea (*27*). These results suggest the possibility to reconstruct the long-term information of algal blooming in Lake Taihu by combining the historical data set Landsat and currently available data set MODIS through the past two decades.

In this analysis, annual bloom duration is defined as the number of months during which the algal blooming was detected throughout one specific year. For example, algal blooms were detected only in May, September, and November from satellite images in 2001, the annual duration was defined as 3 months for 2001. Given the limited images available, this method may provide more accurate information than the single event duration that is hard to capture

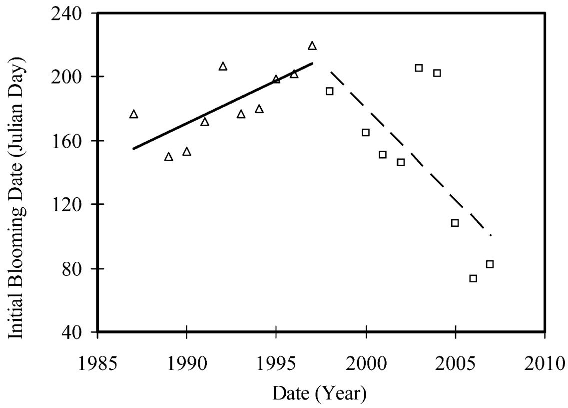

FIGURE 2. The initial outburst date for Lake Taihu algal blooming through the time period of 1987−2007 (△ for 1987−1997; □ for 1998−2007; the dash line is the regression for 1987−1997, the equation is $Y = 5.348 \times X - 10473$ with $P = 0.013$; the solid line is the regression for 1998−2007, the equation is $Y = -11.41 \times X + 22\,999$ with $P = 0.048$).

with inadequate images. To evaluate the seasonal characteristics of algal blooms, blooming frequency was defined. The blooming frequency is the number of year which has seen the blooms on a monthly basis through a time period. For example, the blooms were detected by satellite images in March for two years through 1998−2007, so the blooming frequency of March was set as 2 for the time period of 1998−2007. The population and economic statistic data were derived from statistical yearbook, and the climate data is provided by China Meteorological Administration. All the statistical analyses were conducted using SPSS 12.0 for Windows XP.

Results

Initial Blooming Date. Using 394 satellite images for 1987−2007 (Supporting Information Table S1), we found that the algal blooms occurred every year. The years of 1988 and 1999 were not included in this analysis due to the scarcity of images available for those two years. All the image-derived initial blooming dates in one year were transformed into Julian date format based on Julian Date Calender (http://www.fs.fed.us/raws/book/julian.shtml). Through the past two decades, two distinct changing tendencies were detected (Figure 2); from 1987 to 1998, the algal blooms outbreak showed a slightly delaying tendency, with a delay of 5.35 days per year. However, since 1999, its outburst became earlier and earlier, with an advancing trend of 11.41 days per year (Figure 2).

Duration and Frequency. The duration and frequency for 1987−2007 can be separated into two easily distinguished periods (Figure 3). The annual duration of bloom was only one month every year before 1998 and became more than two months since 1998 (Figure 3A). In the last three years (2005−2007), more than six months have seen algal blooms in each year (Figure 3A). Moreover, there was an accelerating trend of algal blooms in frequency and intensity in recent years (Figure 3A). From 1987 to 1998, the algal blooms only occurred in summer time, for example May, June, and July, and less in August, and never in the winter season and spring season (Last four months and first four months of the year) (Figure 3B). However, since 1999, algal blooms occurred at increasing frequency and on lengthened duration; algal blooms in 2007 were detected through the entire year except January and February. The longer duration and more frequent blooming in the second decade than those in the first decade shown the substantial increase of blooming in times and severity.

Spatial Pattern. Algal blooms were first observed in Meiliang Bay and Gonghu Bay in June, 1987 (Figure 1). Through the past two decades, the yearly initial algal blooming was observed 14 times in Meiliang Bay, and 6 times in Zhushan Bay, in which the initial algal blooming was seen simultaneously in Meiliang Bay and Zhushan Bay in 1991, 1994, 1997, and 2003. Since 2000, the initial algal blooming also was found in western and southern bays and began to spread out and cover a large area with southward shifting trend (Figure 4) (*10*). The annual peak distribution area of algal blooms was relatively constant on a level of approximately 62.2 km^2 for 1987−2000 (Figure 4), then it showed a significantly increasing trend and reached 316.9 km^2 in 2005 and 805.5 km^2 in 2006 (Figure 4J and K), and even increased to the first peak of 979.1 km^2 in late June, and the second peak with 855.1 km^2 in September, 2007 (Figure 4L). For the summer months, mainly July and August, the algal blooming also showed a sprawling trend and the distribution area became larger and larger year by year (Figure 4A−I). For example, there was only 4.8 km^2 on July 23, 1991 (Figure 4A), and it has increased to 112.9 km^2 by August 9, 2005 (Figure 4G), especially in 2006 and 2007 with blooming covering more than 200 km^2 (Figure 4H−I). Gonghu Bay, a mesotrophic bay in the northeast part of Lake Taihu which has rarely seen algal blooming in the past, also has shown blooms occasionally since 2005 and an increasing trend until 2007 (*33*). Actually, algal blooms in the Lake Taihu were overspreading from the northwest to the southeast, from the border area to the center area, which is consistent with the prior evidence (*34*).

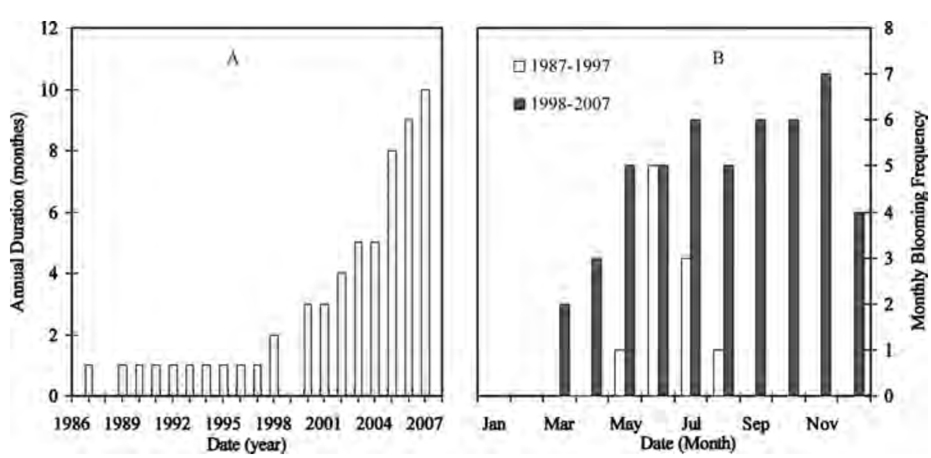

FIGURE 3. The annual duration of algal blooming (A) and frequency of blooming month (B) in the past two decades.

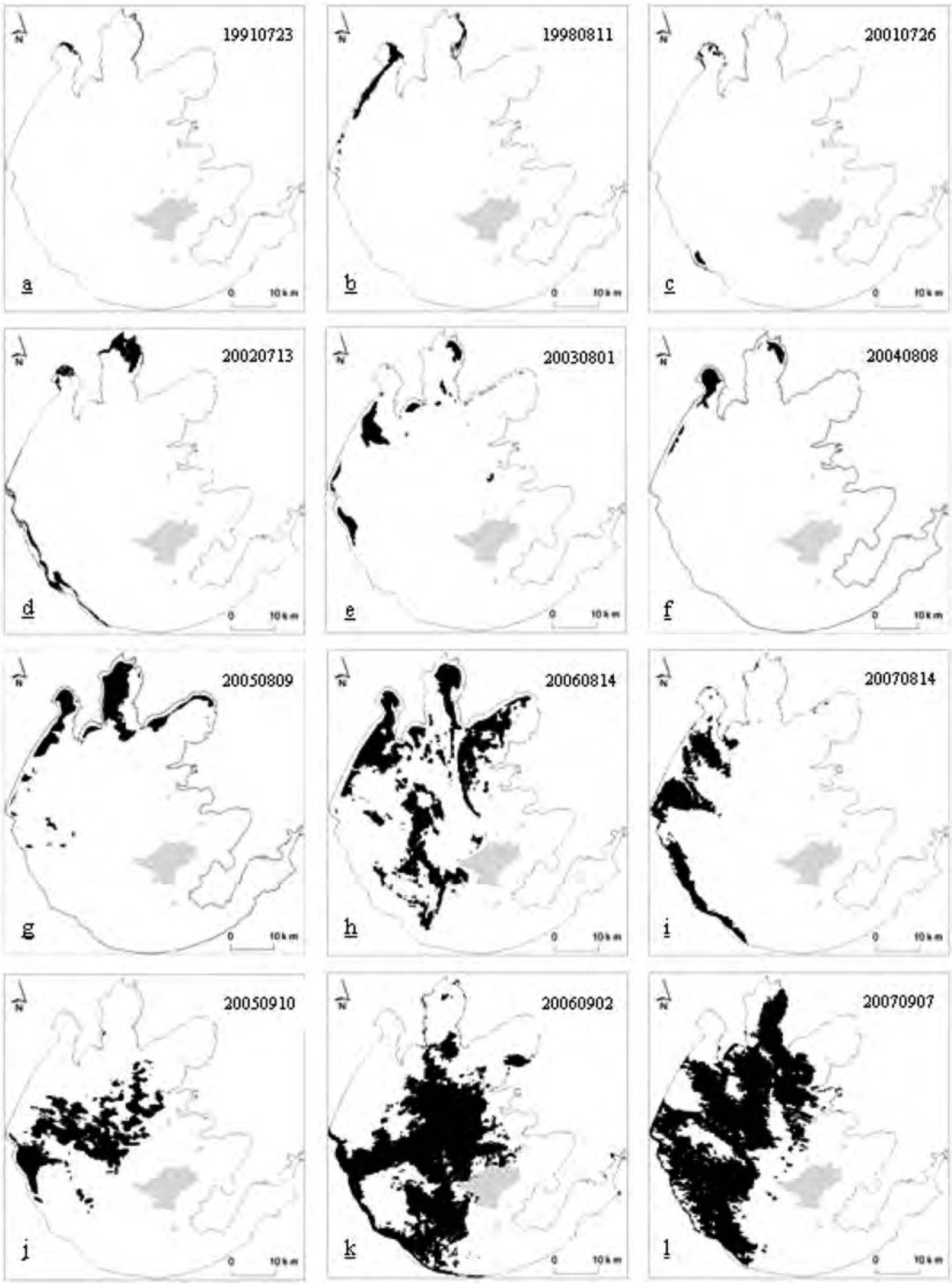

FIGURE 4. Spatial patterns of algal blooming in summer (July, August, or September) for 1987−2007.

Discussion

Temperature is considered as one of the main environmental factors for organism's growth; in this study the previous year's winter temperature was examined for its influences on algal blooming. We found a positive correlation between initial blooming date and average, maximum and minimum temperatures. The correlation of initial blooming is marginally significant to average temperature ($P = 0.055$), nonsignificant to maximum temperature ($P = 0.105$), and significant to minimum temperature ($P = 0.048$), which suggests the different contribution of temperature components to initial blooming date (Figure 5). This correlationship is consistent with a previous study (*35*) in which the temperature was reported as a major factor that stimulates the growth of diatoms, one kind of algae. Actually, a tight correlation between algal recruitment and cumulative temperatures in terms of the sum of effective temperatures has been reported both in laboratory and field study in Lake Taihu (*36*). There are three possible explanations for the effects of winter temperature on algal blooming. First, a higher temperature helps algae survive over winter, one of the important stages for algal life cycle (*37*−*39*), and possibly keeps a sufficient seed population for bloom initiation in the next year (*40*). The blooms' formation in Lake Taihu has been classified as a series of processes: autumnal sedimentation of declining blooms biomass, subsequent overwintering in bottom sediments, recruitment in spring, biomass increase, and bloom formation (*37*). The second explanation may be the stimulus

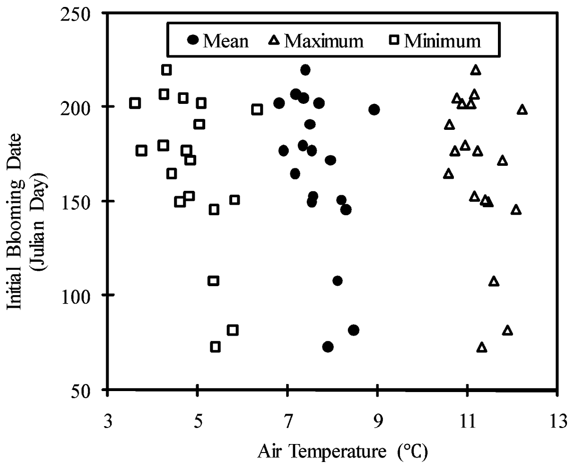

FIGURE 5. Correlation between initial blooming date with the air temperature in previous November and December, and current January (The regression for average temperature, maximum and minimum temperature are: $Y = -33.963 * X + 426.445$, with $R^2 = 0.200$ and $P = 0.055$; $Y = -33.166 * X + 539.549$, with $R^2 = 0.147$and $P = 0.105$; and $Y = -26.930 * X + 297.116$, with $R^2 = 0.211$and $P = 0.048$)

effects of winter temperature on algal recruitment, another important stage for algal blooming in the upcoming year (*37, 41*−*43*); The third reason is a physiological explanation in which the activity of an enzyme that is responsible for algal blooming is significantly correlated with temperature (*30*). In this study, the increasing rates of previous winter (November and December in previous year, and January in current year) temperature were found at 0.0337 °C/year, 0.0079 °C/year, and 0.0539 °C/year for average, maximum, and minimum temperature. Given the highest increasing rate of minimum temperature, it is concluded that the daily minimum temperature may play a critical role in affecting the initial blooming date in the following year.

The winter 2007 was one of the warmest winters in the last 25 years, and the mean temperature from January to March was higher than the mean annual temperature, with 0.36 °C increase in January, 2.78 °C increase in February, and 1.98 °C increase in March, which may produce an elevated water temperature suitable for cyanobacteria, one of the primary species for algal blooms in Lake Taihu (*10*). This increase may explain the algal blooms in summer 2007 (*5*). In addition, warmer and drier conditions appear to have been the spark that ignited the blooms in next year, when Taihu kept a low water level from January to March and the solar intensity per water volume was increased (*5*). Meanwhile, the occurrences of heavy algal blooms in warm seasons have increased in frequency and intensity in recent years (Figure 4B) (*7*). Given that China's climate has experienced enormous changes in the past 40 years, and air temperature increased 0.21 °C per decade from 1961 to 2000 (*44*), it is imperative that the temperature contribution to algal blooming be explored, along with associated strategies to curb its expansion.

The outbreak of algal blooming has long been attributed to nutrient loading, mainly as nitrogen and phosphorus (*10*). It is hypothesized that Lake Tiahu is associated with the nutrient loading resulting from human activities. Actually, only for the time period of 1991−1996, the annual average of total nitrogen concentration increased from 1.18 to 3.62 $mg \cdot L^{-1}$ and total phosphorus levels increased from 0.10 to 0.18 $mg \cdot L^{-1}$ (*45*). Moreover, the concentrations of total nitrogen and total phosphorus in water in 2006 were found to be 200 and 150% higher than those in 1996 (*10*). The data from the Taihu field station showed that the inputs of total nitrogen and total phosphorus from the catchments area were 43151 and 1756 tons in 2002, and increased up to 44705 and 1858 tons in 2003, respectively (*10*).

The spatial pattern of algal blooms also supports the nutrient dominance of algal blooming. The southward growth of algal blooming is likely a result of declining gradient of nutrient concentration caused by main nutrient loading northwest of

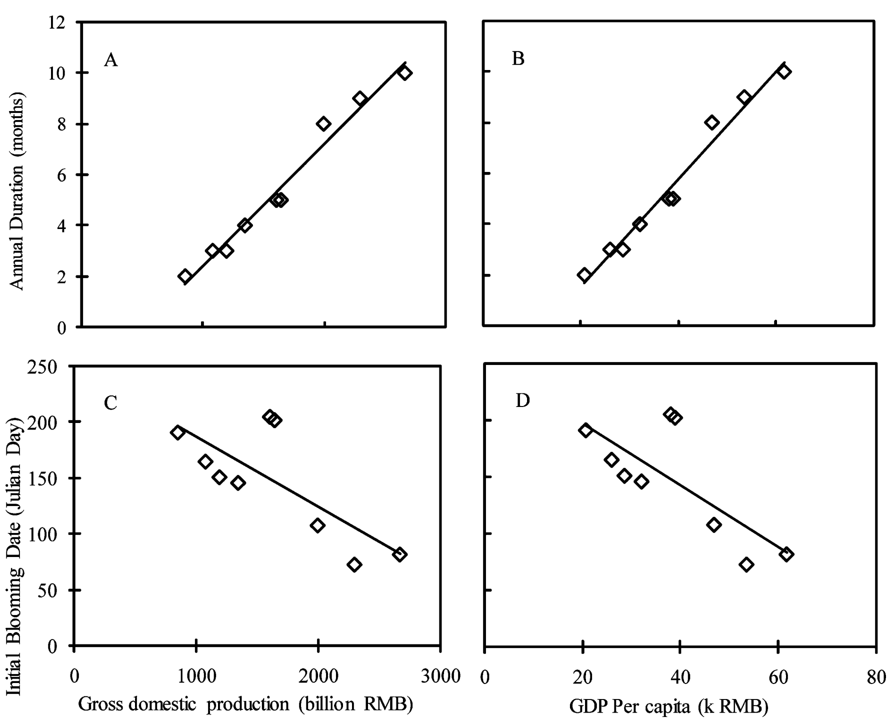

FIGURE 6. Correlation between the algal blooming and GDP and GDP per capita since 1998 (A: annual duration with GDP: $Y = 0.00478 \times X - 167.15$, with $R^2 = 0.976$, and $P < 0.001$; B: annual duration with GDP per capita: $Y = 0.212 \times X - 2.682$, with $R^2 = 0.977$, and $P < 0.001$; C: Initial blooming date with GDP: $Y = -0.063 \times X + 248.721$, with $R^2 = 0.557$, and $P = 0.021$; D: Initial blooming date with GDP per capita: $Y = -2.762 \times X + 253.014$, with $R^2 = 0.553$, and $P = 0.022$).

Lake Taihu. For example, the total phosphorus loading from the northwest catchments area accounted for 55.03% in 2002 and 53.28% in 2003 of the entire Lake Taihu, and the total nitrogen loading accounted for 65.03% in 2002 and 72.05% in 2003. The southward flow of loaded nutrients explains the frequent occurrences of algal blooms in the north of Lake Taihu and increasing detection of algal blooms in the center and south of Lake Taihu. For example, previous studies have shown that Meiliang Bay and Zhushan Bay are two of the most eutrophied bays in the northern part of the lake (*45, 46*), and these findings have been confirmed in this study.

Many studies on eutrophication show that the nutrient sources mainly are sewerage, livestock drainage, soil nutrients and loss of fertilizers in drained agricultural lands (*15*), which could be associated with human population and economic development. In this study, human population and GDP per capita were used to establish the relationship of anthropogenic activities to algal blooms. We used a stepwise method to assess the contributions of population, GDP, GDP per capita, and previous year's winter temperature to the annual blooming duration and initial blooming onset. GDP was found to be the dominant factor for initial blooming date, and GDP per capita was found to be the dominant factor for annual duration of blooming; these are consistent with the results of standardized coefficients by using multivariate regression (Figure 6). This information suggests that the GDP and GDP per capita primarily dominate the environmental influences on blooming, of which the GDP was the dominant factor which influences the initial blooming date ($R^2 = 0.988$), and the GDP per capita controlled the annual duration of blooming ($R^2 = 0.747$). These findings imply that economic activities substantially outweigh the previous year's winter temperature's effects, although the previous year's winter temperature does explain a great portion of variability of algal blooms (previous section). The GDP in the Taihu Basin increased from 847.66 in 1998 to 2662.231 billion Yuan (RMB) in 2007 and the GDP per capita from 2.06×10^4 to 6.16×10^4 Yuan (RMB). Correspondingly, the number of months of detected algal blooms increased from 2 in 1998 to 10 in 2007; the initial blooming date advanced more than 100 days. Significant correlations were found between the annual duration, initial blooming date and total GDP and GDP per capita in the adjacent area for the time period of 1998−2007. The long-term climatic and short-term anthropogenic contributions to thriving algae in Lake Taihu in this study are consistent with a previous study which investigated the sediment since 14000 years ago (*47*). Given the growing human activity projected in this area in the upcoming few decades and the changing climate, protection of Lake Taihu demands urgent efforts to reveal the true causes of Lake Taihu's degradation.

Using available satellite images, we explored the temporal and spatial patterns of algal blooming in Lake Taihu. However, there are several uncertainties in the current study that may need further investigation. First, the missing data in 1988 and 1999 may lead to a bias in this study, and the numbers of frequency and duration were possibly underestimated. Second, due to different technique characters of satellites, the discrepancies in satellite revisiting time might create some bias in understanding the temporal algal blooming. Third, only a portion of the environmental factors, for example, temperature, population, and GDP per capita, were included in this analysis in explaining the algal blooming; more controlling factors are highly needed to investigate the mechanisms of algal blooming. Despite the uncertainties caused by technological limitations and the complexity of aquatic systems, our study provided some evidence in retrieving ecological information from satellite images and revealed the climatic contribution to the algal blooms in inland freshwater lakes. This study may merit the large-scale and long-term ecological research on inland aquatic ecosystems, and modeling efforts. The evidence of the contribution of natural and social factors such as daily minimum temperature, GDP, GDP per capita, etc. to algal blooms in this study may motivate some further investigations of the underlying mechanisms of algal blooms.

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Supporting Information Available

This file contains Table S1 and Figures S1−S4. This material is available free of charge via the Internet at http://pubs.acs.org.

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