Satellite analysis to identify changes and drivers of CyanoHABs dynamics in Lake Taihu

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ABSTRACT

A long-term satellite-based analysis was performed to assess the impact of environmental factors on cyanobacterial harmful blooms (CyanoHABs) dynamics in a typical shallow lake, Lake Taihu. A sub-pixel approach (algae pixel-growing algorithm) was used with 13 years of MODerate-resolution Imaging Spectroradiometer (MODIS) data to evaluate changes in bloom extension, initiation date, duration, and occurrence frequency before and after a massive bloom event (2007). Results indicated that the conditions after this event changed, with a general delay in bloom initiation and a reduction in bloom duration. The environmental drivers of daily, monthly and inter-annual CyanoHABs dynamics were analyzed by detrended correspondence analysis, principal components analysis and redundancy analysis. This demonstrated that wind speed was the main driver for daily CyanoHABs dynamics, and CODmn, total phosphorus and water temperature were closely related to monthly CyanoHABs dynamics. For the year scale, Tmean and nutrients were the main drivers of CyanoHABs initiation date and duration, and meteorological factors influenced CyanoHABs frequency for the whole lake. Regular monitoring of CyanoHABs by remote sensing has become a key element in the continued assessment of bloom conditions in Lake Taihu, and nutrient reduction policies contribute to decrease CyanoHABs occurrence.

Key words | CyanoHABs, environmental drivers, Lake Taihu, MODIS, remote-sensing assessment

INTRODUCTION

In many rapidly developing areas of Asia, the attention to maintaining the environment has lagged behind the attention to economic growth. From the lake eutrophication point of view, one of the most renowned examples of the impact of rapid economic development is the case of Lake Taihu (Figure 1). This shallow lake (2,428 km² with an average depth of 2 m) has undergone four decades of degradation, eutrophication, and massive cyanobacterial harmful blooms (CyanoHABs) (Cai et al. 1996; Chen et al. 2003; Duan et al. 2014b). In 2007, this lake became internationally famous when a severe algal bloom event jeopardized the drinking water supply of millions of people in the surrounding cities (Guo 2007; Duan et al. 2009). Over the last decade, local pollution control and integrated watershed restoration projects have addressed point source pollution (factory closures), non-point source pollution (agricultural practices and land use), ecological restoration, water diversion, and in-lake algae controls (Xu et al. 2010). Considering the extensive and heterogeneous nature of Lake Taihu, spatially and temporally limited measurements do not allow an integrated assessment of the lake’s response to changes in catchment management.

Over the past three decades, significant advances in technology and algorithm development have enabled the use of satellites to monitor water quality and algal blooms in coastal seas and inland lakes (Hu 2009; Wang et al. 2011; Palmer et al. 2015), including several attempts to monitor and delineate CyanoHABs and the most common monitoring on intense scum-forming blooms (Gons et al.
Integrating the spatial and temporal resolutions of the satellite data, significant progress has been made in real-time bloom monitoring of coastal and inland waters especially using the MODerate resolution Imaging Spectroradiometer (MODIS) data (250 and 500 m) (Hu et al. 2010a; Wynne et al. 2013; Kahrur & Elmgren 2014; Mouw et al. 2015). Different variable atmospheric conditions are the first challenge to achieving long-term datasets of algal bloom distributions of inland turbid lakes from MODIS images. To overcome these optical challenges, floating algae index (FAI) was found to be relatively stable and can minimize atmospheric effects (Hu 2009). To date, several studies have been conducted on CyanoHABs dynamics in Lake Taihu by using FAI (Hu et al. 2010c; Duan et al. 2014a; Huang et al. 2014). The second challenge is the coarse spatial resolution of MODIS, where sub-pixel CyanoHABs coverage is necessary to determine accurate spatial coverage. However, MODIS sub-pixel coverage approaches have not been used and can reduce bloom size estimates for blooms > 100 km$^2$ by 10%–30% (Hu et al. 2010c). By taking into account partial coverage, better early warning of the bloom initiation may be achieved. In addition, the drivers of CyanoHABs in Lake Taihu have been discussed in many studies (Hu et al. 2010a; Zhang et al. 2012a; Duan et al. 2014b) using bivariate comparisons between bloom characteristics (area, initiation date and duration) and economic or environmental factors. Their results suggested that the long-term bloom patterns are driven by both nutrients and climatic factors. However, the drivers of CyanoHABs will depend on the specific temporal scale used, hourly, daily, monthly and yearly. This is the first study to explore the impact of potential drivers on multiple temporal scales.

The present study uses the algae pixel-growing algorithm (APA) (Zhang et al. 2014) to explore the spatial and temporal characteristics of CyanoHABs in relation to catchment and meteorological factors. Environmental driver analysis of daily, monthly and inter-annual CyanoHABs by multivariate methods provided new insights into the environmental drivers of CyanoHABs and lake management at different time scales.

**DATA AND METHODS**

**Bloom coverage determination**

A total of 1,312 remote-sensing images over Lake Taihu were used to derive the spatial-temporal information on
CyanoHABs. MODIS-Aqua level 0 data covering the period of 2001 to 2013 were downloaded from the NASA EOS Data Gateway (EDG). To avoid cloud-induced bias in the CyanoHABs area statistics, cloud-covered area was masked during Rayleigh-correction. The MODIS data were georeferenced to Universal Transverse Mercator projection with an error of <0.5 pixel. The 500 m resolution data at 1,240 nm were resampled to 250 m resolution to match the resolution at 645 nm. The MODIS data were corrected by removing the molecular (Rayleigh) scattering effects and then converted to Rayleigh-corrected reflectance (Rrc) (Hu et al. 2004a).

The FAI algorithm was calculated as follows:

\[ FAI_{M O D I S} = R_{rc}(859) - R'_{rc}(859) \]  

with

\[ R'_{rc}(859) = R_{rc}(645) + [R_{rc}(1240) - R_{rc}(645)] \cdot (859 - 645)/(1240 - 645) \]

where \( R_{rc} \) is defined as the difference between the calibrated sensor radiance (after adjustment for ozone \( L_0^* \)) and other gaseous absorption) and Rayleigh reflectance \( (R_r) \) (Hu et al. 2004a),

\[ R_{rc} = \pi L_0^*/F_0 \cos \theta_0 - R_c \]

where \( F_0 \) is the extraterrestrial solar irradiance at data acquisition time, \( \theta_0 \) is the solar zenith angle.

The APA was applied to identify the CyanoHABs coverages of every pixel (Zhang et al. 2014) by using the FAI of the central pixel in a 3 x 3 pixel window as a linear composition of the maximum and minimum FAIs of the other eight pixels as follows.

Considering \( n \) high-resolution pixels \( (R_{rc}^{HI}) \) that make up a low-resolution pixel \( (R_{rc}^{LO}) \), where \( R_{rc}^{LO} \) is the arithmetic mean of all \( R_{rc}^{HI} \),

\[ R_{rc}^{LO} = \frac{R_{rc}^{HI}(I)}{I} \]

Similarly, there exists a relationship between the low-resolution pixel and high-resolution pixels (or sub-pixels within the low-resolution pixel) for FAI:

\[ FAI_{pixel} = FAI_{sub\,pixel} \]

If we assume that, in a 3 x 3 pixel window, the central pixel is a function of the maximum and minimum FAI values present within the window, (4) becomes

\[ FAI_{center} = \gamma \cdot FAI_{max} + (1 - \gamma) \cdot FAI_{min} \]

where \( \gamma \) is the decomposition parameter of the 3 x 3 window that is determined based on the relationship between the known FAI values (center, max and min).

In a mixed pixel, the algae coverage is defined as the proportion (\( \alpha \)) of the pixel covered by floating algae such that

\[ FAI = \alpha \cdot FAI_{thresh \, algae}^{thresh \, water} + (1 - \alpha) \cdot FAI_{thresh \, water}^{thresh \, algae} = (FAI_{thresh \, algae}^{thresh \, water} - FAI_{thresh \, algae}^{thresh \, water}) \cdot \alpha + FAI_{thresh \, algae}^{thresh \, water} \]

where \( FAI_{thresh \, algae}^{thresh \, water} \) and \( FAI_{thresh \, water}^{thresh \, algae} \) are the FAI thresholds for pure algae (100%) and non-algae water (0%) pixels, respectively. Given that the thickness of floating algae is variable, we assumed that the FAI threshold for pure algae pixels is defined, which are covered by the thinnest floating algae.

Assuming that \( FAI_{thresh \, algae}^{thresh \, water} \) and \( FAI_{thresh \, water}^{thresh \, algae} \) are constant in a 3 x 3 window, the FAI of the central pixel could be expressed as follows:

\[ FAI_{center} = (FAI_{thresh \, algae}^{thresh \, water} - FAI_{thresh \, algae}^{thresh \, water}) \cdot \alpha_{center} + FAI_{thresh \, algae}^{thresh \, water} \]

The FAI of max and min pixels in a 3 x 3 window could also be similarly expressed in the same way. Based on (5), (6) and (7), FAI has a linear relationship with the floating algae coverage \( \alpha \) in the mixed pixel:

\[ \alpha_{center} = \gamma \cdot \alpha_{max} + (1 - \gamma) \cdot \alpha_{min} \]

where \( \alpha_{max} \) and \( \alpha_{min} \) are the algae coverage of pixels with maximum and minimum FAI values, respectively, in a 3 x 3 window.
There are three iterative steps in applying the APA to MODIS $R_{cc}$ data, including calculation of $\gamma$ for the central pixel, identification of ‘seed’ pixels and decision of the algae coverage using Equation (8). Through iterations, the algal bloom coverage expands from the initial pure algae pixels or high-coverage pixels to low-coverage pixels, according to the relationship between adjacent pixels in a $3 \times 3$ pixel window. In the end, $\alpha_{\text{MODIS}}$ is the basic value of algal bloom coverage for subsequent analysis. If $\alpha_{\text{MODIS}}$ is not zero, the algal bloom area of the pixel is $0.25 \times 0.25 \times \alpha_{\text{MODIS}}$. For the whole lake, the algal bloom area was calculated by $0.25 \times 0.25 \times \sum_i \alpha_{\text{pixel}}$.

Temporal-spatial characteristics of CyanoHABs

In this study, three bloom aspects were identified, namely, the annual initiation date, duration, and the spatial distribution of bloom frequency.

Previous studies indicated that February is the end of the CyanoHABs cycle (Hu et al. 2010c). For each pixel, CyanoHABs initiation was defined as the first moment of non-zero CyanoHABs coverage after February. Similarly, bloom duration was defined as the number of days from the initiation date to the last day when CyanoHABs became zero. For the whole lake, the significant CyanoHABs initiation date and last date were defined as the first and last moments when $>25\%$ of the pixels in the lake area showed a non-zero CyanoHABs coverage. The bloom duration of the whole lake was defined from the initiation date to the last date of the whole lake. Initiation dates were transformed into Julian date format.

For each pixel, the bloom frequency was calculated as:

$$F_{ij} = \frac{C_{ij}}{TC_j} \quad (9)$$

where $F_{ij}$ is the bloom frequency of $i$ pixel over $j$ days, $C_{ij}$ is the count of bloom occurrence, and $TC_j$ is the total count of MODIS images.

Meteorological and catchment data

Measurement sites (31) across the whole lake were monitored once a month over the study period (Figure 2).

Transparency was measured by Secchi disk. The permanganate method in acid medium via standard procedure was utilized for measuring permanganate index of chemical oxygen demand (COD$_{m}$) (Zhang et al. 2012b). Total phosphorus (TP) and total nitrogen (TN) concentrations were determined using combined persulfate digestion (Ebina et al. 1983), followed by spectrophotometric analysis for soluble reactive phosphorus and nitrate. The TN and TP recovery efficiencies were 98.4% and 99.7%, respectively. Catchment-based nutrient loading and socioeconomic data (2002 to 2013) were obtained from the Jiangsu Statistics Bureau. Meteorological data, including temperature (T), sunshine hours (S), wind speed (W), and precipitation (P), were obtained from meteorology station #58358 of the China Meteorological Administration (Figure 2).

Environmental driver analysis methods of CyanoHABs dynamics

In our research, CyanoHAB drivers at different time scales were analyzed by detrended correspondence analysis (DCA), principal component analysis (PCA) and redundancy analysis (RDA). Firstly, we determined the gradient lengths between characteristics of CyanoHABs and environmental factors at the same time scale, and found that all of the gradient lengths are $<2$. Then linear models were used to analyze annual,
monthly and daily CyanoHABs drivers. Relationships between the daily and monthly drivers were achieved by PCA, and the relationship between annual CyanoHABs characteristics and environmental factors was made by RDA. All of DCA, PCA and RDA calculations were carried out using CANOCO (Ter Braak & Smilauer 2002) computer programs.

RESULTS AND DISCUSSION

Spatial and temporal changes in CyanoHABs area

Some of the segments in Lake Taihu (especially East Lake and East Taihu, Figure 1) are covered by seasonal water plants (e.g., weed, reed, and other macrophytes) (Ma et al. 2008a), which can be mistakenly identified as CyanoHABs (Figure 1). Therefore, East Lake and East Taihu were excluded from this study (Ma et al. 2008b). CyanoHABs were first observed in Meiliang Bay and Gonghu Bay in June, 1987 (Duan et al. 2009). The extensive and long-lasting CyanoHABs in Lake Taihu during 2007 have been studied by many groups by in situ/remote-sensing data (Guo et al.; Duan et al. 2009; Hu et al. 2010c). Following the 2007 water crisis, a number of local pollution control and integrated watershed restoration projects were initiated. A reduction in bloom extent was evident after 2008. Thus, 2007 was a transition point from which to estimate the efficiency of these projects. In 2013, the bloom areas in Gonghu Bay, Meiliang Bay, and Zhushan Bay in the north lake (Figure 1) were 57.5% to 75.0% smaller than in 2007, and the blooms in West Lake, South Lake, and Central Lake decreased to less than 50% of that of 2007. For the whole lake, the annual average area of CyanoHABs was around 160 km² from 2001 to 2004, then increased to a maximum of 652 km² in 2007, and then subsequently decreased to 370 km² (Figure 3(a)). Given that the results were based on sub-pixel values, these algal bloom areas were lower than those previously provided by traditional methods (Zhang et al. 2014).

In our study we regard 200 and 50 km² as the criteria for severe, moderate, and slight CyanoHABs conditions. In the past, the total number of days with severe algal bloom conditions was used for inter-annual comparison (Figure 4). The total number of days of severe CyanoHABs declined after

![Figure 3](https://iwaponline.com/ws/article-pdf/16/5/1451/411915/ws016051451.pdf)
2007, but the frequency of moderate and slight algal bloom events increased. Considering the individual lake sections and a criterion of 25% algal bloom pixel coverage, a decrease in most lake sections was evident after 2007 (Figure 3(b)).

Spatial and temporal distributions of pixel-bloom frequency

The bloom frequency for each lake segment shows a peak in 2007, and a similar trend between sections (Figure 5). Comparatively, the bloom frequency in West Lake changed most significantly: 8% in 2001, 25% in 2007, and 7.5% in 2013. The algal bloom frequency was the highest in the three northern bays before 2005, and the south and west parts of the lakes became important between 2005 and 2007. Subsequently, the high bloom frequency area shrank from the central lake to the north bays gradually, which was also observed by Hu (Hu et al. 2010c) and Duan (Duan et al. 2014a, 2014b). By 2013, extensive bloom areas were observed only along the west lake shore.

The monthly dynamics in bloom frequency distributions show that the possibility of CyanoHABs is the highest (F > 15%) between July to October and the lowest in February (Figure 6). A typical annual cycle begins in March, with CyanoHABs initiating in the south and spreading north to reach Zhushan, Meiliang, and Gonghu bays (Figure 1). After November, CyanoHABs coverage recedes from the north to the south and disappears in January (Figure 6). Therefore, the CyanoHABs cycle in Lake Taihu starts in February and ends in January. Maximum bloom coverage occurs in Meiliang and Zhushan bays (Figure 6).

Distributions of pixel-bloom initiation date and duration

Fish abundance and lake ecology can be affected by CyanoHABs accumulation (Guo 2007; Ren et al. 2008), and the initiation date and duration of the bloom can be the key parameters to estimate this effect (Duan et al. 2009; Hu et al. 2010c; Zhang et al. 2012a). Given the non-continuous nature of the available cloud-free MODIS images and complicated environmental conditions, the
spatial distributions of the bloom initiation date and duration are rather patchy (Hu et al. 2010c). Over the past 13 years, two distinct temporal changes have occurred, and the period of 2007/2008 is regarded as the turning point (Figure 7). For the whole lake and the segments, excluding Meiliang Bay, CyanoHABs initiation occurred progressively earlier each year before 2007 (Hu et al. 2010c; Zhang et al. 2012a). Since 2007, CyanoHABs initiation has been consistently later, especially in the three north bays (Duan et al. 2014b). Figure 8 shows the spatial distributions of bloom durations between 2001 and 2013. The duration underwent significant changes varying from section to section, with a lake maximum in 2005 and 2006 (Figure 3(d)), which was also coincident with the observations of Hu (Hu et al. 2010c). For the whole lake and most segments, 2004 to 2008 showed a longer bloom duration than the periods from 2001 to 2003 and from 2009 to 2013. After 2004, the CyanoHABs

Figure 5 | Annual CyanoHABs frequency distribution from 2001 to 2013.
were first observed in the south of the lake with a duration of >200 d (Figures 7 and 8).

Environmental drivers of daily CyanoHABs dynamics in Lake Taihu

From the results above-mentioned, an apparent CyanoHABs difference existed among the periods of 2001 to 2003, 2004 to 2008, and 2009 to 2013. Figure 9(a)–9(c) show the relationship between these variables during these specific time ranges associated with changing bloom patterns. Daily assorted CyanoHABs records, including CyanoHABs area, daily temperature, sunshine hours and daily average wind speed, were examined by PCA. The cosine of the angle between every two lines with arrow was decided by their correspondence. In total, the angles between CyanoHABs area and temperature or sunshine hours in Figure 9 were almost right angles, indicating little correspondence between them. But, on the contrary, the angle between CyanoHABs and daily wind speed was larger, which indicated a significant negative correlation. For these specific periods, it also illustrated that daily wind speed affected CyanoHABs more and more, especially after 2004. During 2001–2003, daily temperature showed weak positive correlation with CyanoHABs, but there was almost no influence on CyanoHABs in the other two periods.

Several workers have observed that the formation of near-surface accumulations of buoyant cyanobacteria was dependent on the extent of water column turbulence (George & Edwards 1976; Hunter et al. 2008; Wynne et al. 2010). Cao (Cao et al. 2006) suggested that in Lake Taihu,
wind speeds in excess of 4 m/s can sufficiently induce turbulent mixing in shallow lakes and suppress upward migrations through buoyant cyanobacteria, consistently with other studies (George & Edwards 1976). In Lake Taihu, the average wind speed was about 3.5 m/s over the study period, and the wind speed in summer was much lower than that in winter, which favored CyanoHABs formation and duration. Greater than 80% CyanoHABs with >200 km² took place at low wind speeds (1 m/s to 3 m/s). Given the surface accumulation, vertical heterogeneity can often be compounded by the downwind accumulation of CyanoHABs cells entrained within advective currents, which can lead to patchiness in the spatial distribution of blooms in lakes (Hedger et al. 2002, 2004; Hunter et al. 2008). In Lake Taihu, blooms occurred most frequently with an east–southeast wind, followed by northwest winds. An east–southeast wind favored the accumulation of blooms in the northwest shore and the three bays in the north lake. However, no
significant correlation existed between the wind direction and algal bloom coverage.

Environmental drivers of monthly CyanoHABs dynamics in Lake Taihu

Because of the effect of wind on the formation of the surface mats, the monthly bloom coverage may be better represented by the monthly maxima than by the monthly mean (Hu et al. 2014c). CyanoHABs monthly maxima (MaxCyano) and monthly average of environmental factors, including meteorological factors and water quality indicators, were compared by PCA (Figure 10). Considering the seasonal cycle effects of all environmental factors, PCA was calculated with monthly data anomalies determined as the difference between the monthly value and the mean of the monthly value from 2001...
to 2013. Figure 10 illustrates that COD$_{mn}$, TP and water temperature (WT) always had good positive correlation with MaxCyano as a whole. During 2001–2003, MaxCyano had significant positive correlation with T$_{mean}$, and showed negative relationship with TN/TP, TN and transparency. But after 2004, all of these relationships became less and less noticeable. Especially in 2009–2013, TN and T$_{mean}$ had no influence on MaxCyano. It seemed that TP became the main limiting factor driving MaxCyano in Lake Taihu when severe CyanoHABs happened after 2004, even though, during periods of severe CyanoHABs (especially $>500$ km$^2$), TN/TP ratios ranged from 10:1 to 50:1 and TN concentrations were between 1.0 and 2.0 mg/L, which agreed well with previous studies (Tilman 1982; Liu et al. 2011; Zhao et al. 2011).

Environmental drivers of inter-annual CyanoHABs dynamics in Lake Taihu

Annual initiation date, significant bloom days, pixel-bloom frequency and duration were used to represent characteristics of annual CyanoHABs dynamics. Not only nutrient loads but also meteorological factors were reported to influence bloom dynamics, with both direct and indirect impacts on bloom initiation, frequency, and duration (Hallegraeff 1993; Ding et al. 2007; Kong et al. 2007; Ren et al. 2008; Hu et al. 2010b). Figure 11 shows the trend in annual average anomalies of mean (a), maximum (b) and minimum (c) temperatures, precipitation (d), wind speed (e), sunshine hours (f), transparency (g), TN (h), COD$_{mn}$ (i), TP (j), TN/TP (k) and water temperature (l) during the period of 2000 to 2013 in Lake Taihu. The average air temperature over the past 13 years showed two patterns: 2000 to 2007 was characterized by an increase of 0.11 °C per year, and 2007 to 2013 was characterized by a decrease of 0.2 °C per year. The annual maximum temperatures and precipitation showed no significant trends, whereas the annual minimum temperature was stable except in 2007, when it was 3.9 °C higher than in other years. The daily mean wind speed decreased significantly at an average of 0.044 m/s per year ($p < 0.01$,
Figure 11), whereas the anomaly of average daily sunshine hours increased by 0.6 h (p < 0.01, Figure 11). Considering the nutrient inputs from various sources (sewage, industry discharge, agricultural fertilizer, and other point and non-point runoffs), TBA reported that the TN and TP in West Lake and Central Lake showed a continuous increasing trend between 2000 and 2006 (Zhu 2008), as well as a weak decreasing trend after 2007 (Figure 11). Transparency showed similar dynamics, with a minimum in 2005. However, in Meiliang Bay, the TN and TP showed a continuous decrease after 2004. Comparatively, the COD showed a steady reduction trend during the period of 2003 to 2013. The apparent difference in bloom characteristics over the study period was very likely caused by the variation of nutrients in the lake despite the worst bloom year (2007) and was a little later than the highest-nutrient year (2005 to 2006).

Many studies have reported that temperature, insolation, rain, and wind conditions influence bloom dynamics, with both direct and indirect impacts on bloom initiation (temperature), frequency (wind and rain), and duration (wind and insolation) (Ding et al. 2007; Kong et al. 2007; Ren et al. 2008; Hu et al. 2010c). We used RDA calculation to explore the main drivers of annual CyanoHABs characteristics in Lake Taihu (Figure 12). From the angle between environmental factors and CyanoHABs initiation date or duration (Figure 12(a)), it indicated that T_{mean} and nutrients such as TN, TP and transparency were the main drivers affecting the initiation date and duration of significant CyanoHABs. At high temperatures, cyanobacteria...
demonstrate high growth rates and competitive advantages with respect to diatoms, chlorophytes, and cryptophytes (Paerl & Huisman 2009). The unusually warm temperature caused by climate change may be a contributing factor to the growth and senescence of CyanoHABs (Zhang et al. 2014a; Duan et al. 2014a, 2014b; Huang et al. 2014). Duan found that the increases in the previous winter’s mean daily minimum temperature partially contributed to the early blooming onset (Duan et al. 2013). However, our study showed that the algal bloom initiation date and duration did not correspond well with any temperature variables (p > 0.05), whereas the significant bloom days and average algal bloom frequency were found to be sensitive to ΔTmin. The average winter temperatures (from December to February), daily temperature, and effective accumulated temperature for the period prior to the bloom initiation were compared with the date of the first CyanoHABs observation. A significant correlation existed between the bloom initiation date and the effective accumulated temperature of the prior month (r = 0.98, p < 0.01), but the average winter temperature showed no influence. Excessive nutrient loads from human activities were identified as primary drivers of eutrophication and CyanoHABs in the lake (Duan et al. 2009). General increases in phytoplankton biomass and increases in CyanoHABs frequency and duration have often been correlated with increases in nutrient and COD loads (Hallegraeff 1993). In the conditions of P and N enrichment (TP ≥ 0.20 mg/L, TN ≥ 0.80 mg/L), the growth of dominant bloom-forming cyanobacteria, Microcystis spp., was not limited with nutrients (Xu et al. 2010). Hence, Hu’s study (Hu et al. 2010c) hypothesized that some nutrient threshold levels, below which significant blooms rarely occur, may exist. However, high nutrients were not accompanied by increased significant bloom events, while nutrient concentrations were related to initiation date and duration of CyanoHABs in the whole lake.

Figure 12(a) also indicates that meteorological factors such as Tmin, Tmax, sunshine hours and wind speed affected significant CyanoHABs days and average CyanoHABs frequency of the whole lake. Temperatures from 20 C to 30 C favored CyanoHABs, especially the extreme severe blooms, supporting earlier studies by Liu (Liu et al. 2011). Precipitation dynamics are unlikely to directly influence CyanoHABs beyond the reduction in insolation during the rainy season, showing an expected reduction of algal growth and bloom formation, i.e., few extremely severe CyanoHABs occurred between late June and early July.

The biplot of 13 years’ CyanoHABs and 10 environmental variables in RDA ordination (Figure 12(b)) demonstrates that CODmn, nutrients and temperature affected CyanoHABs significantly before 2003 and during 2005 to 2007. Wind speed and precipitation were the main drivers in 2003, 2004, 2010 and 2011, while there were no
significant environmental drivers of CyanoHABs in the other years.

TWO-SIDE EFFECTS OF HUMAN ACTIVITIES

From this analysis, nutrients appeared to be the key drivers for monthly and annual CyanoHABs dynamics. Lake Taihu Basin is one of the most densely populated and economically productive areas in China. Nutrient loads from sewerage, livestock drainage, soil, and fertilizer loss were identified as primary drivers of eutrophication and CyanoHABs in this lake (Duan et al. 2009). These loads are often linked to economic and population growth. The total gross domestic product (GDP) of Wuxi City and Suzhou City (the two largest cities around the lake) doubled from 2007 to 2013 (up to 778.3 and 1301.6 billion RMB, respectively). Similarly, the population increased at 4.6% per year to an average population density of 1,333 persons per km² (Li 2013). Since the 2007 event, major pollution control and mitigation programs have been initiated in the basin by national and local governments. As a result, the total wastewater discharge of Wuxi City and Suzhou City did not increase at the same rate as local GDP (Figure 13). The total COD discharge of the two cities decreased, and the COD discharge per unit GDP was less than a quarter of that in 2007.

Although the positive impacts of the actions undertaken are still difficult to detect, a decreasing trend of CyanoHABs occurred despite a growth in population and economic activity. A basin-wide water quality improvement will require a long-term and large-scale commitment to a reduction in nutrient loads. An interesting impact on bloom conditions can be observed by examining the bloom dynamics in Gonghu Bay following the activation of the Water Transfer Engineering from Changjiang River in 2004. The transfer of river water to this eutrophic bay coincided with a reduction in algal bloom frequency with respect to similar areas of the lake (Zhushan Bay, Meiliang bay).

CONCLUSIONS

Regular monitoring of CyanoHABs by remote sensing allows a macroscopic and cost-effective assessment of the possible impacts of short-term events (e.g., climate-related) and long-term management and mitigation activities. From the present analysis (2001 to 2013), a decreasing trend was identified after 2007. CyanoHABs develop in nutrient-rich and warm water with low winds and high light availability. The present study indicates that wind speed was the main driver for daily CyanoHABs dynamics. On a monthly basis, COD$_{mn}$, TP and water temperature were strongly correlated to monthly CyanoHABs dynamics. On an annual scale, $T_{mean}$ and nutrients appear to be the main drivers of CyanoHABs initiation and duration, and meteorological factors showed key impacts on significant CyanoHABs days and average bloom frequency. On the whole, excessive nutrients and unusually warm temperature caused by climate change were shown to be the main drivers for CyanoHABs dynamics over an extended time scale.
After 2007, favorable meteorological conditions (e.g., continuous low wind speeds) were not accompanied by increased contributions from reduced nutrient loads and biomass reduction in the lake are evident. Ongoing monitoring using MODIS and other satellite sensors will provide additional data to test our hypothesis.

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