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ORIGINAL ARTICLE

Detection of algal bloom and factors influencing its formation in Taihu Lake from 2000 to 2011 by MODIS

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Abstract Time-series MODIS data were used to extract and characterize algal blooms from the Taihu Lake study area. Water quality data including total nitrogen, total phosphorus, and dissolved oxygen; local meteorology data; and global climate trends were examined to reveal the factors influencing the formation of the algal blooms. Results for the 2000–2011 study period show that the annual algal bloom typically begins between March and May in Taihu Lake. All large-scale blooms originate from northern Taihu Lake (Meiliang Bay and Zhushan Bay). Some small-scale blooms originate from southwestern Taihu Lake, but the duration of these blooms is very brief because of episodes of turbulent mixing due to high wind speed. Nutrient supply is the main factor influencing algal mass propagation during bloom periods, and temperature changes may trigger algal recovery. The algal bloom area significantly decreased when wind speed is greater than 4 m/s, causing turbulence and changes in algal buoyancy. A strong East Asian summer monsoon transporting warm air to the lake is shown to extend the duration of algal blooms in Taihu Lake, as occurred in 2007.

Keywords Algal blooms · MODIS image · El Niño/southern oscillation · East Asian summer monsoon · Taihu Lake

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Introduction

Algal blooms caused by eutrophication are frequently found in highly turbid inland water, such as Taihu Lake, China (Hu et al. 2010b; Duan et al. 2009; Wang and Shi 2008; Guo 2008). These blooms are mostly dominated by *Microcystis aeruginosa*, a kind of cyanobacteria found in inland lake waters (Huang et al. 2011). Algal blooms have a significant influence on the development of the social economy, residential life, and on human health. The harmful toxin in cyanobacteria is believed to be a hazard to mammalian, fish, birds and vertebrate life. Epiphysitis, enterogastritis, and even gastrointestinal cancers caused by drinking cyanobacteria-polluted water have been widely reported (Schwimmer and Schwimmer 1968; Gorham and Carmichael 1979; Carmichael 1986). Algal blooms in Taihu Lake have significantly affected industrial and agricultural production, as well as the life of city dwellers since the 1990s in Taihu Basin. For instance, algal bloom led to massive mortalities of fish and shrimp, and triggered a serious drinking water crisis in the summer of 1998. The notorious drinking water crisis in Wuxi city in 2007 was also due to an algal bloom in Taihu Lake (Wang and Shi 2008; Guo 2008).

It is essential that algal blooms in inland waters be detected, and their distribution and dynamics monitored. While traditional ship-based field sampling and analysis are limited in both space and time, remote sensing technology provides rapid, synchronic, and ongoing water property data, overcoming the shortcoming of traditional methods. As such, remote sensing is a good choice for detecting and monitoring algal blooms. The moderate resolution imaging spectroradiometer (MODIS) and the medium resolution imaging spectrometer (MERIS) are current satellite sources of water color data, popular for studying ocean color and for monitoring inland water quality. A number of studies have been conducted to detect and monitor algal blooms using satellite data (Ahn et al. 2006; Peñaflor et al. 2007; Liu et al. 2009; Wynne et al. 2010; Martinez et al. 2011; Odermatt et al. 2012; Shang et al. 2012; Alikas et al. 2010). Fluorescence line height (FHL) is a well-known index for detecting chlorophyll-a and is widely used in ocean and inland water (Hu et al. 2005). Based on the representation of FHL, several similar indexes have been developed. Gower et al. (2005) developed the maximum chlorophyll-a index (MCI) for MERIS to detect algae and chlorophyll-a according to the reflectance peak at 709 nm caused by chlorophyll-a absorption and fluorescence. Using MCI and MERIS (at full (300 m/pixel) and reduced (1,200 m/pixel) resolution), Gower et al. (2005) successfully detected and assessed the Sargassum distribution in the Gulf of Mexico and North Atlantic Ocean. Another index, the cyanobacteria index (CI), expanded upon the MCI (Gower et al. (2005) for MERIS (Wynne et al. 2006, 2010) and was used to detect and monitor cyanobacteria in Lake Erie (Stumpf et al. 2012). Neither MCI nor CI is specific to floating algal blooms and MERIS full resolution data are also primarily available only for European waters. Consequently, Hu (2009) developed a novel index for MODIS known as the floating algal index (FAI) to detect floating algae, and successfully applied the FAI to Taihu Lake (Hu et al. 2010a, b, c).

The object of this two-part study is to better understand the dynamics behind algal blooms. In the first part of the study, time series chlorophyll-a data from an in situ monitor were used to validate the FAI, and the FAI was then used to detect and extract data from the algal bloom area. In the second part of the study, we used water quality data (total phosphorus, total nitrogen, and so on), weather data (wind speed, wind direction, and water temperature), and climate data [Multivariate El Niño/Southern Oscillation (ENSO) Index (MEI), East Asian summer monsoon] to analyze the factors influencing algal bloom formation.

Data and method

Study area and data description

Taihu Lake is located between 30°90′–31°54′N and 119°55.3′–120°59.6′E. It is the third of the five largest freshwater lakes in China with an area of 2,428 km^2 (water surface area is 2,338 km^2, the islands' area is 90 km^2), and a mean depth of 1.9 m. The water quality in East Lake and in East Bay is much better than in other areas. There is an abundance of aquatic vegetation in these areas, and almost no algal blooms occur. The dynamic ratio [(square root of the area)/depth] of Taihu Lake can reach to 25.4 (Bachmann et al. 2000). Thus, sediment re-suspended by monsoons is a frequent occurrence. In recent years various pollutants, including local industrial and agricultural wastes and residential wastewater, have significantly contaminated the lake (Yang et al. 2010; Wang et al. 2011). Large areas of algae blooms caused by eutrophication of the lake have occurred over many years. The research data in this study include long time series water-quality monitoring data (including total phosphorus, total nitrogen and chlorophyll-a, water temperature, etc.), the FAI, and the algal bloom areas derived from MODIS, weather, and climate data.

The weather data (air temperature, wind speed, wind direction, etc.) were downloaded from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do). The climate data (MEI) were downloaded from the Earth System Research Laboratory—Physical Sciences Division (http://www.esrl.noaa.gov/psd/enso/mei/mei.html). The MODIS data were downloaded from the National Aeronautics and Space Administration (NASA) (http://modis.gsfc.nasa.gov/) and processed using ENVI + IDL image analysis software to extract data from the algal bloom areas. The weather, climate, and MODIS data covered the period from 2000 to 2011. Water quality data were measured by the Wu Xi Environmental Monitoring Center and covers the period from 1997 to 2005 (sampling points shown in Fig. 1). For details regarding the water quality measurement method, please refer to the water and wastewater monitoring analysis method published by the Environmental Protection Department of the People's Republic of China (Guo et al. 2002).

Processing of MODIS data

MODIS level 0 data, downloaded from NASA, were calibrated to the radiance data via SeaDAS software. The gaseous absorption and Rayleigh scattering were corrected using software developed by the MODIS data processing team. The reflectance [$R_{rc}(\lambda)$, where λ is the wavelength] from the processed data was georeferenced to WGS-84 by the georeference MODIS module in the ENVI + IDL software. Finally, the FAI was calculated by the following equation (Hu 2009; Hu et al. 2010b):

$$\mathrm{FAI} = R_{rc}(859) - \left\{ R_{rc}(645) + [R_{rc}(1{,}240) - R_{rc}(645)] \times \frac{859 - 645}{1{,}240 - 645} \right\}$$

where $R_{rc}(645)$, $R_{rc}(859)$, and $R_{rc}(1{,}240)$ are the reflectances at 645, 859 and 1,240 nm, respectively.

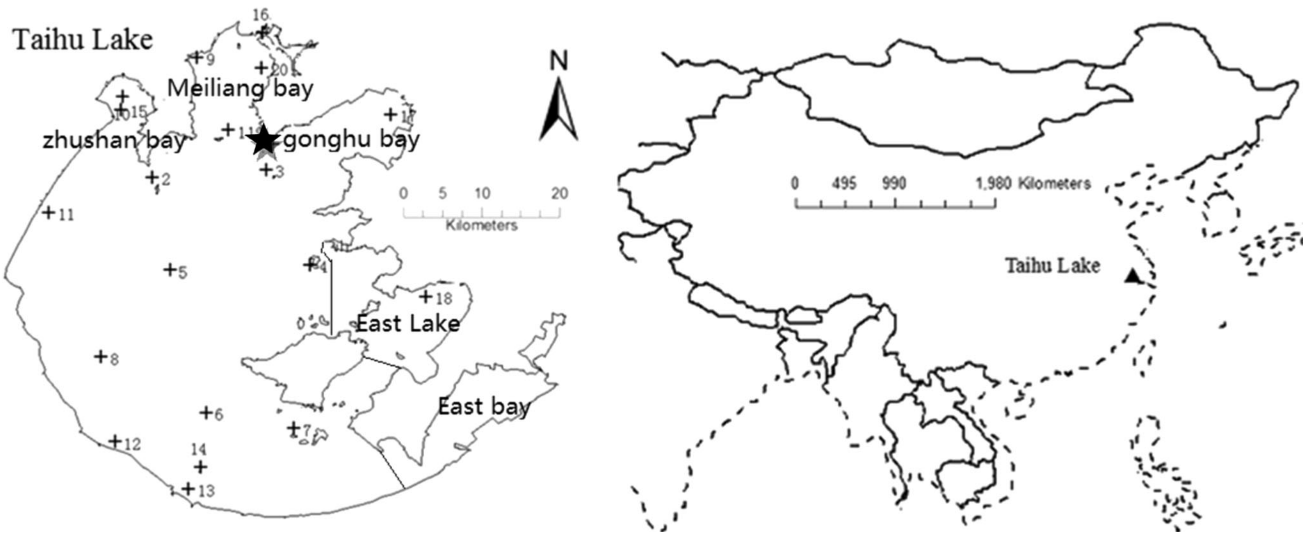


Fig. 1 The *left figure* is the research area (Taihu Lake) and water quality sampling points, the *right figure* is the location of Taihu Lake in China. Eastern Taihu Lake includes East Lake and East Bay

Results

Validation of the FAI in Taihu Lake

FAI is a more stable and better index than either the normalized difference vegetation index (NDVI) or the enhanced vegetation index (EVI) for detecting floating algal blooms in the ocean and in lakes (Hu 2009). However, aquatic vegetation in East Lake and in East Bay can easily be mistaken as floating algae due to the high reflectance of the aquatic vegetation in the near-infrared band. Both of the floating algal bloom areas, excluding eastern Taihu Lake but including East Bay, were counted according to the FAI (at a threshold value of -0.004) (Hu et al. 2010b). Figure 2 shows the multi-year sequence between January 2000 and December 2011 of the mean monthly percentage of the harmful algal bloom (PHAB) area of the total Taihu Lake area observed from MODIS images. The PHAB is dramatically overestimated when the eastern Taihu Lake area is included in the summer and autumn data, but is not so distinct a problem in the spring and winter data. The overestmation may be caused by one of the following three factors. First, aquatic vegetation may cause the overestimation of PHAB. Second, water turbidity, which reduces the reflectance of aquatic vegetation that transfers to the water surface, may decrease the actual estimation of PHAB caused by aquatic vegetation. Third, the overestimated PHAB may in fact be due to algae floating in from other areas. According to our in situ data and results from a previous study (Ma et al. 2008), most of the time, the first and the third factors account for the overestimation. To avoid the complex influence of aquatic vegetation on our algal bloom estimations, we decided to exclude from our analyses PHAB estimations for the eastern Taihu Lake area, based on the previous in situ investigations and upon the suggestion of Hu et al. (2010b).

Comparisons between the in situ measurements of the concentration of chlorophyll-a ($C_{\text{chl-a}}$) and PHAB from January 2000 to November 2005 (Fig. 3) show that there is good consistency and correlation between $C_{\text{chl-a}}$ and PHAB (correlation coefficient (refer to Person correlation coefficient) is 0.66, $p < 0.0005$, $N = 66$). However, some cases are not consistent, especially in July 2005 (see point in the ellipse in Fig. 3). This will be discussed in "Drifting and mixing effect of wind". This overall consistency indicates that the FAI is a valid method for detecting algal blooms in Taihu Lake, although the factors influencing the consistency between $C_{\text{chl-a}}$ and PHAB are complex and varied.

Spatial and temporal distributions of harmful algal bloom

Figure 4 shows the spatial and temporal distribution of algal blooms in Taihu Lake from January 2006 to December 2008. The spatial distribution of algal blooms indicates that the most significant blooms initially occurred in Meiliang Bay and Zhushan Bay, where the lake provides freshwater to more than three million people living in Wuxi and Yixing cities. The algae then proliferate from northern Taihu Lake into western and central Taihu Lake. Mass propagation of algae begins when dormant algae that had previously sunk below the surface, begins to recover (Kong et al. 2009). This assumption suggests that the first place the algal bloom occurs might be where the floating algae sank in the previous year. Most of floating algae in Meiliang and Zhushan Bays typically settles to sediment

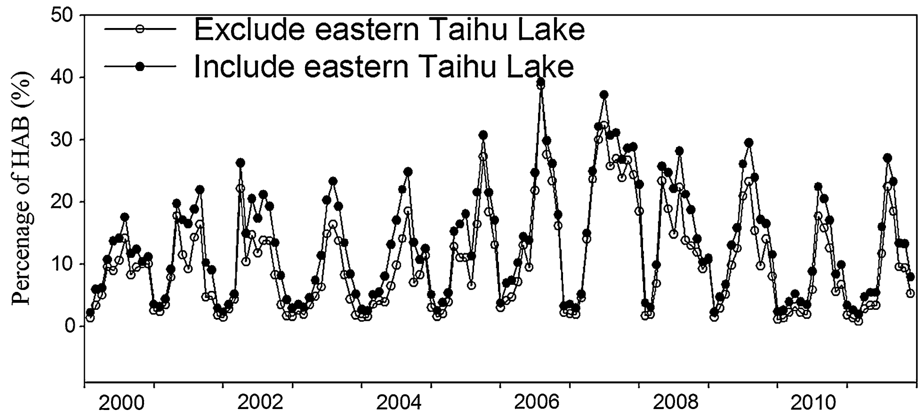


Fig. 2 Percentage of algal bloom areas in Taihu Lake area from January 2000 to December 2011 [PHAB is the monthly mean value according to Hu et al. (2010a, b, c)]. The area of algal bloom is calculated by counting the number of pixels, with FAI value is > −0.004

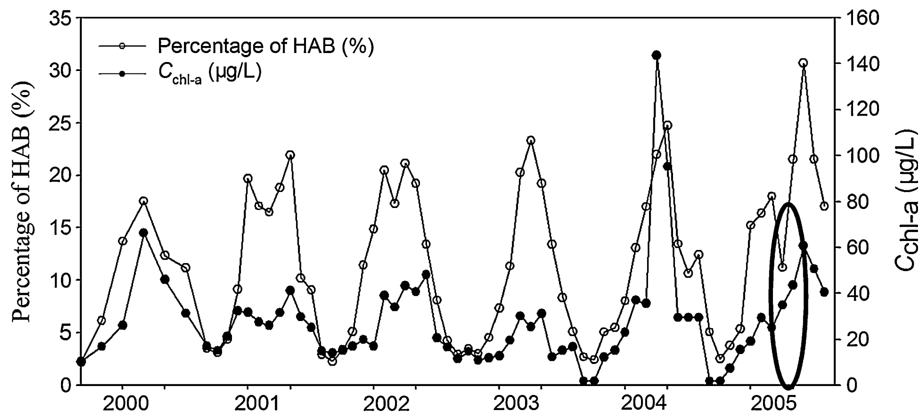


Fig. 3 Comparison between C_{chl-a} and PHAB from January 2000 to November 2005. The C_{chl-a} is the pace and monthly mean value (except point 18, because it is in eastern Taihu Lake)

and the remaining algae floats towards southern Taihu Lake. The earliest record of the place where an algal bloom occurred was in March 2007, and this is where the floating algae had disappeared in southwestern Taihu Lake in November 2006 (Fig. 4; 2006). However, large areas of algal bloom also occurred in Meiliang and Zhushan Bays. This may be because Meiliang and Zhushan Bays are semi-enclosed bays, and the influence of the wind turbulence mixing effect in Meiliang and Zhushan Bays is smaller than in the open areas of southwestern (or western) Taihu Lake. An algal bloom occurred in southwestern Taihu Lake in March 2007 and that area increased in April 2007, but the bloom disappeared in May 2007. Meanwhile, a substantial bloom area occurred in Meiliang and Zhushan Bays (Fig. 4; 2007). The 2007 bloom began in March 2007 and lasted into February 2008 (Fig. 4). These long-lasting blooms in 2007 caused the notorious "2007 bloom event".

The spatial and temporal distribution of the algal blooms reveals that the sediment re-suspension, caused by high wind speed, released a large number of dormant algal spores from the sediment to the water column, and this was conducive to the algae's recovery. However, high wind speed makes it hard for a large area of algal bloom to form. Consequently, conditions in southwest Taihu Lake are more conducive for the formation of algal blooms, but less conducive for the formation of large areas of algal blooms.

Drifting and mixing effect of wind

Wind has two significant effects on algal distribution: a drifting effect during periods of low wind speed and a turbulent mixing effect during high wind speed periods. Figure 5a shows the drifting effect when the mean wind speed is 2.3 m/s and the maximum wind speed is 5.6 m/s. The algae floated in a southerly direction due to the northerly wind. The algae in Meiliang Bay moved to central Taihu Lake, and algae in Zhushan Bay diffused to the western side of the lake. In the lake's eastern area, aquatic vegetation is virtually stationary (the green circle), but the algae shows a significant shift (the red circle). This comparison easily distinguishes the aquatic vegetation from the algae. However, the area in the yellow circle is a mixture of aquatic vegetation and algae, and it is hard to separate them there, as discussed in "Validation of the FAI in Taihu Lake".

Figure 5b shows that the area of the algal bloom decreased when under the effect of turbulence mixing due to high winds. Compared with the 2009290-1 image, the area of algal bloom in 2009290-2 is significantly reduced, from 14.7 to 4.2 %, especially in Meiliang and Zhushan Bays. While turbulent mixing can reduce the area of algal bloom, it does not decrease the algae's total biomass. The ellipse in Fig. 3 shows that the PHAB is significantly

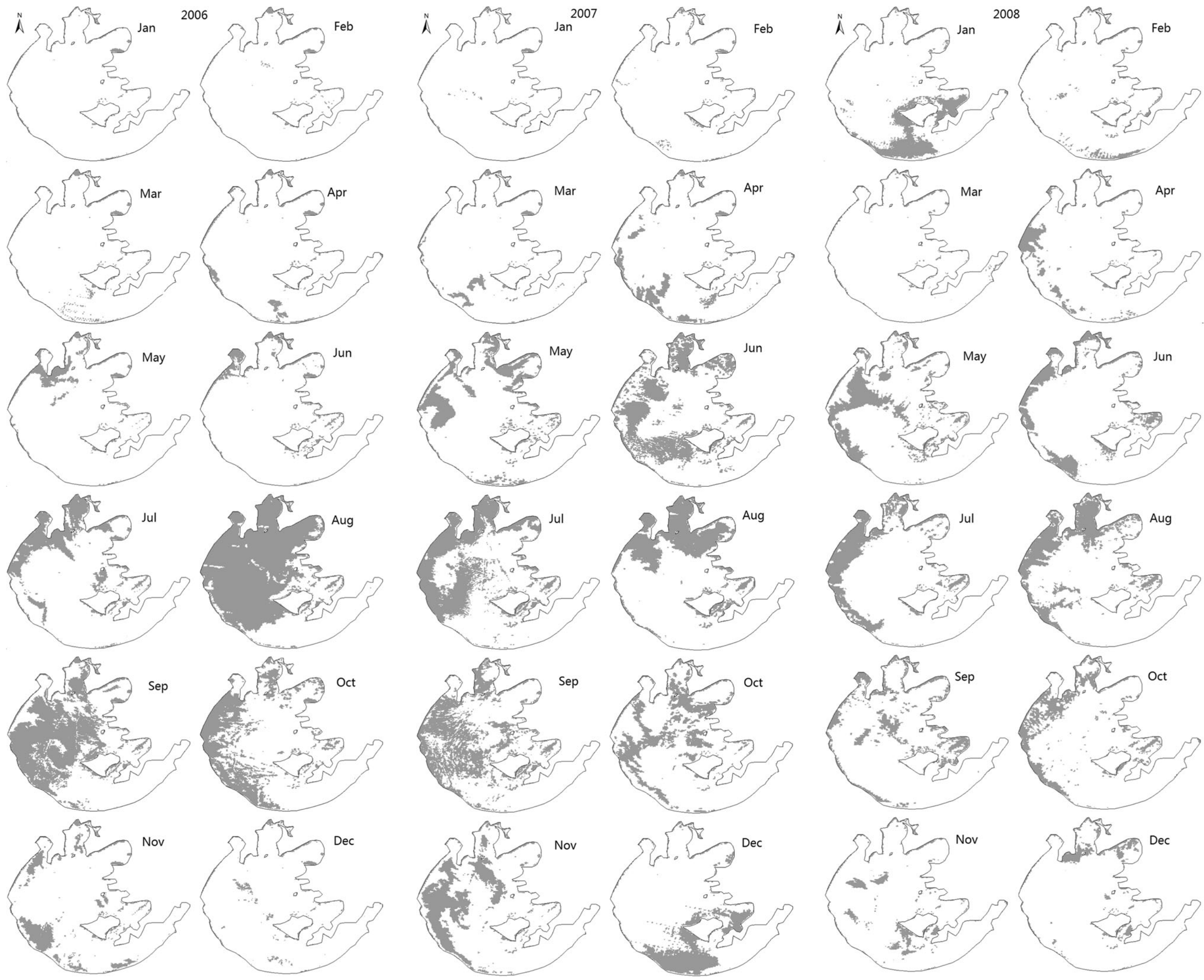


Fig. 4 Spatial and temporal distribution of PHAB from January 2006 to December 2008

reduced, but $C_{\text{chl-a}}$ continues to increase during the June 2005 to September 2005 period. This is due to the high wind speed (wind speed: June 2.9 m/s, July 4.4 m/s, August 3.3 m/s, September 2.5 m/s) suspending the floating algae in the water column, but having almost no effect on the $C_{\text{chl-a}}$.

Nutrients, water temperature and other water chemical parameters

While wind speed has a considerable effect on the formation and disappearance of algal blooms, algal biomass is the actual determinant of the extent of an algal bloom and $C_{\text{chl-a}}$ is a useful indicator of algal biomass. Consequently, a correlation analysis between $C_{\text{chl-a}}$ and the factors influencing algal blooms is used to confirm the effect of nutrients, water temperature and water chemical parameters on algal blooms. Figure 6a shows the correlation coefficients between $C_{\text{chl-a}}$ and water chemical properties. The highest correlation coefficient for each year occurs between May and September (marked in Fig. 6a), when chemical and biological activity is relatively strong. The correlation coefficients between $C_{\text{chl-a}}$ and chemical and biochemical oxygen demand (COD and BOD) are much larger than those between $C_{\text{chl-a}}$ and *pondus hydrogenii* (PH) and dissolved oxygen (DO). This suggests that the hypoxia levels in Taihu Lake are highly correlated to the algal blooms.

Nutrients are highly correlated with $C_{\text{chl-a}}$, especially in the summer and autumn (maximum correlation coefficients are marked in Fig. 6b). This is likely due to the high nutrient requirements of algae during growth phases. Compared to the correlation coefficients between TN and $C_{\text{chl-a}}$ and between TP and $C_{\text{chl-a}}$, TP influences $C_{\text{chl-a}}$ more strongly than does TN. Therefore, controlling the nutrients in Taihu Lake, especially TP, will be crucial for curbing future eutrophication and algal blooms.

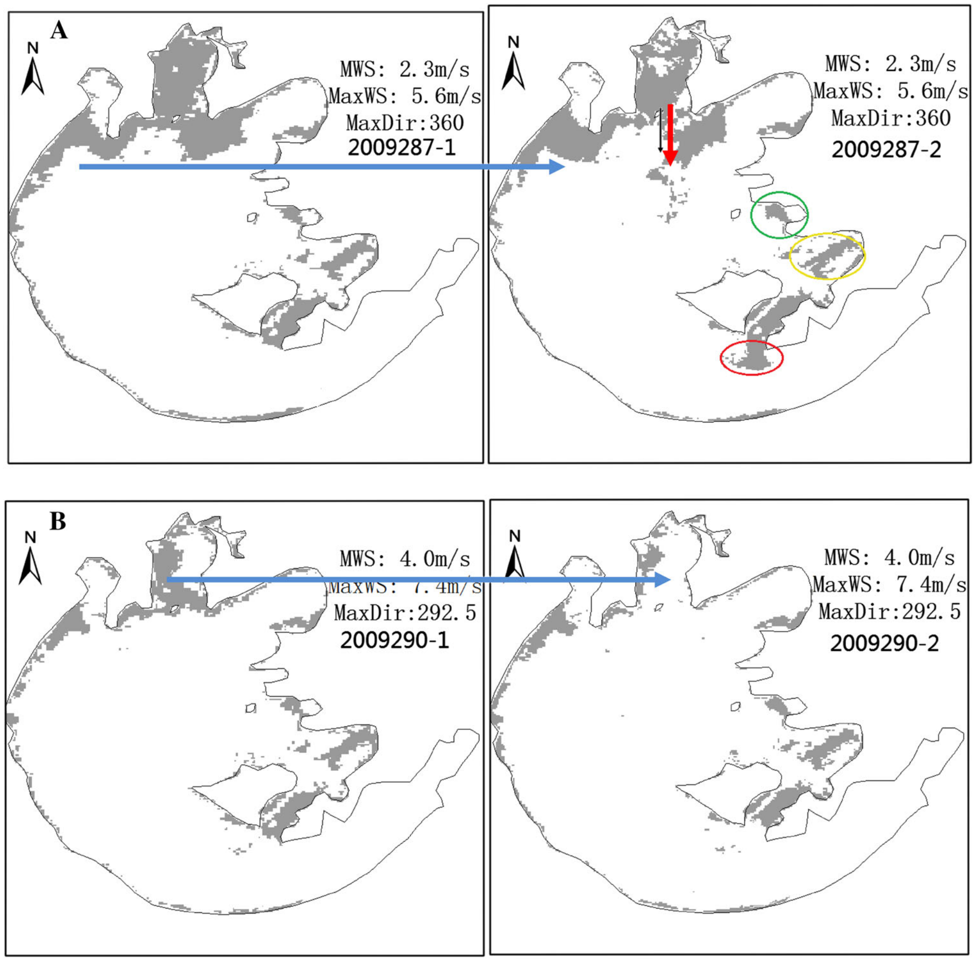


Fig. 5 **a** Drifting effect of wind, these two images are in the same data (20092870325 and 20092870500) at different times. MWS is mean wind speed, MaxWS is maximum wind speed, MaxDir is direction of maximum wind speed. The north direction is defined as 0 or 360, and east direction is defined as 90, south direction is defined as 180, and west direction is defined as 270. *Red arrow* is the wind direction, similar to MaxDir. **b** Suspended effect of wind, image times are 20092900215 and 20092900531, respectively

Discussion

Effect of global climate on harmful algal blooms

The above analyses suggest that algal blooms in Taihu Lake are not only driven by nutrient status, but are also regulated by weather conditions. In fact, recent studies show that algal blooms are also affected by climate (Cloern et al. 2005; Moore et al. 2008). Climate warming may benefit some species of algae, providing more optimal growth conditions (Paerl and Huisman 2008, 2009). The time series data for air and water temperature show that the air and water temperatures in winter 2006 were warmer than in other study years (Fig. 7). The balmy winter temperatures caused the 2007 algal blooms to occur much earlier than in other years (see Fig. 4, algal bloom distribution in 2007). Under the effect of the warm climate, the duration of algal bloom extended from February 2007 to February 2008. Moreover, the colder winters in 2002 and 2008 delayed the 2003 and 2009 algal bloom starting times. This indicates that climate warming could lead to greater and earlier algal blooms.

Taihu Lake, located in the Yangtze River Delta, has an East Asian monsoon climate. Thus, the East Asian monsoon and the ENSO markedly affect the climate of the Taihu Lake area. The ENSO is the coupled ocean–atmosphere phenomenon causing the most global climate variability on inter-annual time scales. The MEI rank and East Asian summer monsoon index (EASMI) are used to reveal their potential influence on algal bloom. A weak El Niño occurred approximately four times from 2000 to 2011, specifically in 2002, 2005, 2006, and 2009 (Fig. 8). A strong La Niña event occurred only twice from 2000 to 2011, in 2007 and 2010. A very substantial algal bloom occurred in 2007, causing the drinking water crisis in Wuxi city. However, the algal bloom area in 2010 was smaller than in 2007. This might be because the farmers around Taihu Lake began salvaging algae in 2008, salvaging a total of 2.8 million tons of algae from 2008 to 2012. There is obvious correlation between PHAB and MEI rank. The correlation coefficients between PHAB and MEI rank is strong in the 2007 and 2010 La Niña years, −0.83 ($N = 12$) and −0.73 ($N = 12$), respectively. However, the correlation coefficients between PHAB and MEI rank in

Fig. 6 Correlation coefficients between $C_{\text{chl-a}}$ and nutrients, and water temperatures from 1996 to 2005. *PH pondus hydrogenii*, *DO* dissolve oxygen, *CODMN* chemical oxygen demand, *BOD5* biochemical oxygen demand for 5 days, *TN* total nitrogen, *TP* total phosphorus, *NH4-N* ammonia nitrogen, Temperature is the water temperature

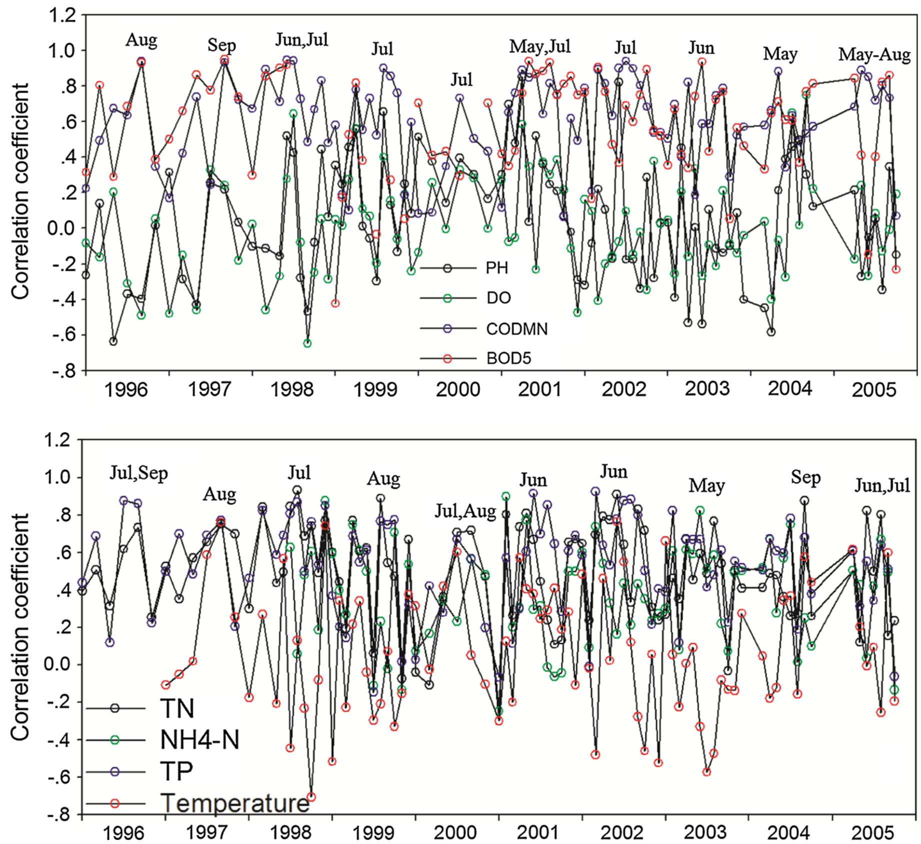
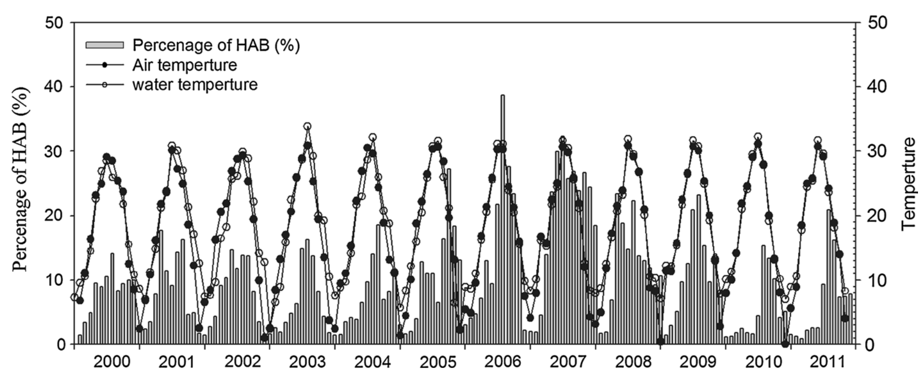


Fig. 7 Monthly mean value of PHAB and water, air temperature from February 2000 to November 2011



the weak El Niño years (2002, 2005 and 2006) are only 0.39 ($N = 12$), -0.61 ($N = 12$), and 0.57 ($N = 12$), respectively (Fig. 9).

The strong La Niña year in 2007 indicates that more warm air transferred from the ocean to inland by the strong EASM effect. This warm air helped to extend the duration of the algal bloom in 2007. There is an apparent negative correlation between the EASMI and summer rainfall in the middle and lower reaches of the Yangtze River in China (Li et al. 2010). Drought years are associated with a strong EASM (high EASMI) and flood years with a weak EASM (low EASMI). The flood year with a weak EASM in 2006 would have produced a large run off of nutrients from Taihu Lake's total watershed. 2006 also experienced more heavy rain periods than did 2007 (*Wuxi statistical yearbook* Wuxi Municipal statistics Bureau 2008). The strong EASM in 2007 resulted in a drought year, so the reduced rainfall also resulted in a reduction in the algal bloom.

Effect of lake morphology and algal buoyancy to algal bloom

Increasing the gas-filled cavities in algal cells reduces algal cell density. Decreasing algal cell density leads to the algae floating on the surface and the formation of algal blooms. Several studies suggest that the formation of floating algal blooms is dependent on the strength of water column turbulence (Yamamoto and Okai 2000; Webster and Hutchinson

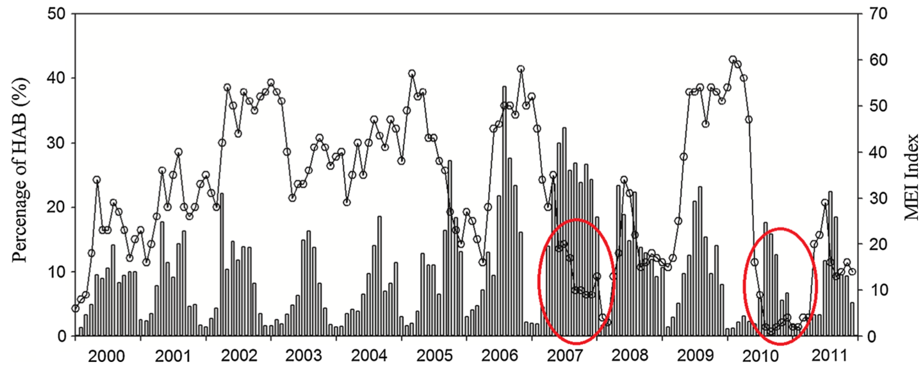


Fig. 8 Monthly mean value of PHAB and MEI ranking from 2000 to 2011. MEI ranking from 1 to 19 denotes weak to strong La Nina conditions, while 44–62 denotes weak to strong El Nino conditions

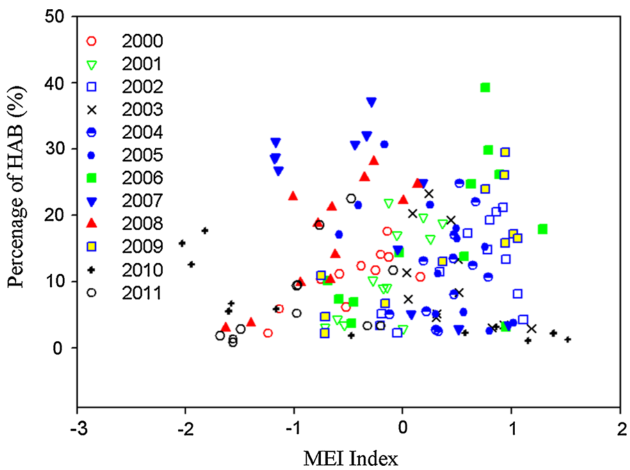


Fig. 9 Scatter diagram comparing PHAB and MEI index

1994; Fennel and Boss 2003; Wong et al. 2007; Carstensen et al. 2007). In fact, both algal buoyancy and water turbulence control the relative sinking and floating status of algae (Humphries and Lyne 1998; Brookes and Ganf 2001). Algal bloom areas decrease when diurnal wind speed exceeds approximately 4 m/s (Fig. 5b). This is consistent with the observation of Cao et al. (2006), who suggested that near surface aggregations of *M. aeruginosa* in Taihu Lake were only observed when the wind speed was less than 4 m/s. However, this value is less than that observed by Hunter et al. (2008) (6 m/s) in Barton Broad (UK) with a 0.81 dynamic ratio (mean depth 1.4 m and maximum area 1.3 km^2). This is also lower than observations made by Wynne et al. (2010) (7.7 m/s) in Lake Erie with a 8.44 dynamic ratio (mean depth 19 m and maximum area 25,744 km^2). Webster and Hutchinson (1994) found that *Microcystis* algae disappeared when wind speed exceeded 3.6 m/s in Clear Lake with a 1.64 dynamic ratio (mean depth 8.2 m and maximum area 180 km^2) by numerical simulation and in situ observation. Binding et al. (2011) utilized the function described by Oliver and Ganf (2000) to reveal that the threshold wind speed, at which an algal bloom might be dispersed, is 3 m/s in Wood Lake with an 8.3 dynamic ratio (mean depth 7.9 m and maximum area 4,348 km^2). The empirical model of algal particle size and buoyant velocity (Wallace et al. 2000) suggests that the buoyant velocity of an algae colony in Taihu Lake can reach 0.009 m/s (with the radius of the algal colony being 750.236 μm). A high buoyant velocity of algae generally requires great turbulence (high wind speed) to suspend floating algae into the water column. However, the high dynamic ratio of Taihu Lake generates considerable turbulence at low wind speed, resulting in a very high buoyant velocity of the algae colony in Taihu Lake, so floating algae are easily suspended in the Lake Taihu water column without requiring high wind speed. The relationship function between the threshold wind speed (W_s) and the dynamic ratio (R_{dr}) can be expressed as $W_s = 4.867 \times (R_{dr})^{-0.1}$ according to the data in Hunter et al. (2008), Webster and Hutchinson (1994), Binding et al. (2011) and in this study. (The data in Lake Erie is not included here due to the strong influence of rainstorm.)

Conclusion

Based on our quantitative analysis of the Taihu Lake algal bloom distribution and the relationships between the algal bloom area and water qualities, and weather and climate data, some following promising conclusions can be made from this study.

First, the FAI is a stable and good index for detecting floating algal blooms in Taihu Lake, although the floating algal area is overestimated because of the influence of aquatic vegetation (the position of aquatic vegetation is nearly fixed).

Second, wind is a primary factor influencing the formation of floating algal blooms. The bays of the lake are great places to form floating algal blooms, whereas open lake areas are less conducive environments for the formation of floating algal blooms over time. Algal bloom areas decrease considerably when wind speed is greater than 4 m/s, according to satellite observations.

Third, warming weather benefits the occurrence of algal blooms, and a strong EASM transports more warm air and helps to extend the duration of algal blooms.

Finally, both the algal bloom size (radius) and lake morphology (dynamic ratio) affect the vertical distribution of algae. A large algal colony radius and a low dynamic ratio readily lead to the formation of a floating algal bloom.

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