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SHORT COMMUNICATION

# Are algal blooms occurring later in Lake Taihu? Climate local effects outcompete mitigation prevention

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Using Landsat and Moderate-resolution Imaging Spectroradiometer (MODIS) satellite data, cyanobacteria bloom initiation dates over two decades (1987–2011) in Lake Taihu showed three distinct trends. Initial blooms occurred later each year between 1987 and 1997 and then generally earlier until 2007, when the earliest and most extensive blooms occurred. After 2007, bloom initiation dates occurred later each year. Climate and catchment control over bloom dynamics was observed, in particular winter temperature minima and nutrient ratios.

KEYWORDS: bloom initiation; climate change; nutrients; Lake Taihu

The occurrence of cyanobacterial harmful algal blooms (CyanoHABs) has increased in both fresh and marine waters throughout the world, with associated negative effects on human health and aquatic life. CyanoHABs pose a major threat to drinking and irrigation water supplies, as well as fishing and recreational use of surface

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waters (Paerl *et al.*, 2011). In May 2007, a massive *Microcystis* dominated CyanoHAB in Lake Taihu overwhelmed the Wuxi water treatment facilities, leaving more than 1 million people without drinking water for a week (Guo, 2007). This event brought Lake Taihu into the national spotlight and drew the attention of the international scientific community.

Changes in the timing of bloom initiation can have significant effects on life cycles of upper trophic levels, influencing vulnerable phases of larval fish and zooplankton growth cycles, with implications for community composition (Koeller *et al.*, 2009; Brody *et al.*, 2013). However, bloom initiation is high variable and difficult to identify in the annual cycle of phytoplankton biomass (Vargas *et al.*, 2009). Satellite remote sensing provides a valuable tool to examine phytoplankton bloom initiation at a basin scale. In the present study, we focus on bloom initiation dates in Lake Taihu determined by satellite data over more than two decades (1987–2011). We evaluate the trends and tipping points in bloom dynamics and explore the underlying mechanisms of these changes.

This work was based on operational Moderate-resolution Imaging Spectroradiometer (MODIS) 250-m resolution data and Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data at 30-m resolution. MODIS Level-0 (raw digital counts) data from both Terra and Aqua satellites were obtained from the U.S. NASA Goddard Flight Space Center (GSFC), and Landsat data including nearly all cloud-free images over Lake Taihu since 1987 were provided by the United States Geological Survey (USGS).

MODIS images were selected with minimal cloud cover (<25%), allowing for more than 700 near cloud-free Level-0 granules of Lake Taihu between February 2000 and December 2011. MODIS Level-0 data were converted to calibrated radiance data using the SeaDAS software package (version 6.1). Atmospheric absorption and Rayleigh scattering were corrected using computer software provided by the MODIS Rapid Response Team, based on the 6S radiative transfer calculations code (Vermote *et al.*, 1997). The resulting reflectance data, $R_{rc}$ ($\lambda$), where $\lambda$ is the wavelength center of the MODIS bands (469, 555, 645, 859, 1240, 1640, 2430 nm), were geo-referenced to a cylindrical equidistance (rectangular) projection. The resulting geo-reference errors were <0.5 pixel. Bloom initiation date was defined as the first observation of surface bloom area >150 km$^2$. Note that these are surface accumulations and initiation date is not intended to identify the start of cyanobacteria bloom within a water column. Blooms were identified using the Floating Algae Index (FAI) algorithm (equation 1 for MODIS data) with the threshold −0.004 (Hu *et al.*, 2010):

$$\begin{aligned} \text{FAI} &= R_{rc}(859) - R'_{rc}(859), R'_{rc}(859) \\ &= R_{rc}(645) + (R_{rc}(1240) - R_{rc}(645)) \\ &\quad \times (859 - 645)/(1240 - 645). \end{aligned} \tag{1}$$

Owing to the longer revisit time (16 days), Landsat data may not capture the initial bloom date. Previous research on the same lake shows a strong consistency between Landsat and MODIS for the detection of the bloom initiation ($Y = 0.85X + 32.148$, with $N = 8$, $R^2 = 0.83$ and $P < 0.0001$; Duan *et al.*, 2009). Given that they were correlated, we limited the use of Landsat data to the identification of inter-annual trends. A Landsat specific FAI algorithm in a similar fashion as with MODIS was used to retrieve the bloom initiation between 1987 and 2000. $R_{rc}$ data at 660, 825 and 1650 nm were used to generate the Landsat FAI images in a similar manner to Equation (1) (Hu *et al.*, 2010).

Algal blooms occurred every year between 1987 and 2011 (1988 and 1999 were not included in this analysis due to a limited number of available images). Three distinct tendencies were detected (Fig. 1a). Between 1987 and 1997, the initial algal bloom showed a negative trend, with a mean delay of more than 5 days per year. In the second decade of our analysis, 1997–2007, bloom initiation showed a positive trend (earlier) of nearly 10 days per year. After 2007, the bloom initiation again showed a negative trend, averaging nearly 12 days later each year until 2011.

There is a general consensus that the formation of cyanobacterial blooms is a result of synergistic combination of environmental factors and nutrient concentrations. To quantify the impacts of anthropogenic activities and short-term climate variability on bloom dynamics, a comparison of initial blooming date was made with minimum winter temperature (Tem), nutrient concentrations (TP and TN) and nutrient ratio (TN:TP) (Table I). The winter minimum temperature was defined as the average of daily minimum temperature measured between November and January of the previous winter. Data were obtained from the local lake meteorological station. Total phosphorus (TP) and total nitrogen (TN) concentrations were determined using persulfate digestion and spectrophotometric analysis for soluble reactive phosphorus and nitrate at the Taihu Laboratory for Lake Ecosystem Research, China.

In the present analysis, the initial blooming date appears to be strongly sensitive to nutrient concentrations since TP and TN:TP had the highest correlation to initial blooming date (Table I). TP was found to play a more central role in bloom formation with respect to TN. This

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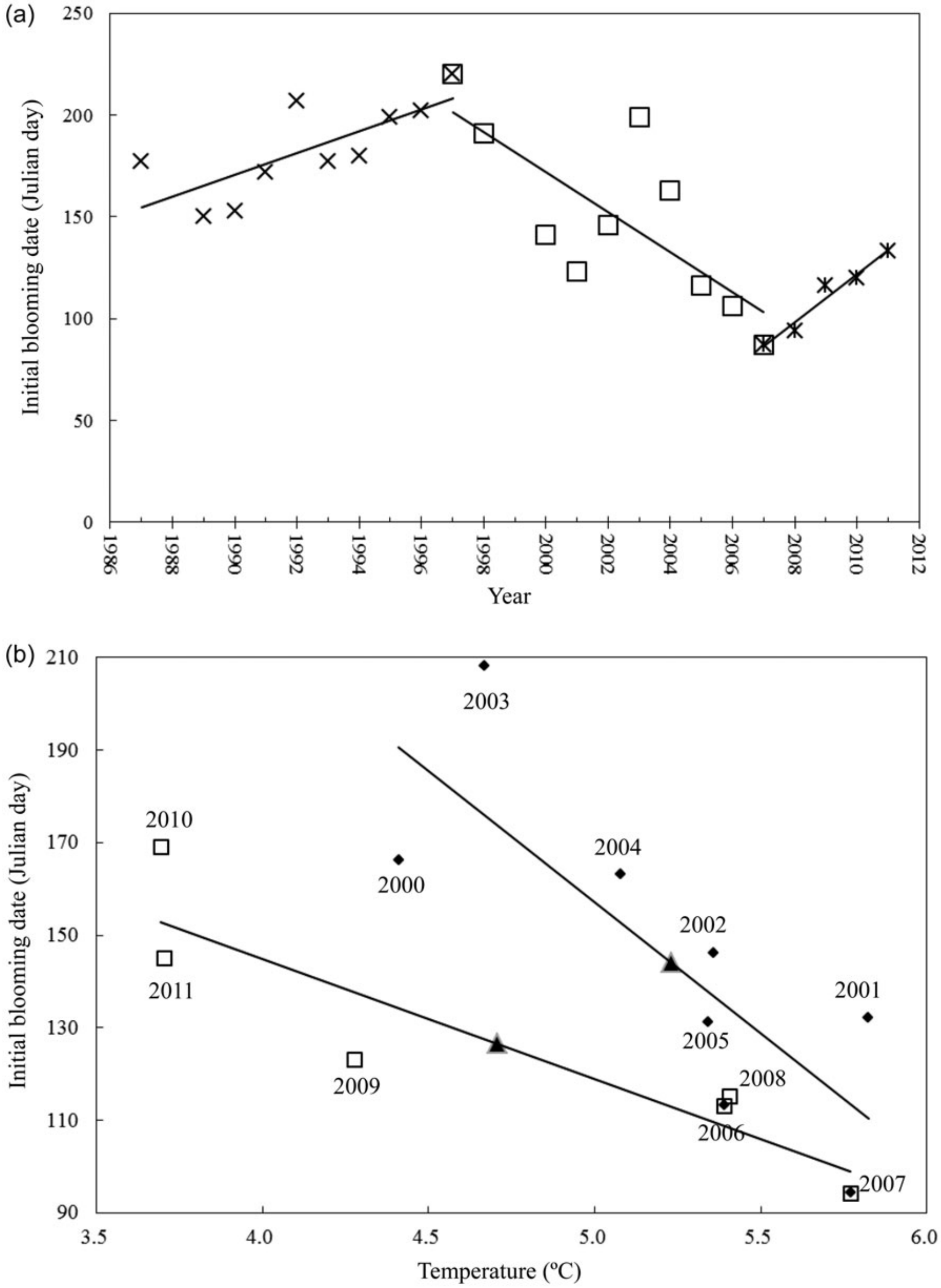


**Fig. 1.** (**a**) Initial bloom date for each year from 1987 to 2011 (1987–2007: $Y = 5.35X - 10\,473$, with $R^2 = 0.56$ and $P < 0.05$; 1997–2007: $Y = -9.84X + 19\,844$ with $R^2 = 0.57$ and $P < 0.05$; 2007–2011: $Y = 11.80X - 23\,596$ with $R^2 = 0.96$ and $P < 0.01$). (**b**) Regressions between initial blooming date and the previous years' winter minimum temperature. (The regressions for 2000–2007 and 2006–2011 were: $Y = -56.8X + 441.2$, with $R^2 = 0.63$ and $P < 0.05$; and $Y = -26.0X + 249.0$, with $R^2 = 0.82$ and $P < 0.05$). Solid diamonds represent the data between 2000 and 2007; empty squares represent the data between 2006 and 2011; solid triangles represent the average data between 2000–2007 and 2006–2011, respectively.

result is consistent with the P limitation observed in Lake Taihu in the winter and spring with respect to N limitation observed during the summer and fall months (Paerl *et al.*, 2011). Interestingly, TP concentrations were found to have a negative relationship with initial blooming date, indicating that high TP is associated with earlier bloom



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*Table I: Regression analysis of blooming initiation dates and environmental factors (the previous year's winter minimum temperature (Tem: °C), the current year's average TN (mg/L), the current year's average TP (mg/L), and TN:TP) during 2000–2011 (sample number = 12)*

| Group | Variables | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $b$ | $R^2$ | $P$ |
|---|---|---|---|---|---|---|---|---|
| 1 | Tem | −21.20 | | | | 246.18 | 0.26 | 0.09 |
| | TP | −1077.40 | | | | 286.08 | 0.38 | 0.03[a] |
| | TN | 3.30 | | | | 129.92 | 0.01 | 0.84 |
| | TN:TP | 3.82 | | | | 36.14 | 0.33 | 0.05[a] |
| 2 | Tem and TP | −8.87 | −852.73 | | | 299.61 | 0.41 | 0.09 |
| | Tem and TN | −32.34 | 24.67 | | | 210.02 | 0.43 | 0.08 |
| | Tem and TN:TP | −22.98 | 4.07 | | | 141.86 | 0.63 | 0.01[a] |
| | TN and TP | 17.42 | −1303.25 | | | 252.11 | 0.49 | 0.05[a] |
| | TN and TN:TP | −34.41 | 7.03 | | | 73.55 | 0.56 | 0.02[a] |
| | TP and TN:TP | −815.27 | 2.63 | | | 177.92 | 0.49 | 0.04[a] |
| 3 | Tem and TN and TP | −19.84 | 26.34 | −916.39 | | 264.98 | 0.60 | 0.05[a] |
| | Tem and TN and TN:TP | −17.46 | −13.36 | 5.26 | | 131.02 | 0.65 | 0.03[a] |
| | Tem and TP and TN:TP | −19.97 | −198.50 | 3.75 | | 162.53 | 0.64 | 0.04[a] |
| | TN and TP and TN:TP | −137.06 | 2750.95 | 20.61 | | −293.27 | 0.62 | 0.04[a] |
| 4 | Tem and TN and TP and TN:TP | −16.33 | −107.57 | 2487.97 | 17.66 | −204.48 | 0.70 | 0.05[a] |

Equations for Group 1: $y = a_0x + b$; for Group 2: $y = a_0x_0 + a_1x_1 + b$; for Group 3: $y = a_0x_0 + a_1x_1 + a_2x_2 + b$; for Group 4: $y = a_0x_0 + a_1x_1 + a_2x_2 + a_3x_3 + b$.
[a]Indicates the regression is statistically significant.

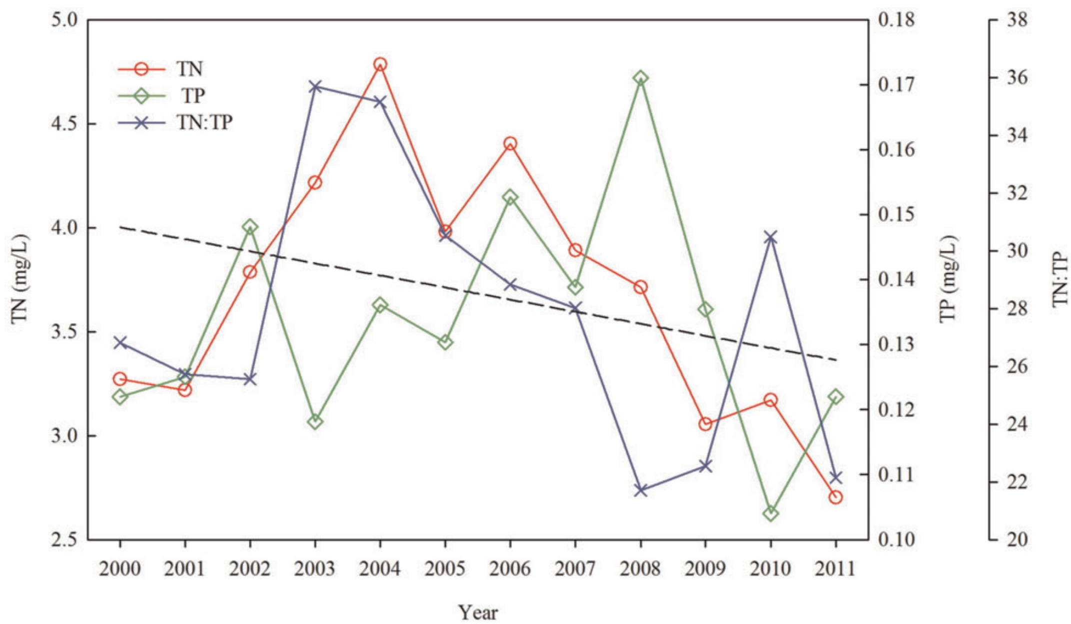


**Fig. 2.** Annual mean TN and TP concentrations and nutrient ratio (TN:TP) during 2000–2011 in Lake Taihu (data provided by Taihu Laboratory for Lake Ecosystem Research).

formation. Nutrient ratios were also well correlated to initial blooming dates. Recent studies in Lake Taihu's Meiliang Bay confirmed that *Microcystis* tends to dominate at low TN:TP (Liu *et al.*, 2011). Similar relationships have been reported in earlier studies of cyanobacteria dominated lakes (Smith, 1983).

Meteorological conditions (air temperature, wind, rain, etc.) have been found to influence bloom dynamics (Qin *et al.*, 2010) and temperature is an important factor in bloom formation (Zhang *et al.*, 2012). Winter minimum temperature and initial blooming date have several links, as higher temperatures: (i) improve algal survival over winter (Shikata *et al.*, 2008); (ii) facilitate algal recruitment (Kong and Gao, 2005) and (iii) increase activity rates of the enzymes responsible for algal blooms (Duan *et al.*, 2009). The absence of benthic recruitment has been shown to



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reduce summer algal blooms by 50% (Verspagen *et al.*, 2005). Several studies hypothesize a benthic "seed bank" for highly adaptable cyanobacterial recruitment, where higher winter temperatures reduce die back of benthic cyanobacteria in lake sediments (Kong and Gao, 2005; Tan *et al.*, 2008).

In Lake Taihu, winter minimum temperature alone was not significantly correlated with bloom initiation, even though an earlier study indicated a simple negative correlation between winter temperature and bloom occurrence in the same lake (Duan *et al.*, 2009). However, when the dataset was divided into pre-2007 and post-2007, significant relationships between initial blooming data and minimum temperature ($P < 0.05$) emerged (Fig. 1b). The initiation of algal blooms in April 2007 was the earliest recorded of the series (1987–2011). Following 2007, there is a clear shift in initial blooming dates and the correlation to winter minimum temperature. The exceptional bloom of 2007 appears as a tipping point for temperature control of bloom dynamics. Studies have shown that ecological, as well as social systems may "wobble" before a critical transition (Brock and Carpenter, 2006; Biggs *et al.*, 2009). Long-term eutrophication with high concentrations of nitrogen and phosphorus, plus an unusually warm winter, causes the exceptional bloom (in dimension as well as initiation date) of 2007 in Lake Taihu (Fig. 1b). This kind of extreme event may have caused the lake system to switch between alternative states (Wang *et al.*, 2012).

By combining information on different variables, insights can be gained into the combined effects of climate and catchment variables. Multiple regression showed that using both Tem and TN:TP were the best predictors ($P = 0.01$) of bloom initiation. Less significant correlations were found with TN and TN:TP ($P = 0.02$), TP and TN:TP ($P = 0.04$), TN and TP ($P = 0.05$) and the combination of all three variables. Note that the initial blooming dates (1987–2000) are not included in this analysis due to the lack of nutrient data before 2000.

The strict catchment management policies initiated by the central government and local authorities have led to a general reduction in the TN and TP concentrations (Fig. 2). However, extensive algal blooms have continued, making it clear that restoring Lake Taihu is a long-term challenge that needs to consider multiple drivers. Major changes in the climate system are now considered unequivocal and temperature models forecast that the Taihu Basin will undergo increasing temperatures in the coming decades (Qin *et al.*, 2010). Even though nutrient loading is the single most important factor to control, the complex feedback between temperature and algal productivity implies that long-term management must consider both local and global drivers on algal bloom dynamics and their impacts on water supply in this and other large lakes characterized by elevated eutrophication.


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