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Long-term joint effect of nutrients and temperature increase on algal growth in Lake Taihu, China

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Abstract

To study how global warming and eutrophication affect water ecosystems, a multiplicative growth Monod model, modified by incorporating the Arrhenius equation, was applied to Lake Taihu to quantitatively study the relationships between algal biomass and both nutrients and temperature using long-term data. To qualitatively assess which factor was a limitation of the improved model, temperature variables were calculated using annual mean air temperature (AT), water temperature (WT), and their average temperature (ST), while substrate variables were calculated using annual mean total nitrogen (TN), total phosphorus (TP), and their weighted aggregate (*R*), respectively. The nine fitted curves showed that TN and AT were two important factors influencing algal growth; AT limited growth as algal photosynthesis is mainly carried out near the water surface; N leakage of phytoplankton and internal phosphorus load from sediment explains why TN was the best predictor of peak biomass using the Monod model. The fitted results suggest that annual mean algal biomass increased by 0.145 times when annual mean AT increased by 1.0°C. Results also showed that the more eutrophic the lake, the greater the effect AT had on algal growth. Subsequently, the long-term joint effect of annual temperature increase and eutrophication to water ecosystems can be quantitatively assessed and predicted.

Key words: lake; eutrophication; algal bloom; global warming

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Introduction

The occurrence of algal blooms in estuarine, marine, and fresh water systems continues to increase worldwide (Carvalho and Kirika, 2003; Schrope, 2008), with regional impacts of climate warming on water ecosystems representing a new and growing threat (Liboriussen et al., 2005). Global warming is a worldwide environmental problem, which is enhanced by the greenhouse effect. Evidence has suggested that water temperature and air temperature have increased during the global warming process (Jones et al., 2006). Global warming over the past 30 years has been significant (Kintisch and Kerr, 2007), with land surface temperatures increasing at a faster rate than ocean surface temperatures (about 0.27°C vs. 0.13°C per decade after 1979) (Trenberth and Jones, 2007). Less is known, however, on how global warming and eutrophication can affect water ecosystems (Bronmark and Hansson, 2002; de Figueiredo et al., 2006).

As nitrogen and phosphorus are two elements with the lowest concentrations in algae to act as limiting factors for water eutrophication induction (Mainstone and Parr, 2002; Yang et al., 2008), total phosphorus (TP) and total nitrogen (TN) at low levels control algal blooms in lakes and oceans (French and Petticrew, 2007). With an increase in TN and TP concentrations, nutrient levels become sufficient for increased algal growth. In addition, when nutrients are not limited, increased temperatures will accelerate algal growth. Inter-annual changes in TN and TP and phytoplankton chlorophyll-*a* (Chl-*a*) in Lake Taihu were analyzed using monthly monitoring data collected during 1991–1999. The concentrations of TN, TP, and Chl-*a* showed significant spatial and temporal relationships in the lake (Chen et al., 2003a, 2003b). The Monod model has been successfully used to model nutrient effects on algal growth rates (Kayombo et al., 2003). The Arrhenius equation was inserted into the Monod model by Goldman and Carpenter (1974) to develop a multiplicative growth

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model to describe the algal growth rate using the product of temperature and nutrient expressions (Eq. (1)).

$$\mu = \frac{A \times b^T \times S}{K + S} \tag{1}$$

where, μ (day^{-1}) is the specific growth rate of phytoplankton; A (day^{-1}) is the maximum specific growth rate at a certain temperature; b is the activation energy dependent constant; S (mg/L or mg/m^3) is the limiting nutrient concentration, N or P; K (mg/L) is the half saturation coefficient; and T (°C) is temperature.

As each *Microcystis* cell contains about 3.4×10^{-13} g Chl-*a*, the Chl-*a* concentration has been used as a representative of phytoplankton biomass. Sterner and Grover (1998) developed quantitative relationships between periphytic algal biomass with N and P concentrations using the Monod model (Eq. (2)).

$$\text{PB} = \frac{\text{PB}_{\max} \times S}{K + S} \tag{2}$$

where, PB (mg/m^3) is the concentration of Chl-*a*, and $\text{PB}_{\max}$ (mg/m^3) is the maximum concentration of Chl-*a*.

However, a simplified model to describe the long-term combined effect of annual temperature and nutrient concentrations on algal biomass in natural water systems has not yet been developed. In this article, a multiplicative growth model was applied to Lake Taihu to quantitatively study the relationship of algal biomass with both nutrients and temperature using long-term data. Subsequently, the effect of annual temperature increase and eutrophication interfering with water ecosystems could be quantitatively assessed and predicted.

1 Experiment

1.1 Site description and methods

Lake Taihu is a well-known eutrophic lake located in the south of Jiangsu Province, China (30°56′N–31°33′N, 119°53’E–120°36′E), with an average length of 68.5 km (N–S), width of 34 km (E–W), total shoreline of 405 km, and water surface of 2428 km^2. The lake's mean depth is 1.9 m and its total storage capacity is 4.76 km^3. Since 1980, the water quality in Lake Taihu has continuously worsened due to algal blooms (Ye et al., 2007), with the predominant blue-green algal blooms often formed by *Microcystis* sp. These algal blooms, in turn, lead to dying algae producing significant cyanotoxins (Rantala et al., 2006), including cytotoxins and biotoxins, which are responsible for acute lethal, chronic, and sub-chronic poisoning of humans and wild and domestic animals. In 2007, the worst blue-green algal bloom ever recorded in Lake Taihu occurred, depriving nearby residents of clean tap water and alarming officials nationwide.

There is obviously a great need for quantitative data to study the joint effect of temperature and nutrients on phytoplankton growth in natural waters. Long-term data on annual mean TN, TP, and water temperature (WT) were obtained from the Environmental Monitoring Head Station in China and the Jiangsu Environmental Monitoring Center. All measurements and analyses followed the Chinese standard methods for lake eutrophication surveys. The annual average values of each research parameter were calculated on the basis of daily values. Data on Chl-*a* concentrations before 1999 were taken from Chen et al. (2003a, 2003b) and from 2000 were determined in the Jiangsu Environmental Monitoring Center by a spectrophotometer (UV-2450PC, Shimadzu Corporation, Japan) after a 24 hr extraction in 90% buffered acetone (Rier and Stevenson, 2006). Each sample was analyzed three times, and the mean value was obtained. Multivariate statistical analysis using STATGRAPHICS plus (V3.0) was applied to calculate the correlation coefficients between each two parameters. Data of annual air temperature (AT) around Lake Taihu from 1980 to 2008 were obtained from the Jiangsu Meteorological Bureau (Jiangsu Province Climate BO, 2004–2008).

1.2 Data analysis

According to Eqs. (1) and (2), the effect of temperature on algal biomass was incorporated into a product expansion of the Monod model. Thus, a new modified Monod model was described as Eq. (3).

$$C_{\text{Chl-}a} = \frac{a \times b^T \times S}{K + S} \tag{3}$$

where, $C_{\text{Chl-}a}$ (mg/m^3) is the concentration of Chl-*a*; and a (mg/m^3) is the maximum concentration of Chl-*a* at a certain temperature.

It was a difficult task to determine the temperature and nutrient dependent coefficients, including a, b and K in one equation. Two linear regression equations were deduced to calculate the parameters as follows:

$$\frac{1}{C_{\text{Chl-}a}} = \frac{K}{a \times b^T} \times \frac{1}{S} + \frac{1}{a \times b^T} \tag{4}$$

$$\ln\left(\frac{C_{\text{Chl-}a}}{(a \times S)/(K + S)}\right) = T \ln b \tag{5}$$

To solve the two equations, the interpolation method was used. Firstly, b was given a certain value, such as 1.066 ($\mu = 0.851(1.066)^T$), according to Goldman and Carpenter (1974). The value of a and K were then determined by linear regression of Eq. (4). Finally, K and b were substituted into Eq. (5) to obtain a new b value (b') by linear regression. If $b' \neq b$, b' was set as b for recalculation from the beginning. The value of a, b, and K were determined till $b' = b$.

By studying the long-term joint effect of temperature and eutrophication on algal growth, other variables were considered to have a similar effect, such as light intensity and number of cloudy or rainy days. To qualitatively assess which factor was a limitation, temperature variables were calculated using annual mean air temperature, water temperature, and their average, and substrate variables were calculated using annual mean TN, TP, and their weighted aggregate, respectively. Average temperature (ST) and weighted aggregate (R) were defined as Eq. (6) and Eq. (7), respectively.

$$\mathrm{ST} = \frac{\mathrm{AT} + \mathrm{WT}}{2} \tag{6}$$

$$R = \mathrm{TN} + 25 \times \mathrm{TP}/1000 \tag{7}$$

Hereafter, mean square error (α) was used to determine goodness-of-fit with coefficients of determination.

$$\alpha = \sqrt{\frac{\sum\limits_{i=1}^{n} (C_{(\text{Chl-}a)i} - (\frac{A \times b^T \times S}{K+S})_i)^2}{n-1}} \tag{8}$$

where, $C_{(\text{Chl-}a)i}$ (mg/m^3) is the concentration of Chl-a at i year; $(\frac{A \times b^T \times S}{K+S})_i$ (mg/m^3) is the calculated concentration of Chl-a at i year; and n is the number of data.

2 Results and discussion

2.1 Historical records and trends

Long-term data of annual mean TN and TP from 1980 to 2008 are shown in Fig. 1. After 1990, the lake's annual mean TN and TP concentrations often reached 3.0 mg/L and 100 mg/m^3, respectively. The highest annual mean TN reached 5.34 mg/L in 2004 and the highest TP reached 205 mg/m^3 in 2000. Escalating population, improvement in the standard of living, and agricultural and industrial development have all contributed to increasing water pollution. The increases in TN and TP concentrations accelerate algal growth and water blooms, and water algal blooms have occurred each year since the 1990s. As a consequence, water pollution and water shortages have become major environmental problems around Lake Taihu. While TN and TP concentrations in Lake Taihu decreased by a little after 2003, algal bloom outbreaks have continued to show an upward trend. In May 2007, a huge algal bloom broke out, and significantly impacted the supply of fresh water to about 6.10 million people in Wuxi City.

Historical records of annual mean AT in the Lake Taihu region show a significant warming process similar to global patterns. The annual mean AT in the region had an average increase of 0.800°C per decade (R = 0.8604, n = 29, P < 0.0001) from 1980 to 2008 (Fig. 2), higher than the average global warming rate on land, which is about 0.27°C per decade (Trenberth and Jones, 2007). However, our results are similar to Bohannon's finding in Mongolia, which showed warming at more than twice the rate of the global average (Bohannon, 2008). The highest annual mean AT of 17.5°C occurred in 2007, with the area also experiencing unseasonably warm winters in recent years. Evidently, Lake Taihu is an appropriate case to study the effect of global warming on water quality.

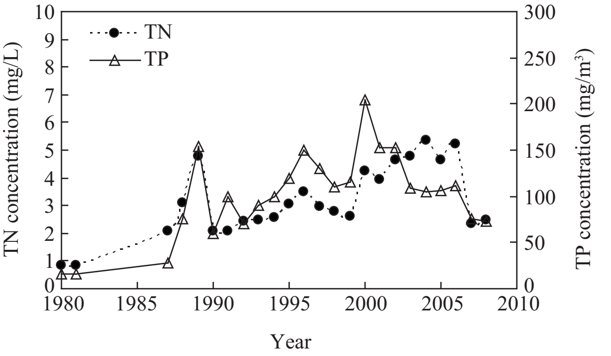

Fig. 1 Variation of annual mean TN and TP concentrations from 1980 to 2008 in Lake Taihu. AT: air temperature; WT: water temperature.

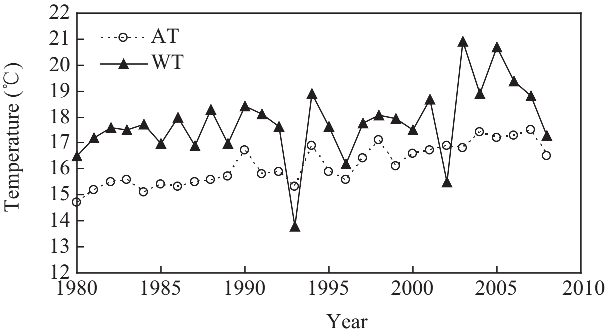

Fig. 2 Variation of annual mean air temperature (AT) and water temperature (WT) from 1980 to 2008 in Lake Taihu.

Variation in annual mean WT from 1980 to 2008 in Lake Taihu can be seen in Fig. 2. The annual mean WT increased by 0.626°C per decade (R = 0.3834, n = 29, P = 0.0401). This indicates that annual mean WT increased by 0.78°C statistically with annual mean AT increasing by 1.0°C in Lake Taihu. Our results showed that average surface water temperature increased by 0.8–1.0°C, which accords well with previous studies showing a 1.0°C rise in air temperature (Hosomi, 1996; Fukushima et al., 2000). Annual mean WT was the highest in 2003 (20.9°C). Significant correlations occurred between water temperature and air temperature (R = 0.61, n = 29). However, the deviation of water temperature was larger than that of air temperature. This probably relates to WT being disturbed by transport ships, water flows, and other human activities in the lake.

Variation in annual mean plankton biomass in Lake Taihu from 1980 to 2008 is displayed in Fig. 3. In 2006, annual mean Chl-a reached its highest concentration of more than 100 mg/m^3 and has shown a generally upward trend since 1990. However, variation in Chl-a concentration has also been irregular. Algal growth is inherently complex, predominantly showing nonlinear responses to various environmental parameters such as temperature,

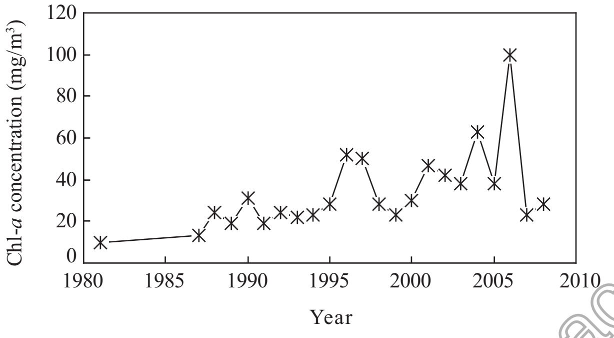

Fig. 3 Variation of annual mean Chl-a concentration from 1980 to 2008 in Lake Taihu.

light, and several nutrients. In the natural field, algae do not grow under highly controlled conditions of temperature, light intensity, and well-designed chemical concentrations. Its variation was not consistent with separate factors, such as AT, WT, TN or TP. Inter-annual changes of TN and TP and phytoplankton Chl-*a* in Lake Taihu showed that each summer, a single phytoplankton biovolume peak appeared (Chen et al., 2003a, 2003b). A distinct temporal shift in species composition also occurred between summer and winter. Wind speed and direction affected the horizontal distribution of phytoplankton in the lake, especially for *Microcystis*. The wax and wane of phytoplankton assemblages were mainly controlled by temperature, wind, and turbidity, while long-term biomass dynamics were influenced by the level of nutrients. Nevertheless, an accurate portrayal of algal growth is one of the most difficult areas in field water quality modeling.

2.2 Kinetic approach to multiplicative growth model

Former empirical methods confirmed that TN and TP are both important determinants of phytoplankton community structure and function (Yang et al., 2008). Thereby, *R*, defined as the weighted aggregate of TN and TP, was used as a substrate variable for the Monod model analysis. Surface water temperatures on Lake Taihu were usually between 10 and 30°C, with the rate of photosynthesis increasing exponentially with increased temperature (less than 35°C). As photosynthesis happens mainly on the surface of water, it is influenced by both AT and WT. Hence, ST was defined as the average of AT and WT for the kinetics analysis of algal growth. To investigate the kinetic parameters of the multiplicative growth model, AT, WT, and ST were used as temperature variables to regress the modified Monod model while TN, TP, and *R* were used as substrate variables. Therefore, nine regression curves were achieved, as shown in Fig. 4, with their α values listed in Table 1. The three α values of the modified Monod model with TN and AT, WT or ST were very similar. This is likely due to the fact that significant correlations occurred between water temperature and air temperature. However, the α value of the modified Monod model with TN and AT was the smallest. This indicates that the modified Monod model with TN and AT had better consistency with the

Table 1 Mean square error (α) values fitting to the multiplicative growth model

	α value		
	AT	WT	ST
TN	15.45	16.10	15.54
TP	16.90	17.54	16.94
R	16.20	16.84	16.25

ST = (AT+WT)/2, *R*= TN + 0.025 × TP.

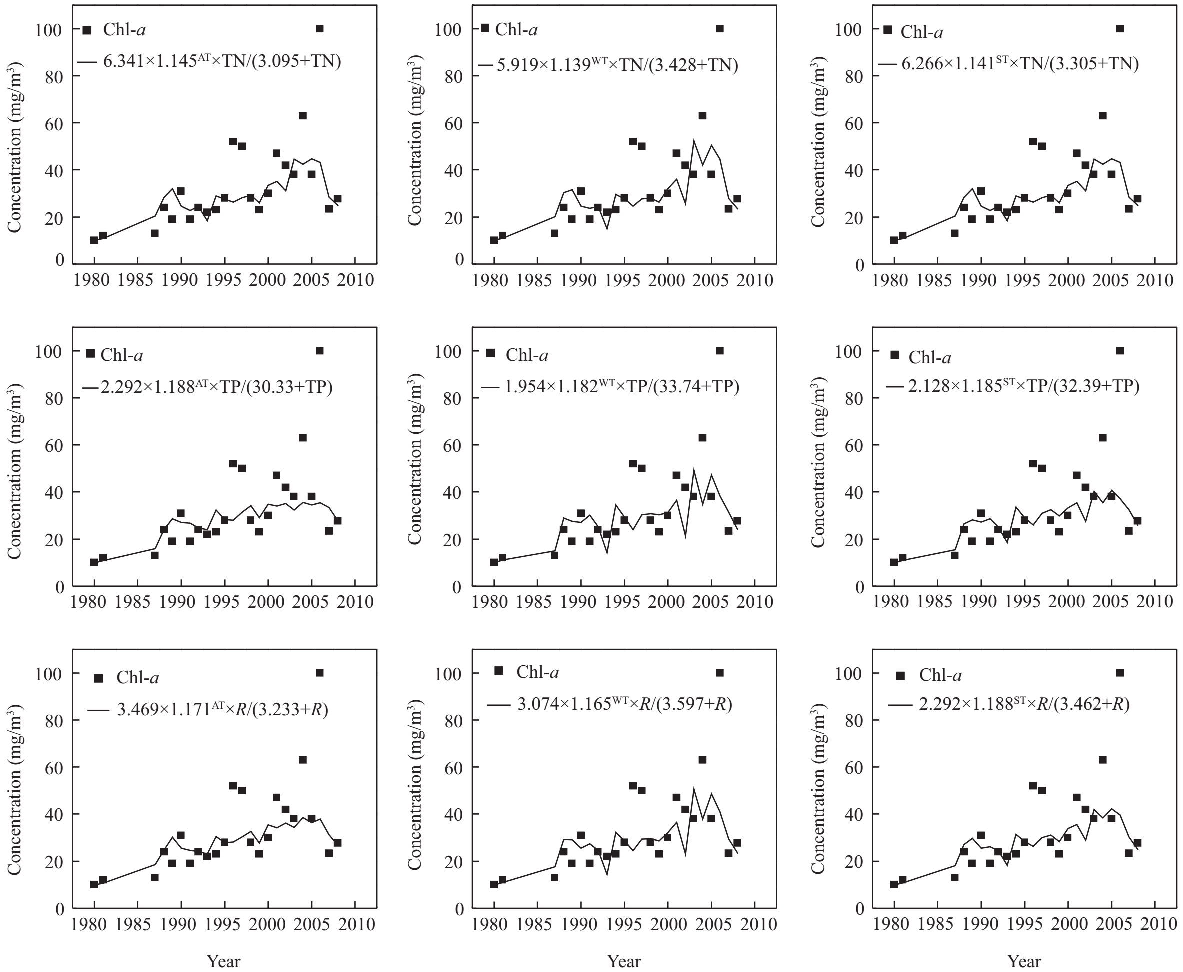

Fig. 4 Fitted curves of Chl-*a* concentration according to the multiplicative growth model with AT, WT and ST as *T* variables and TN (mg/L), TP (mg/m^3) and *R* (mg/L) as *S* variables.

historic records than with others, as given in Eq. (9).

$$C_{\text{Chl-}a} = \frac{6.341 \times (1.145)^{\text{AT}} \times \text{TN}}{3.095 + \text{TN}} \tag{9}$$

where, 6.341 (mg/m^3) is the theoretical maximum concentration of Chl-*a* at 0°C, and 3.095 (mg/L) is the half saturation TN concentration.

Apparently, TN and AT are two key factors limiting algal growth; AT has a great effect on growth because algal photosynthesis mainly takes place near the water surface. The fitted results show that annual mean algal biomass increased by 0.145 times when annual mean AT increased by 1.0°C. The more eutrophic the lake, the greater the effect AT has on the algal growth.

According to the historic records, the mass ratio of TN:TP is about 35:1, which is larger than 25:1 (Lenard, 2009). While this suggests a strongly P limited environment, algal biomass is more related to TN than to TP (Rier and Stevenson, 2006). The reason that algal growth is limited by N may lie in three factors: (1) the phytoplankton assemblage is diverse and dominated species often subrogate in natural water conditions (Sterner and Grover, 1998). Simultaneously, the process of subrogation is hypersensitive to temperature, spreading significantly with very fast algal bloom formations under adequate temperatures; (2) since algae bind excess P as polyphosphate and cells do leak nutrients, phytoplankton might leak N from cells at higher rates than that of P, which could maintain the demand for higher and higher N supply to saturate peak biomass. It is very important that nitrate is reduced in cells and subsequently N is leaked into water in the form of ammonia due to heterotrophic decomposition of organic N. The conversation of nitrate to ammonia subsequently leaking into the water likely explains why TN is the best predictor of peak biomass using the Monod model (Rier and Stevenson, 2006); and (3) the internal phosphorus load from sediment is a significant source of dissolved reactive phosphorus (DRP) to the lake water column. Research has shown that internal DRP loads might be greater than external surface DRP loads for shallow, subtropical lakes (Fisher et al., 2005). When there is a lack of phosphorus in the water column, its release from sediment will increase according to the balance theory.

Algae have the ability to store nutrients in their tissues to sustain growth during low nutrient periods, allowing them to successfully compete with other primary producers. Algae can take up 73%–98% of N and 79%–88% of P from water (Fong et al., 2004) during bloom development (McGlathery et al., 2007). In return, they release nutrients into water during decomposition after they are deposited onto the sediment. Nutrient accumulation by algae increases sedimentary N, P cycling flux, and retains large amounts of nutrients within water. Consequently, this results in a positive feedback of eutrophication and algal growth stimulation. In addition, this harmful feedback is accelerated by global warming.

3 Conclusions

A multiplicative growth Monod model, modified by incorporating the Arrhenius equation, was applied to Lake Taihu to study the long-term joint effect of temperature and eutrophication on algal growth. The results showed that TN and AT were two key factors influencing algal growth, which might be due to that algal photosynthesis mainly occurred near the water surface, and that there were great N leakage of phytoplankton and internal phosphorus load from sediment in lakes. As algae could absorb most nutrients from lakes, there was a positive feedback of algal growth on lake eutrophication.

Acknowledgments

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