

Research Progress on Cyanobacteria Bloom Monitoring Methods and Driving Factors

Qingzhu Zhang*

Beijing University of Civil Engineering and Architecture/School of Geomatics and Urban Spatial Informatics, Beijing, China

*Corresponding Author: 2108570022110@stu.bucea.edu.cn

ABSTRACT

Cyanobacteria bloom is one of the most serious water ecological environment problems in the world and have large impact on public health and aquatic ecosystems worldwide. The harmful effects of algal blooms not only include reduced aesthetics and recreational opportunities, but more seriously, algal toxins are produced during the outbreak, killing plants and animals in the water, threatening the safety of drinking water and quality of life of local residents. Scientific and accurate inversion of the temporal and spatial changes of cyanobacteria bloom and comprehensive and in-depth analysis of the causes of cyanobacteria bloom outbreak are the current research focus. This paper describes the main monitoring methods of cyanobacteria bloom and the influencing factors of the outbreak. Finally, through the investigation and summary of the research status of cyanobacteria bloom at home and abroad, it analyzes the existing problems in the field of research status, and finally analyzes its future development trend in related directions.

KEYWORDS

Cyanobacteria bloom; Remote sensing; Influencing factors.

1. THE ALGAL BLOOMS MONITORING RESEARCH OVERVIEW

"Bloom" usually refers to the phenomenon that the biomass of phytoplankton is significantly higher than the average in the general water body, and a large amount of accumulation on the surface of the water body, forming a visible algal accumulation[1]. Cyanobacteria bloom is one of the most important water ecological environment problems facing the world at present, and its outbreak and extinction will have adverse or even harmful effects on the drinking water safety of surrounding residents, aquaculture, tourism and entertainment[2]. The outbreak of cyanobacteria bloom will obviously change the water color and reduce the water quality. Large cyanobacteria blooms can overwhelm aquatic vegetation and suffocate microorganisms, plants and animals in the water. When cyanobacteria die, they produce pungent odors and toxic compounds that further pollute the water. Studies have shown that since the Industrial Revolution, nearly 60% of lakes in North America and Europe have experienced increasing cyanobacteria blooms, far outpacing the growth of other phytoplankton. With the increasing influence of climate change and human activities, lake eutrophication is becoming more and more serious, and the outbreak of cyanobacteria bloom is more frequent and the impact is more serious.

In recent years, great progress has been made in monitoring cyanobacteria blooms worldwide. A large number of studies have shown that factors such as water eutrophication, human activities and global warming may further aggravate the frequency, intensity and duration of cyanobacteria bloom[3]. This paper summarizes the monitoring methods of cyanobacteria blooms on a global scale, the

environmental drivers that may cause blooms, and the feasible measures to prevent and control blooms.

2. MONITORING METHODS FOR CYANOBACTERIA BLOOMS

For the monitoring of cyanobacteria bloom, there are mainly two technical means: water quality sampling based on site and remote sensing monitoring based on satellite remote sensing image. The traditional monitoring method is to set up point sampling in the lake reservoir and then conduct laboratory analysis, which is time-consuming and laborious, and it is often difficult to quickly and comprehensively monitor the distribution and change of cyanobacteria bloom in a large area of water[4]. In contrast, remote sensing monitoring has the characteristics of fast, wide range and dynamic, and has become the main method of cyanobacteria bloom monitoring. Therefore, making full use of the technical advantages of different observation methods to realize three-dimensional and comprehensive monitoring of cyanobacteria blooms is the focus of extensive attention at this stage[5].

The remote sensing monitoring of cyanobacteria bloom is based on the difference between the monitored water and cyanobacteria bloom spectrum. The difference in the concentration of cyanobacteria in the water body will cause the difference in the color, density, transparency and other indicators of the water body, which is the difference in the reflection spectral characteristics received by the sensor. Therefore, cyanobacteria blooms can be identified by visual interpretation, vegetation index and other methods. Domestic and foreign scholars have developed extraction algorithms such as vegetation index method, supervised classification and automatic recognition based on machine learning for the identification and extraction of cyanobacteria bloom in lakes[6][7]. In addition, by studying the relationship between water reflection spectral characteristics and water quality parameter concentration, water quality parameter inversion algorithm was established to realize the extraction of water quality parameter information such as chlorophyll a concentration, suspended matter content and water transparency.

Cyanobacterial blooms of remote sensing monitoring data sources can be divided into the ground remote sensing data, aviation remote sensing data and remote sensing data. Remote sensing data is the most widely used, MODIS, SAR, Landsat TM/ETM+, Sentinel, can identify and monitor the spatial distribution and outbreak range of cyanobacteria bloom. With the development of hyperspectral technology of surface objects, many researchers also use spectrometers to measure reflection spectrum of water, and to monitor cyanobacteria bloom through quantitative inversion of water quality parameters.

Bloom area and distribution are the primary concerns when cyanobacteria bloom occurs. The research on the use of remote sensing data to identify blooms and analyze the area, intensity and time of cyanobacteria blooms has been relatively mature. Based on the ETM data from August 2003 to December 2008, Li Xuwen obtained the area of cyanobacteria bloom in Taihu Lake by visual interpretation method, and concluded that the intensity of cyanobacteria bloom outbreak in Taihu Lake had intensified. Hu Zunying studied the band ratio algorithm to interpret the application of MODIS data in the cyanobacteria bloom in Taihu Lake, showing that the ratio of near-infrared and visible bands can distinguish cyanobacteria bloom from water body, and compared the ratio algorithm with visual interpretation, the two results were basically consistent, and the ratio algorithm could identify cyanobacteria bloom faster than the visual interpretation method. Lu Weikun used false color synthesis method and NDVI normalized vegetation index method to extract cyanobacteria bloom information from MODIS data of Dianchi Lake, and compared the two methods. Among them, false color synthesis method has the advantage of good visual effect, and the normalized vegetation index method can be used for quantitative research after modeling.

Through the interpretation of a series of remote sensing images, the temporal and spatial variations of bloom occurrence can be separated. Ma Ronghua collected NIR, CEB ERS, TM/ETM and IRS P6

satellite remote sensing images of Taihu Lake since 1979 to analyze the spatial and temporal distribution and development trend of water blooms in Taihu Lake. At the same time, the meteorological and environmental factors such as water temperature, total nitrogen and total phosphorus were analyzed. The concentration of chlorophyll a is one of the important indicators to measure the number of algae. The most important objective of remote sensing monitoring of cyanobacteria bloom is to dynamically monitor the concentration of chlorophyll. Other indicators related to algae growth density, water temperature, water transparency, etc., are also important targets of remote sensing monitoring. Leaf vegetative degree is widely regarded as an indicator to estimate the biomass of cyanobacteria, but some researchers believe that phycocyanin is the signature pigment of cyanobacteria, which is more accurate to evaluate the biomass of cyanobacteria. The hyperspectral sensor is equivalent to the traditional multi-spectral sensor, which has the spectral resolution of nanometer level, can obtain the diagnostic spectral characteristics of the target object, capture the absorption peak and reflection peak of chlorophyll in the water body, and solve the problem of insufficient spectral resolution in conventional remote sensing. Application of hyperspectral technology of ground objects. It also promotes the in-depth study of spectral characteristics and algorithms of water quality parameters.

The use of satellite remote sensing to monitor the water environment has the advantages of large-scale, long time series, periodic, rapid and dynamic monitoring, etc. Xu Yinsheng extracted algal blooms by calculating the plankton algae index (FAI) in the multi-spectral data set of Sentinel-2 and obtained the area distribution map of cyanobacteria blooms in Taihu Lake Basin at different times. Based on sentinel images and spectral characteristics of algal blooms, Megan M. Cooffer [46] established a cyanobacteria index (CI) based on algal bloom abundance to assess the occurrence of algal blooms in the United States.

Remote sensing monitoring can quickly and timely obtain the bloom information of the whole water area, conduct continuous monitoring, study the drift rule of the bloom, and evaluate the loss caused by the bloom, which has an incomparable advantage in the prediction and early warning of the bloom. Tomlinson used Landsat ETM+ data to predict the lake bloom outbreak 5 weeks in advance, which is a successful case of remote sensing application in the prediction and warning of lake bloom. However, remote sensing forecasting and early warning still has some defects, such as poor accuracy, low detection frequency, high cost, only after the outbreak detection and monitoring, and can not predict its movement. The technology of using remote sensing data to identify cyanobacteria blooms, analyze spatiotemporal dynamics and estimate algae concentration has been mature. Making full use of remote sensing monitoring and simulating the impact of cyanobacteria bloom on the environment is also one of the application directions. In order to make real-time and accurate prediction and prediction of cyanobacteria bloom dynamics, it is still necessary to strengthen the research in the following aspects: First, to integrate multiple remote sensing data sources to accurately achieve quantitative analysis and dynamic tracking of cyanobacteria bloom.

3. DRIVING FACTORS OF CYANOBACTERIA BLOOM

It is generally believed that eutrophication of water body is one of the main causes of cyanobacteria bloom. In eutrophic lakes, suitable hydroclimatic conditions can easily promote the occurrence of cyanobacteria blooms, and climate change directly or indirectly affects cyanobacteria growth, floating accumulation, community succession and phenological changes through temperature, light, precipitation and wind[8][9][10][11]. The outbreak of cyanobacteria bloom is the result of the comprehensive influence of physical, chemical and biological factors on lakes. On the one hand, there are internal factors, such as lake eutrophication. On the other hand, external factors, such as environmental factors, play an important role in the outbreak and diffusion of cyanobacteria bloom[12], and meteorological conditions such as wind speed, temperature and precipitation have a significant impact on the outbreak of cyanobacteria blooms[13]. Therefore, the research on the

driving factors of cyanobacteria bloom outbreak, combined with environmental conditions such as wind speed, wind direction, precipitation and water quality conditions such as nitrogen and phosphorus content and chlorophyll a concentration, can predict cyanobacteria bloom outbreak in advance, which is conducive to adopting relevant policies to protect the aquatic ecological environment[14].

Human activities, especially intensive agriculture, have greatly increased the intake of trace elements such as nitrogen and phosphorus in aquatic ecosystems, which in turn has led to eutrophication in rivers, lakes and estuaries, promoting algae and cyanobacteria blooms, which have been widely recognized as a global environmental problem since the 1960s. Since then, many countries have introduced measures to reduce nutrient inputs to improve water quality and control harmful bloom[15] [16] [17]. Overall, these efforts have been much more effective in reducing phosphorus than in reducing nitrogen inputs[18].

In recent decades, the global use of nitrogen fertilizer has gradually exceeded the use of phosphate fertilizer[19]. As a result, the ratio of nitrogen to phosphorus in many lakes, rivers and coastal waters is currently rising. Increasing nitrogen loads and higher nitrogen to phosphorus ratios may change the species composition of algae in lakes. In particular, the number of non-nitrogen-fixing cyanobacteria was increased at the expense of nitrogen-fixing cyanobacteria. In addition, increased nitrogen load is more conducive to the production of nitrogen-rich cyanobacteria toxins and microcystin[21].

With global warming, cyanobacteria, stimulated by high temperature, will proliferate to form cyanobacteria blooms [20]. Many algae reach their maximum growth rate when the temperature is higher than 25°C. Although the growth rate of other aquatic plants will also increase, it is far lower than that of cyanobacteria. Higher water temperatures also lead to more stable stratification of water bodies, reducing vertical mixing[22] [23] [24]. The stratification of the water provides ideal conditions for cyanobacteria to float upward to the surface of the water to gain better exposure to light and cover underwater phytoplankton[25] [26].

In temperate and high-latitude regions, the time of lake ice cover in winter is shortened, the time of water stratification in spring is advanced, and the time of stratification in summer is extended to autumn. These factors all contribute to extending the duration and range of cyanobacterial bloom[27] [28] [29] [30]. Nutrient availability and lake morphology can alter the temperature response mentioned above, and in shallow eutrophic lakes, nutrients and temperature tend to have a synergistic effect on the growth of cyanobacteria. This means that in a warmer climate in the future, further reductions in nutrient loads may be needed to inhibit the growth of cyanobacteria. In deep mesotrophic and oligotrophic lakes, heat action is strong, and stratification tends to reduce nutrients flowing into the surface from below, thus inhibiting rather than promoting the growth of cyanobacteria[31]. The effects of nutrients and temperature on cyanobacteria growth also vary from species to species. For example, a statistical analysis of cyanobacteria abundance in more than 1,000 lakes revealed that some taxa are more sensitive to increased nutrients, while others are more sensitive to increased temperature[32]. Some species may even benefit from the combination of less nutrition and warming, such as a five-fold decrease in total phosphorus concentrations in Lake Zurich, accompanied by a decrease in eukaryotic phytoplankton in the surface mixed layer. At the same time, climate warming leads to stronger thermal stratification of the lake, which is conducive to the emergence of significant algal blooms near the thermocline in summer[33].

Another warning phenomenon of climate change is storm events, including tropical cyclones and summer thunderstorms, which will cause climate change to become more extreme, with higher rainfall, and droughts to intensify and potentially last longer. In the short term, severe storms and rain can temporarily disrupt the growth of cyanobacteria due to de-stratification and scouring[34]. However, heavy rainfall increases nutrient loss, which can lead to deep nutrient enrichment in downstream waters. If such a rainfall event is followed by a prolonged drought in the summer, and

the residence time of nutrient-rich water increases, conditions conducive to the growth of cyanobacteria will be greatly increased[35].

With the rapid development of agriculture, more and more nitrogen and phosphorus entered aquatic ecosystems, intensifying eutrophication in rivers, lakes, estuaries and offshore waters, leading to algal blooms and bloom formation. In the 1960s, humans recognized this global environmental problem and began to take measures to reduce the amount of nutrients discharged into water bodies to improve water quality and control blooms. Because measures to reduce phosphorus emissions are more effective than those to reduce nitrogen emissions, and because nitrogen fertilizer use has gradually exceeded phosphate in recent decades, the ratio of nitrogen to phosphorus in many lakes, rivers and coastal waters has been rising. The increase of N content and N/P ratio may change the species composition of cyanobacteria blooms, especially the decrease of nitrogen-fixing cyanobacteria and the increase of non-nitrogen-fixing cyanobacteria. Events in Lake Erie have shown that because microcystin is rich in nitrogen, higher nitrogen concentrations in water promote the production of this toxin.

Regarding the cause of cyanobacteria bloom, it has been generally believed that nutrient salt concentration is no longer a limiting factor affecting the growth of cyanobacteria in eutrophic water bodies, and other environmental conditions such as meteorological factors may be the main factors inducing cyanobacteria bloom outbreak[36]. The decreased wind speed may potentially lead to cyanobacteria outbreaks and concentrations in the surface waters of the dominant and eutrophic lakes.

Therefore, most of the existing studies focus on the effects of temperature[37], precipitation[38], wind speed and direction[39] and sunshine duration[40] on cyanobacteria bloom occurrence, and tend to describe the qualitative effects of different values of meteorological conditions on cyanobacteria bloom occurrence, while the importance measurement of each factor and the impact of interaction on cyanobacteria bloom are less involved. In addition, due to the influence of many environmental factors such as physiological characteristics of cyanobacteria, nutrient concentration of water and meteorological conditions, the formation mechanism of cyanobacteria bloom is relatively complex[41], and the influence of various factors on cyanobacteria bloom usually presents a nonlinear change mode. There are certain limitations in the quantitative analysis of the cause of cyanobacteria bloom at different stages by continuing to use traditional statistical methods. The rise of machine learning and artificial intelligence technology provides new solutions for dealing with high-dimensional data and nonlinear problems, and has been widely used in the process of solving complex problems such as ecology and environment.

Water disturbance caused by wind affects the growth competition of phytoplankton by changing the concentration of nutrients in water and the structure of aquatic biota. The motion caused by wind on water surface leads to the propagation of turbulent eddy currents in water, including horizontal and vertical motion. Wind disturbance is one of the most important factors driving lake mixing and nutrient level and vertical distribution, and has an impact on the migration, transport and accumulation of phytoplankton[42]. In shallow lakes, sediment re-suspension caused by frequent wind significantly increases light attenuation and sediment nutrient release[43], thus affecting phytoplankton growth. At the same time, the water potential energy caused by the decrease of wind speed weakened, slowed down the water mixing, and helped the cyanobacteria with pseudo-vacuoles to aggregate, float and migrate, forming a floating cyanobacteria bloom visible to the naked eye. Breezes help cyanobacteria blooms spread more widely across the surface.

Zhu Yongchun and CAI Qiming[44] established a three-dimensional algae migration model in Meiliang Bay of Taihu Lake on the basis of Webster et al., and believed that algae migration in the lake mainly depended on the critical wind speed greater than or less than 3m/s, which corresponds to two completely different algae migration processes. When the actual wind speed is less than the critical wind speed, the lake surface is approximately regarded as hydrodynamic smooth, and floating algae will not sink into the water due to the effect of wind field, but just pile up on the windward

shore. Zhang et al. obtained image data of cyanobacteria bloom in Taihu Lake, Chaohu Lake and Dianchi Lake through MODIS satellite remote sensing for research, and believed that wind speed 3.0m/s was the critical threshold for vertical distribution of chlorophyll a concentration in lakes.

The artificial experiment ignored the characteristics of the lake itself, and the results could not represent the specific lake. The satellite remote sensing data were limited by the spatiotemporal resolution, and the corresponding data of cyanobacteria bloom and wind speed and direction were not accurate enough, so the quantitative response of cyanobacteria bloom to rapid changes in wind speed has not been fully demonstrated.

The formation of cyanobacteria bloom is generally caused by the physiological characteristics of cyanobacteria itself and many environmental factors. The change of a single environmental factor has a certain suitable range for the growth and reproduction of cyanobacteria, and only when the environmental factor exceeds or falls below the range will it have an impact on cyanobacteria. This range of change is called the threshold of environmental factor, which can be used as a symbol of the critical state (bloom) in the growth and reproduction process of cyanobacteria. By referring to the threshold of environmental factors related to cyanobacteria bloom, managers can reduce human interference or increase intervention measures, and restore the self-regulation mechanism of the lake system, so as to reduce the occurrence of cyanobacteria bloom. Therefore, it is very important to scientifically elucidate the driving mechanism of wind on cyanobacteria bloom and accurately quantify its threshold range for the prevention and control of cyanobacteria bloom. Considering that the process of cyanobacteria blooms often occurs within hours or even minutes, the minute hour scale high-frequency observation is crucial to accurately depict the drive of cyanobacteria blooms by wind processes.

4. THE EXISTING PROBLEMS AND FUTURE DEVELOPMENT TREND

There is growing evidence that harmful cyanobacteria blooms have increased globally in recent decades, and that they are likely to expand further in the coming decades due to continued eutrophication, rising atmospheric carbon dioxide concentrations, and global warming[45]. The current problems caused by cyanobacteria blooms and the increasing frequency and severity of their outbreaks urgently require scientific and rational monitoring methods and relevant mitigation or preventive measures. At local and regional scales, preventing cyanobacteria from proliferating will require more effective control of nutrient inputs into aquatic ecosystems. Globally, curbing emissions of carbon dioxide and other greenhouse gases is the only way to avoid large-scale outbreaks of cyanobacteria blooms.

Many recent studies have introduced a framework based on network theory to study the spatiotemporal characteristics of extreme hydroclimates. Cyanobacteria is a relatively common phytoplankton species in freshwater lakes. Under suitable meteorological conditions and nutrient concentration, cyanobacteria bloom will be formed. The cyanobacteria bloom leads to the deterioration of water quality, then destroys the structure of lake ecosystem, causes the degradation of water ecosystem function, and causes serious ecological environment risk or direct environmental pollution. Understanding the dynamic change characteristics of cyanobacteria bloom in lakes and exploring the factors of cyanobacteria bloom outbreak are very important for controlling bloom, establishing early warning mechanism and evaluating the ecological and environmental risks of cyanobacteria, and are also the main research directions in this field in the future.

REFERENCES

- [1] Yun-huai, Zhang. "Simulation of illumination influences to cyanobacteria's vertical migration in THE THREE GORGES RESERVOIR AREA." *Resources and Environment in the Yangtze Basin* (2010): n. pag.

- [2] Qin BQ, Zhou JJ, Elser JJ et al. Water depth underpins the relative roles and fates of nitrogen and phosphorus in lakes. *Environmental Science & Technology*, 2020, 54(6): 3191-3198.
- [3] Wen Chengcheng, Huang Tinglin, Kong Changhao, et al. Analysis of Mechanism and Start-up Thresholds of Seasonal Algal Blooms in a Northern Eutrophic Stratified Reservoir[J]. *Environmental Science*, 2023, 44(3): 1452-1464.
- [4] BoQiang Qin , GuiJun Yang , Jianrong Ma. (2016). Dynamics of variability and mechanism of harmful cyanobacteria bloom in Lake Taihu, China.[J]. *Chin Sci Bull*, 2016.
- [5] Tang Xiaoxian, Shen Ming, Duan Hongtao. Temporal and spatial distribution of algal blooms in Lake Chaohu, 2000-2015[J] *Journal of Lake Sciences*, 2017, 29(2): 276-284.
- [6] Hu C. A novel ocean color index to detect floating algae in the global oceans [J]. *Remote Sensing of Environment*, 2009, 113(10): 2118-2129.
- [7] Ma J, Jin S, Li J, et al. Spatio-temporal variations and driving forces of harmful algal blooms in Chaohu Lake: a multi-source remote sensing approach [J]. *Remote Sensing*, 2021, 13(3).
- [8] Kann J, Welch EB. Wind control on water quality in shallow, hypereutrophic upper Klamath Lake, Oregon. *Lake and Reservoir Management*, 2005, 21(2): 149-158.
- [9] Havens KE, Jin KR, Rodusky AJ et al. Hurricane effects on a shallow lake ecosystem and its response to a controlled manipulation of water level. *The Scientific World Journal*, 2001, 1: 44-70.
- [10] Shi K, Zhang YL, Zhang YB et al. Phenology of phytoplankton blooms in a trophic lake observed from long-term MODIS data. *Environmental Science & Technology*, 2019, 53(5): 2324-2331.
- [11] Berman T, Shteinman B. Phytoplankton development and turbulent mixing in Lake Kinneret (1992-1996). *Journal of Plankton Research*, 1998, 20(4): 709-726.
- [12] Li Jialong, Luo Chunliang, Lu Heng, et al. Spatio-temporal variation and driving factors of algal bloom at Lake Dianchi during 2002-2018 [J]. *Acta Ecologica Sinica*, 2023, 43(2) : 878—89110.
- [13] Gao Rui, Chen Xizi, Qian Yuan, et al. Analysis to Dynamic changes and Driving Factors of Cyanobacteria Blooms in Chaohu Lake from 2012 to 2021 [J]. *Journal of Anhui Agricultural Sciences*, 2023, 51(18): 69-73.
- [14] Zhang M, Duan H, Shi X, et al. Contributions of meteorology to the phenology of cyanobacterial blooms: implications for future climate change [J]. *Water Research*, 2012, 46(2): 442–452 13.
- [15] Schindler, D. W. Eutrophication and recovery in experimental lakes: implications for lake management. *Science* 184, 897–899 (1974).
- [16] Jeppesen, E. et al. Lake responses to reduced nutrient loading: an analysis of contemporary long-term data from 35 case studies. *Freshwater Biol.* 50, 1747–1771 (2005).
- [17] Fastner, J. et al. Combating cyanobacterial proliferation by avoiding or treating inflows with high P load: experiences from eight case studies. *Aquat. Ecol.* 50, 367–383 (2016).
- [18] Grizzetti, B., Bouraoui, F. & Aloe, A. Changes of nitrogen and phosphorus loads to European seas. *Glob. Change Biol.* 18, 769–782 (2012).
- [19] Glibert, P. M., Maranger, R., Sobota, D. J. & Bouwman, L. The Haber Bosch–harmful algal bloom (HB–HAB) link. [J] *Environ. Res. Lett.* 9, 105001 (2014).
- [20] Paerl, H. W. & Huisman, J. Blooms like it hot. [J] *Science* 320, 57–58 (2008).
- [21] Van de Waal, D. B. et al. The ecological stoichiometry of toxins produced by harmful cyanobacteria: an experimental test of the carbon–nutrient balance hypothesis. *Ecol. Lett.* 12, 1326–1335 (2009).
- [22] Jöhnk, K. D. et al. Summer heatwaves promote blooms of harmful cyanobacteria. *Glob. Chang. Biol.* 14, 495–512 (2008).
- [23] Paerl, H. W. & Huisman, J. Climate change: a catalyst for global expansion of harmful cyanobacterial blooms. *Environ. Microbiol. Rep.* 1, 27–37 (2009).
- [24] Elliott, J. A. The seasonal sensitivity of cyanobacteria and other phytoplankton to changes in flushing rate and water temperature. *Glob. Chang. Biol.* 16, 864–876 (2010).
- [25] Walsby, A. E., Hayes, P. K., Boje, R. & Stal, L. J. The selective advantage of buoyancy provided by gas vesicles for planktonic cyanobacteria in the Baltic Sea. *New Phytol.* 136, 407–417 (1997).
- [26] Huisman, J. et al. Changes in turbulent mixing shift competition for light between phytoplankton species. *Ecology* 85, 2960–2970 (2004).
- [27] Michalak, A. M. et al. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proc. Natl Acad. Sci. USA* 110, 6448–6452 (2013) 29.
- [28] Przytulska, A., Bartosiewicz, M. & Vincent, W. F. Increased risk of cyanobacterial blooms in northern high-latitude lakes through climate warming and phosphorus enrichment. *Freshwater Biol.* 62, 1986–1996 (2017). 144.

- [29] Taranu, Z. E., Zurawell, R. W., Pick, F. & Gregory-Eaves, I. Predicting cyanobacterial dynamics in the face of global change: the importance of scale and environmental context. *Glob. Change Biol.* 18, 3477–3490 (2012).
- [30] Nneville, O., Domaizon, I., Kerimoglu, O., Rimet, F. & Jacquet, S. Blue-green algae in a “Greenhouse Century” New insights from field data on climate change impacts on cyanobacteria abundance. *Ecosystems* 18, 441–458 (2015).
- [31] Thomas, M. K. & Litchman, E. Effects of temperature and nitrogen availability on the growth of invasive and native cyanobacteria. *Hydrobiologia* 763, 357–369 (2016).
- [32] Posch, T., Köster, O., Salcher, M. M. & Pernthaler, J. Harmful filamentous cyanobacteria favoured by reduced water turnover with lake warming. *Nat. Clim. Change* 2, 809–813 (2012).
- [33] Reichwaldt, E. S. & Ghadouani, A. Effects of rainfall patterns on toxic cyanobacterial blooms in a changing climate: between simplistic scenarios and complex dynamics. *Water Res.* 46, 1372–1393 (2012).
- [34] Michalak, A. M. et al. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proc. Natl Acad. Sci. USA* 110, 6448–6452 (2013).
- [35] LI Yachun, Xie Xiaoping, Hang Xing, et al. Analysis of wind field features causing cyanobacteria bloom in Taihu Lake combined with remote sensing methods [J]. *China Environmental Science*, 2016, 36(2): 525-533.
- [36] Rigosi A, Carey CC, Ibelings BW, et al. The interaction between climate warming and eutrophication to promote cyanobacteria is dependent on trophic state and varies among taxa. *Limnology and Oceanography*, 2014, 59(1): 99-114.
- [37] Lu Weikun, Yu Lingxiang, Ou Xiaokun, et al. Relationship between occurrence frequency of cyanobacteria bloom and meteorological factors in Lake Dianchi. [J]. *Lake Sci.* 2017, 29(3): 534-545.
- [38] Qin Boqiang, Yang Guijun, Ma Jianrong, et al. Dynamics of variability and mechanism of harmful cyanobacteria bloom in Lake Taihu, China [J]. *Chinese Science Bulletin*, 2016, 61(7): 759-770.
- [39] Yu P, Gao R, Zhang D, et al. Predicting coastal algal blooms with environmental factors by machine learning methods [J]. *Ecological Indicators*, 2021, 123.
- [40] Deng J, Zhang W, Qin B et al. Effects of climatically-modulated changes in solar radiation and wind speed on spring phytoplankton community dynamics in Lake Taihu, China. *Plos One*, 2018, 13(10): e0205260.
- [41] Wang H, Zhang Z, Liang D et al. Separation of wind’s influence on harmful cyanobacterial blooms. *Water Research*, 2016, 98: 280-292.
- [42] Zhang Y, Loiselle S, Shi K et al. Wind effects for floating algae dynamics in eutrophic lakes. *Remote Sensing*, 2021, 13(4): 800.
- [43] Chapra, S. C. et al. Climate change impacts on harmful algal blooms in US freshwaters: a screening-level assessment. *Environ. Sci. Technol.* 51, 8933–8943(2017).
- [44] Przytulska, A., Bartosiewicz, M. & Vincent, W. F. Increased risk of cyanobacterial blooms in northern high-latitude lakes through climate warming and phosphorus enrichment. *Freshwater Biol.* 62, 1986–1996 (2017).
- [45] XU Yinsheng; ZHAO Lin. Analysis of Spatial and Temporal Changes of Cyanobacteria Bloom in Taihu Lake Based on Remote Sensing Technology [J]. *Henan Water Resources & South-to-North Water Diversion*. 2023, 52(06): 5-6.
- [46] Cofer, M. M., Schaefer, B. A., Darling, J. A., Urquhart, E. A. & Salls, W. B. Quantifying national and regional cyanobacterial occurrence in US lakes using satellite remote sensing. *Ecol. Indic.* 111, 105976 (2020).