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Separation of wind's influence on harmful cyanobacterial blooms

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ABSTRACT

Wind is an important physical factor involved in Harmful Cyanobacterial blooms (CyanoHABs). Its integrated influence was separated to three components: (a) Direct Disturbance Impact (DDI) on cyanobacterial proliferation, (b) Indirect Nutrient Impact (INI) by sediment release and (c) Direct Transportation Impact (DTI) by both gentle wind-induced surface drift and wave-generated Stokes drift. By the combination of field investigation, laboratory experiment and numerical simulation their individual contributions to the severe bloom event in May 2007 in Meiliang Bay, Lake Taihu, was explored. Wind synthetically made 10.5 percent promotion to the bloom on May 28, 2007, but the impact varied with locations. DTI was featured with the strongest contribution of wind's impacts on CyanoHABs, while INI stood at the lowest level and DDI played an intermediate role. From the point of whole Meiliang Bay, the influencing weights of DTI, DDI and INI were approximately 48.55%, 32.30% and 19.15% respectively. DTI exerted the higher promotion in the regions of middle-east (ME), southwest (SW) and southeast (SE), and its actual contribution rate on CyanoHABs ranged from 6.41% to 7.46%. Due to the background nutrient load, INI was characterized by a tiny effect with the contribution rate being 2.18% on average. From the south bay to the north, DDI was detected with a decreasing tendency, with the practical contribution rate generally falling from 4.13% to 2.7%.

1. Introduction

Harmful Cyanobacterial blooms (CyanoHABs), one of the serious consequences of eutrophication in freshwater ecosystems (Wrigley and Horne, 1974), has become a global environmental and public health concern (Paerl and Huisman, 2008; Wang et al., 2013). With the excessive nutrient inputs from industrialization, urbanization and intensive agriculture, these blooms are increasing worldwide and pose a serious threat to drinking water supplies, aquatic life, human health, fish industry, local tourism and the ecological and economic sustainability of the freshwater ecosystems (Li and Pan, 2013; Nakamura et al., 1993; Zhang et al., 2012). Examples can be observed in Lake Victoria, the largest of the African rift lakes, Lake Winnipeg, Canada, Lake Erie (North America), Lakes Biwa and Kasimagaura, Japan's largest lakes, and Lake Taihu, the 3rd largest freshwater lake in China (Xu et al., 2015; Paerl et al., 2011). CyanoHABs are dominated by the combination of biological, chemical and physical factors (Chen et al., 2012; Davis et al., 2015; Song et al., 2007). Given that the *in situ* environmental conditions can support adequate population of cyanobacterial cells, the bloom is always promoted by series of physical factors (Chen et al., 2003; Ishikawa et al., 2002).

Wind is one of these contributors. Among early studies of the impacts of wind on CyanoHABs are those of Johnson (1949), Verduin (1951) and Ragotskie and Bryson (1953), who identified that wind could cause considerable heterogeneity in the horizontal distributions of planktonic populations. Based on field investigation and numerical simulation, George and Edwards (1976) and Webster (1990) outlined that the *Microcystis* population should be more strongly concentrated toward the downwind end of a lake due to the wind-generated turbulence in the upper layers. Webster and Hutchinson (1994) experimented with a population of *Microcystis* placed in a water tank in the floor of a wind tunnel and suggested

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that winds having speeds >2–3 m/s were required to mix floating *Microcystis* cells (or colonies) away from the water surface. They hypothesized that the nature of the dynamic processes of *Microcystis* differed depending on whether wind speed was above or below a critical level. Below the critical wind speed, wind-generated turbulence was incapable of mixing floating *Microcystis* cells into the water below the surface. Surface scums of floating *Microcystis* will develop. When the wind turned still stronger above the critical wind speed, surface blooms disappeared and most cyanobacteria were distributed in deeper layers. This prediction was in good agreement with the simulated results (Zhu and Cai, 1997) and measured surface *Microcystis aeruginosa* bloom distributions (Cao et al., 2006; Wu et al., 2010). Recently Bresciani et al. (2013) made a continuous monitoring of chlorophyll-a concentration in the Mantua Superior Lake in northern Italy and found that wind speed was one of the key factors regulating the daily phytoplankton growth and dynamics. Zilius et al. (2014) combining remote sensing and numerical simulation discussed the role of wind speed during algal blooms, from the point of hypoxia in bottom waters. Wu et al. (2015) using long-term historical data, short-term field process measurement, and satellite images identified the importance of changes in wind patterns on the cyanobacterial bloom in Lake Taihu (China) and demonstrated that the floating condition determined by self-buoyancy and wind-induced hydrodynamics was important for the extension of surface cyanobacterial blooms and the annual mean monthly maximum cyanobacterial bloom area (MMCBA) was significantly correlated with wind speed ($R = -0.61$, $P < 0.05$).

The above researchers had made much effort to explore the impacts of wind on cyanobacterial blooms and disclosed the horizontal movement and vertical distribution of cyanobacterial under varied wind-induced disturbance. However, wind influences cyanobacterial bloom in various forms, not limited to this. It can generate an intensified water turbulence, which may impose a direct impact on phytoplankton's own biochemical process (Healey, 1985; Borchardt, 1994). Another way that wind could affect cyanobacterial bloom is to alter the chemical nutrient status by enhancing the suspension of deposited sediment (Zhu et al., 2013; Orihel et al., 2013). Furthermore, especially in case of strong winds, although surface blooms disappeared, phytoplankton distributed in deeper layers can still be drove by the wind-generated Stokes drift which interacts with, and often contributes to the future bloom area (Cao et al., 2006; Thomas and Takhar, 1992; Constantin, 2006). Little attention has been paid to these processes.

At the present study, we aimed to separate the influences of wind on CyanoHABs into the following three components: (a) direct impact on cynbacterial cell growth by disturbance; (b) indirect influence on nutrient status by the wind-induced sedimental release; and (c) direct transportation including the surface floating when the wind speed is below a critical value, and the wave-generated Stokes drift under a stronger wind force. Meiliang Bay, situated at the north end of Taihu Lake in China, was selected as the study area and *Microcystis aeruginosa* was considered as the tested species. Based on laboratory experiment, field monitoring and numerical simulation, we (1) explored the proliferation processes of *Microcystis aeruginosa* under varied disturbance intensities and established the relationship between shear stress and sediment nutrient release, which were synchronously applied to improve the growth governing equation; (2) developed a numerical CyanoHABs model in which the influences of wind were incorporated, validated it against the field investigated data, and proposed a mathematical method to separate the integrated impact of wind on CyanoHABs; (3) quantified the individual contributions of the three components to the serious CyanoHABs happened in the summer of 2007 in Meiliang Bay.

2. Methods and materials

2.1. Lake description

Lake Taihu is located in the southeastern part of Yangtze River Delta (30°55′40″-31°32′58″N; 119°52′32″–120°36′10″E), Fig. 1. It is a large, shallow (mean depth 1.9 m) freshwater lake, with an area of 2338.1 km^2, a catchment area of 36,500 km^2 and a volume of 4.4 billion m^3. The lake is 68.5 km long is the north-south direction and on average 34 km wide from east to west (Li et al., 2013a; Duan et al., 2009; Qiao et al., 2006). It is located in the southeast monsoon climate area and the wind directions around the lake in summer are dominated by ESE and SE. The lake is surrounded by highly developed cities and towns, which account for more than 14% of gross domestic product of China. When it's healthy, it also provides drinking water for more than 2 million people, and it sustains one of China's most important fisheries for crabs, carp, and eels (Guo, 2007). However, over the past 3 decades, industrial effluents, farm runoff, and sewage have besieged Taihu, knocking its ecosystem out of balance. Every summer, *Microcystis* blooms became a regular phenomenon, turning sections of Taihu pea green (Stone, 2011). Meiliang Bay situated in the northern part of the lake is one of its most eutrophic bays. The surface area of the bay is 132 km^2 (about 5% of the area of Taihu Lake) with a mean depth of 2.0 m. Recently, cyanobacterial blooms which could be recorded every year from May to October have brought severe problems to this region and created great public concern for the close relationship with drinking water quality (Xu et al., 2014).

2.2. Wind's influence separation

It is recognized that wind contributes to outbreaks of cyanobacterial blooms in the lakes (Chen et al., 2003; Webster, 1990; Cao et al., 2006; Wu et al., 2015). The wind-induced physical properties play a fundamental role in driving the dynamics of cyanobacterial communities. Below a critical wind speed, cyanobacterial cells are apt to float on the water surface and accumulate toward the downwind axis, while under the stronger wind speed; the generated turbulence will be capable of mixing floating cells or colonies into the deeper water and make a homogeneously vertical distribution throughout the water column (Webster and Hutchinson, 1994). However, wind's forcing not only shapes the structure of the hydrodynamic environment but also affects biological processes in some direct and indirect ways. From physiological viewpoint, wind-induced turbulence can affect the air-water gas (O_2, CO_2) exchange process, impose on cyanobacterial carbon resource absorption and respiration especially during the dark period when dissolved oxygen falls down, and then regulate or alter the degree to which dense components such as carbohydrate and protein accumulate in the cell (Borchardt, 1994). In addition, the wind-generated disturbance could play a key role in the substance exchanges between deposited sediment and overlying water, which will renew the nutrient zone and affect the taking up of cyanobacterial cells.

Thus, we tentatively separate the integrated impacts of wind on CyanoHABs in shallow lakes into three components: (a) direct disturbance impacts on cyanbacterial cell growth rate by wind force; (b) indirect influence on its population by the wind-induced internal nutrient release; (c) direct transportation for cyanbacterial cells, including both surface floating and horizontal drift in deeper water column. Under a calm wind, the lake surface can be approximately recognized as a smooth hydrodynamic layer and the leading physical impact is reflected by surface drift. When the wind speed is above a critical value, although the surface cyanobacterial cells tend to be distributed in the deeper layer, they are still