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RESEARCH PAPER

On the horizontal distribution of algal-bloom in Chaohu Lake and its formation process

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Abstract Based on the remote sensing images of algae, the present work analyzes the horizontal distribution characteristics of algal blooms in Chaohu Lake, China, which also reveals the frequency of algal blooms under different wind directions. Further, an unstructured-grid, three-dimensional finite-volume coastal ocean model (FVCOM) is applied to investigate the wind-induced currents and the transport process to explain the reason why algal blooms occur at the detected places. We first deduce the primary distribution of biomass from overlaid satellite images, and explain the formation mechanism by analyzing the pollution sources, and simulating the flow field and transportation process under prevailing wind over Chaohu Lake. And then, we consider the adjustment action of the wind on the corresponding day and develop a two-time scale approach to describe the whole formation process of algae horizontal distribution in Chaohu Lake. That is, on the longer time scale, i.e., during bloom season, prevailing wind determines the primary distribution of biomass by inducing the characteristic flow field; on the shorter time scale, i.e., on the day when bloom occurs, the wind force adjusts the primary distribution of biomass to form the final distribution of algal bloom.

Keywords Chaohu Lake · Algal bloom · Horizontal distribution · Wind-driven current · Two-time scale process

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1 Introduction

Chaohu Lake, located at the middle and lower Yangtze River, is one of the large shallow lakes in China. Generally, it is divided into two parts: the western half and the eastern half by the line of Zhongmiao-Mushan-Qitouzui as shown in Fig. 1. As a result of excessive nutrients and carbon loading from surrounding catchments, Chaohu Lake suffers from eutrophication as well as other contamination problems and becomes one of the three most severe eutrophic lakes in China. Algal blooms can be observed there from May to November each year [1]. Both water quality and algal blooms in Chaohu Lake show great heterogeneity in space distribution. The eastern half lake is of mesotrophic state and the western half is of hypertrophic state [2, 3]. And algal bloom is much more severe in the western lake than in the eastern, with the northwest corner the most severe bloom area [1, 4].

Fig. 1 The underwater topography of Chaohu Lake, and schematic of rivers around

Heterogeneity in the distribution of algal bloom is a common phenomenon in large water areas. It was first studied from the viewpoint of distribution of nutrient sources and their loading, and the results show that chlorophyll α level is related with external nutrient loading [5] and external nutrient input would have a great influence on the biomass in areas around [6]. In fact, biomass is not only related with local nutrient distribution, but also influenced by hydrodynamic process of a variety of scales. For instance, the vertical mixing caused by small-scale turbulence would mix floating phytoplankton away from water surface and change the vertical profile of phytoplankton concentration [7]; and the wind-induced current would lead to floating phytoplankton's gathering at the downwind end [8].

To find out the formation mechanism of algal bloom's heterogeneity, the impact of wind-driven current during bloom period on the primary distribution of biomass has been discussed in a number of studies. Kanoshina et al. [9] showed that the average distribution of the cyanobacterial bloom was determined by the prevailing wind of the year. Ishikawa et al. [10] studied the distribution of algae in Lake Biwa of Japan and proposed the hypothesis that cyanobacteria were generated inshore and advected offshore by a clockwise gyre during the stratification period. Yin [11] thought that the horizontal transportation caused by prevailing monsoon wind should be blamed for the red tide occurrence in the NE bays of Hong Kong waters, where the nutrients were not high enough to support the blooms. However, it is still not enough to explain the actual distribution of algal blooms just in terms of the characteristic flow structure and primary biomass distribution. Taking Taihu Lake in China as an example, Chen et al. [12] pointed out that the locations of pollution sources and the horizontal advection caused by southeast wind (the prevailing wind during bloom season) led to great aggregation of Microcystics at Meiliang Bay. However, Meiliang Bay is too large a water area to precisely describe the actual places of algal bloom occurrence. Based on a continuous observation, Wu et al. [13] found out that Microcystics can highly concentrate either at the eastern shore or at the western part, or even at the open water outside of the bay. Obviously, this can not be explained by merely studying the characteristic flow field during the bloom season.

In this paper, we first explore the characteristics of horizontal distribution of algae and the frequency of algal blooms under different wind directions in Chaohu Lake based on remote sensing images. We further study the formation process of such distribution from the primary biomass distribution formed under prevailing wind and the adjustment effect of the wind of the day. Numerical experiments are then carried out to support.

2 Study area

Chaohu Lake, locating at east longitude 117°16′54″–117°51′46″ north latitude 31°25′28″–31°43′28″, covers an area of 780 km^2. It has a mean depth of 2.7 m and the underwater topography is shown in Fig. 1 [14]. The Chaohu Sluice, controlling water exchange between Chaohu Lake and Yuxi River, has been at the east end of the lake since 1962. It was rebuilt in 2002 for extension with a design discharge of 1 370 m^3/s.

There are 11 rivers around Chaohu Lake, and the water quantity from Hangbu–Fengle River, Nanfei River, Baishitian River, Dianbu River and Pai River, accounts for over 90% of the total runoff [15]. And rivers, which bring 68.5% and 76.5% of total TN and TP into the lake, are the important nutrient sources of Chaohu Lake [15]. Guan [16] summarized the comprehensive pollution indexes of rivers around Chaohu Lake from 2001 to 2010, and the result is shown in Fig. 2. It indicates that the water quality of rivers is quite stable during nearly a decade. According to the 2012 Annual Report of the Environment in Anhui Province, five rivers are shown to be the most seriously polluted ones, with heavy pollution state (above Grade V), while the water in eastern and western Chaohu Lake is of mild pollution (Grade IV) and moderate pollution (Grade V).

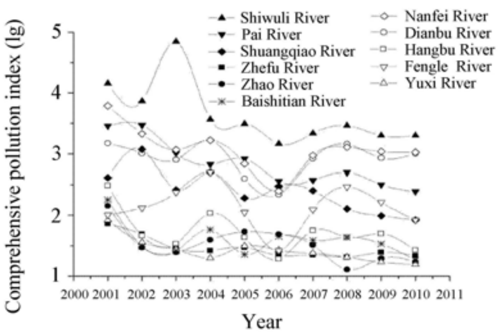

Fig. 2 Comprehensive pollution indexes of rivers around Chaohu Lake

3 Material and method

A set of remote sensing images from the Institute of Meteorological Science of Anhui Province is used to analyze the characteristics of algae distribution in Chaohu Lake. These images were taken from June to November in 2012, which showed 35 occurrences of algal blooms. The images of algal blooms were extracted from raw images of moderate-resolution imaging spectroradiometer (MODIS) on TERRA satellite. And normalized difference vegetation index method was used to process the raw images, based on different reflection properties of water and algae in infrared and near-infrared wavebands [4].

Satellite image is good at showing algal blooms on a large spatial scale [17]. However, a satellite image could represent one algal bloom only, and is far from revealing the regularity of blooms. Thus, technique of image overlay is used in this study to better illustrate the distribution characteristics based on the bloom images in one year.

Wind-driven currents are simulated using the finite-volume coastal ocean model (FVCOM). FVCOM is a 3D free-surface model using unstructured grid. The governing equations used in this study combine momentum equations and continuity equation. Momentum equations at three directions are as follows [18]

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+u\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fv = -\frac{1}{\rho}\frac{\partial P}{\partial y}+\frac{\partial}{\partial z}\Big(K_m\frac{\partial u}{\partial z}\Big)+F_u, \tag{1}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu = -\frac{1}{\rho}\frac{\partial P}{\partial y}+\frac{\partial}{\partial z}\Big(K_m\frac{\partial v}{\partial z}\Big)+F_v, \tag{2}$$

$$\frac{\partial P}{\partial z}=-\rho g. \tag{3}$$

Continuity equation is

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0. \tag{4}$$

Variables in the above equations are defined as below, x, y, z are the axes pointing towards east, north and vertical; u, v, w are the velocity components in the x, y, z directions, respectively; T and S the temperature and salinity; ρ is the density; P the pressure; f the Coriolis parameter; g the gravitational acceleration; K_m the vertical eddy viscosity coefficient.

Boundary conditions at the surface and bottom are

$$K_m\Big(\frac{\partial u}{\partial z},\frac{\partial v}{\partial z}\Big)=\frac{1}{\rho}(\tau_{sx},\tau_{sy}),\quad w=\frac{\partial\zeta}{\partial t}+u\frac{\partial\zeta}{\partial x}+v\frac{\partial\zeta}{\partial x},\quad \text{when}\quad z=-\zeta(x,y,t), \tag{5}$$

$$K_m\Big(\frac{\partial u}{\partial z},\frac{\partial v}{\partial z}\Big)=\frac{1}{\rho}(\tau_{bx},\tau_{by}),\quad w=-u\frac{\partial H}{\partial x}-v\frac{\partial H}{\partial y},\quad \text{when}\quad z=-H(x,y), \tag{6}$$

where ζ is the height of free surface, τ_{sx} and τ_{sy} are surface wind stresses in the x and y directions, respectively, $\tau_{bx} = C_d u\sqrt{u^2+v^2}$ and $\tau_{by} = C_d v\sqrt{u^2+v^2}$ are bottom stresses in the x and y directions, respectively. The drag coefficient C_d is calculated by

$$C_d=\max\left(k^2\Big/\ln\left(\frac{z_{ab}}{z_0}\right)^2,\ 0.002\,5\right), \tag{7}$$

where the von Karman constant $k = 0.4$, z_{ab} is the height of a logarithmic bottom layer and z_0 is the bottom roughness parameter.

The governing equations are solved in Cartesian coordinate, while in the vertical direction the σ coordinate is used. The governing equations are transformed according to the following equation.

$$\sigma=\frac{z-\zeta}{H+\zeta}=\frac{z-\zeta}{D}, \tag{8}$$

where H is the bottom depth, D the total water column depth.

After transformation, the primitive equations become

$$\frac{\partial\zeta}{\partial t}+\frac{\partial Du}{\partial x}+\frac{\partial Dv}{\partial y}+\frac{\partial\omega}{\partial\sigma}=0, \tag{9}$$

$$\frac{\partial uD}{\partial t}+\frac{\partial u^2D}{\partial x}+\frac{\partial uvD}{\partial y}+\frac{\partial u\omega}{\partial\sigma}-fvD = -gD\frac{\partial\zeta}{\partial x}-\frac{gD}{\rho}\Big[\frac{\partial}{\partial x}\Big(D\int_\sigma^0\rho d\sigma'\Big)+\sigma\rho\frac{\partial D}{\partial x}\Big] +\frac{1}{D}\frac{\partial}{\partial\sigma}\Big(K_m\frac{\partial u}{\partial\sigma}\Big)+DF_x, \tag{10}$$

$$\frac{\partial vD}{\partial t}+\frac{\partial uvD}{\partial x}+\frac{\partial v^2D}{\partial y}+\frac{\partial v\omega}{\partial\sigma}+fuD = -gD\frac{\partial\zeta}{\partial y}-\frac{gD}{\rho}\Big[\frac{\partial}{\partial y}\Big(D\int_\sigma^0\rho d\sigma'\Big)+\sigma\rho\frac{\partial D}{\partial y}\Big] +\frac{1}{D}\frac{\partial}{\partial\sigma}\Big(K_m\frac{\partial v}{\partial\sigma}\Big)+DF_y. \tag{11}$$

Tracer tracking used in this study is based on the convection-diffusion equation with a source term, the equation in the σ coordinate is shown as

$$\frac{\partial DC}{\partial t}+\frac{\partial DuC}{\partial x}+\frac{\partial DvC}{\partial y}+\frac{\partial\omega C}{\partial\sigma}-\frac{1}{D}\frac{\partial}{\partial\sigma}\Big(K_h\frac{\partial C}{\partial\sigma}\Big)-DF_c = DC_0(x,y,\sigma,t), \tag{12}$$

where C is the concentration of the tracer, K_h is the vertical thermal diffusion coefficient, F_c is the horizontal diffusion term, and C_0 is the concentration of a point source

$$C_0(x,y,\sigma,t)=\begin{cases}1, & t_s\leqslant t\leqslant t_e;\ \ \sigma_k\leqslant\sigma\leqslant\sigma_{k+n};\\ & x=\{x_i\};\ \ y=\{y_i\},\\ 0, & \end{cases} \tag{13}$$

where t_s and t_e are the start and end time of tracer source, σ_k and σ_{k+n} the upper and lower-bound sigma levels in which tracer is added. x_i, y_i are the x, y locations of the tracer sources.

The horizontal diffusion is calculated using Smagorinsky eddy parameterization method [19], and the vertical uses the Mellor and Yamada level 2.5 turbulent closure model [20]. The equations are solved using mode splitting method, and the currents are divided into external and internal modes with two different time steps.

Wind data used in this paper are obtained from Binhu automatic weather station in Hefei, Anhui Province (as shown in Fig. 1), which records hourly data of wind direction and speed. To achieve the daily-averaged wind speed, the hourly data is processed by vector averaging. And the mean wind speed used in simulation is calculated based on the daily wind speed data of Binhu automatic station from 2002 to 2012.

4 Results and discussion

4.1 Distribution of algal blooms in Chaohu Lake

Algal blooms in Chaohu Lake occurred 35 times in 2012 between June to November according to the remote sensing data. To study the relation between the wind direction and the distribution of algal blooms, the remote sensing images are divided into 4 groups, which represent wind blowing from northeast (0°–90°), southeast (90°–180°), southwest (180°–270°) and northwest (270°–360°), respectively, based on the daily-averaged wind direction on the day when blooms occurred. The images in each group are overlaid respectively, and the results are shown in Fig. 3 with varied color illustrating the times of occurrence under different wind direction.

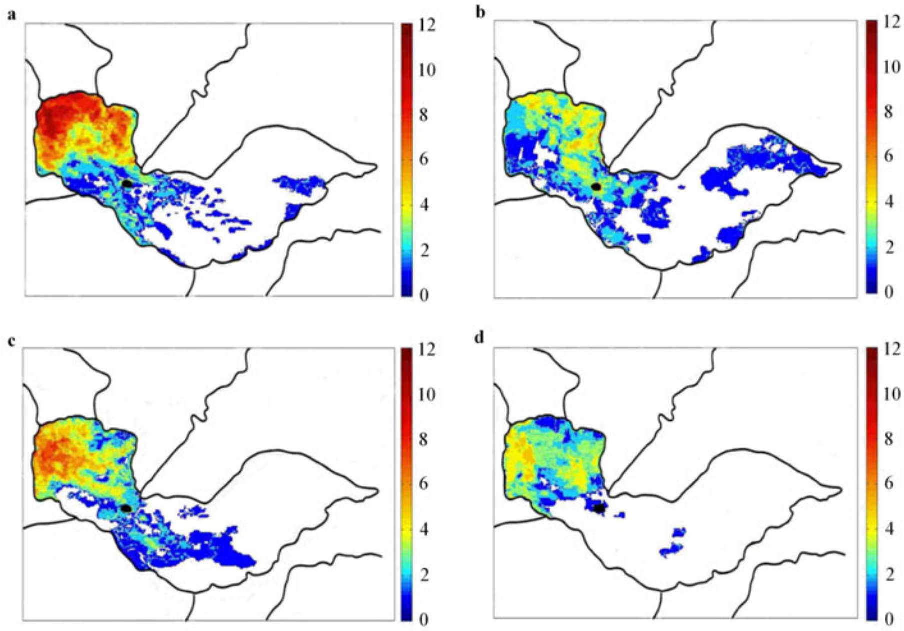

Fig. 3 Overlaid remote sensing images of algal blooms under different wind conditions. **a** Southeast wind; **b** Southwest wind; **c** Northeast wind; **d** Northwest wind

Obviously, it can be observed in Fig. 3 that the algal bloom is more severe in western Chaohu Lake than in the eastern, both in frequency and in covered area. Most of the algal blooms happen in the western lake and the northwest corner is the most severe place. As algal blooms happened only twice in the east part of the eastern lake in 2012, the blooms occurring there are not discussed in our paper since the number of the samples is not large enough, and thus we mainly focus on the western lake and the west part of the eastern lake. It can be seen that the wind direction of the day has an obvious influence on the actual distribution of algae. In detail, under the condition of south wind, algae aggregates severely at the north part of the lake. And the aggregation place changes to be the middle of the lake when north wind blows. Under east wind condition, algal blooms mostly happen in the west part of both the western and eastern lakes. However, when it is west wind, more algal blooms occur at the east shore of the western lake, and algae distributes more dispersive in the eastern lake, reaching as far as the middle of the lake. In sum, it is apparent that algal bloom tends to occur on the downwind side.

What should be noted is that the wind action of the day when bloom occurs is not the only deterministic factor, though it has big influence on the distribution of algae. Figure 3 also shows that algae gather at the north shore under south wind condition, whereas it aggregates in the middle of the lake rather than the south shore when it is north wind. Similarly, algae appear most in the west part under east wind, but it does not occur severely at the east shore under west wind. These phenomena imply that, there should exist another mechanism which works together with the wind of the corresponding day to determine the horizontal distribution of algae.

4.2 The primary biomass distribution and its formation

The satellite images record the accumulation of the bloom when it happens. However, it could not show us its formation process from initiation, which is required for both the prediction and the control of algal blooms. As discussed above, algae appears to occur on the downwind side under the wind of the day, which indicates that algal bloom would not only occur at the first occurrence places, but also move to the downwind side, driven by the wind of the day. Thus, one would ask where the algal bloom will occur first and why it happens there. In this section, we start from studying the first occurrence place of algal bloom and the primary distribution of biomass, followed by an analysis of the cause of such distribution.

4.2.1 The first occurrence places of algal bloom and primary biomass distribution

The places where algae first occur can be deduced by the actual aggregation places indicated by Fig. 3 and the wind direction on the corresponding day. For example, when algal bloom occurs in the middle of the lake under north wind on that day, the algae should come from the places north to the occurrence place, as algae drifts downwind under the wind force as mentioned above. Accordingly, all possible places of algae first occurrence under different winds are overlaid to take their union (overlap area), which represents the places where algae aggregates severely and blooms first occur in Chaohu Lake, as shown in Fig. 4a. It implies that algae of the western lake mainly gathers in the north (the northwest corner is more severe than the northeast one), and algae of the eastern lake gathers in areas around Zhongmiao–Mushan area, the northwest part of the eastern lake. Notice that as the western lake is much more heavily polluted than the eastern lake, algal-bloom is much more severe in the western lake than in the eastern regarding the occurrence frequency. Thus, some places in the western lake would have more severe aggregation than those in the Zhongmiao–Mushan area, and the Zhongmiao–Mushan area is more severely aggregated only compared with the other places in the eastern lake. Moreover, it can be inferred from Fig. 3 that there are algal blooms in the Zhongmiao–Mushan area no matter what wind is blowing, which indicates that it is a place of accumulation in the eastern lake where algae would easily gather.

Based on the observation of the nutrient and biomass at 0.5 m depth of 35 sites in August, 1987 and October, 1988, Tu et al. [15] drew the map of eutrophic state of Chaohu Lake (Fig. 4b). The results exhibit an area of extremely hypereutrophic at the northwest corner of the western lake and three areas of hypereutrophic in the north part of the western lake, the area around Zhongmiao–Mushan and around Zhefu River mouth. Deng et al. [21] observed the biomass distribution of Chaohu Lake, and the results are shown in Figs. 4c and 4d. In summer and autumn when algal blooms mostly occur, the highest biomass in the western lake and the eastern lake was found at the northwest corner and Zhongmiao–Mushan area, respectively. These observation results agree well with the aggregation places of algae we deduced from the remote sensing images. Therefore, Fig. 4a can approximately describe the primary distribution of biomass in Chaohu Lake, which is characterized by the comparatively severe aggregation places in the north of the western lake and the area around Zhongmiao–Mushan.

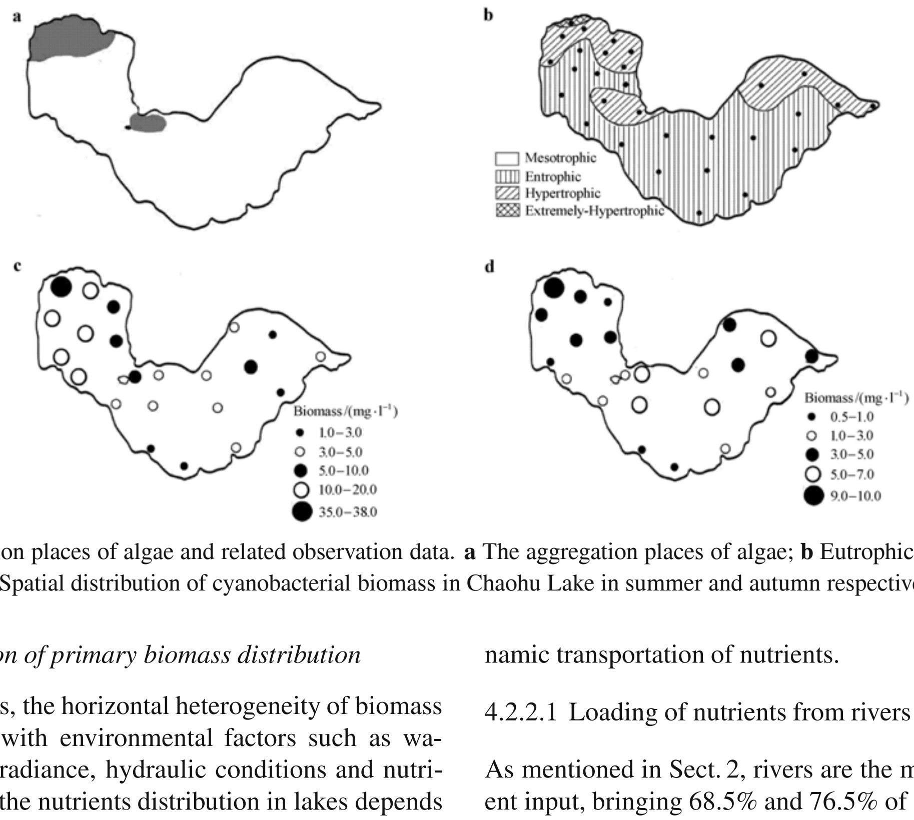

Fig. 4 The aggregation places of algae and related observation data. **a** The aggregation places of algae; **b** Eutrophic state of Chaohu Lake by Tu et al.; **c** and **d** Spatial distribution of cyanobacterial biomass in Chaohu Lake in summer and autumn respectively by Deng et al.

4.2.2 The formation of primary biomass distribution

In large water areas, the horizontal heterogeneity of biomass is always related with environmental factors such as water temperature, irradiance, hydraulic conditions and nutrients [22, 23]. And the nutrients distribution in lakes depends on the input source and its transport by wind-induced current [24]. As for Chaohu Lake, an inland shallow lake, water temperature distributes quite even in the lake and its influence on biomass distribution is negligible. Thus, to seek for the mechanism of heterogeneity of primary biomass distribution in the lake, we mainly discuss the following two factors: nutrients loading and its distribution, and hydrodynamic transportation of nutrients.

4.2.2.1 Loading of nutrients from rivers

As mentioned in Sect. 2, rivers are the main source of nutrient input, bringing 68.5% and 76.5% of the total TN and TP into the lake [15]. Guan [18] summarized the comprehensive pollution indexes of rivers around Chaohu Lake from 2001 to 2010, which indicates that the water quality of rivers is quite stable during nearly a decade and Shiwuli River, Nanfei River, Dianbu River, Pai River and Shuangqiao River are the most seriously polluted ones (Fig. 2). These five rivers are shown to be of heavy pollution state (above Grade V) according to the 2012 Annual Report of the Environment in Anhui Province, while the other rivers around the lake are moderately or mildly polluted. Also, the report indicates that the water in eastern and western Chaohu Lake is in mild pollution (Grade IV) and moderate pollution (Grade V) states, respectively. That is to say, the moderately or mildly polluted rivers, whose quality is not worse than the water quality in Chaohu Lake, is not the major sources of the nutrient in Chaohu Lake. Therefore, considering the present water quality in Chaohu Lake, the pollution sources should be the heavily polluted rivers, which would still deteriorate the water quality in the lake. Four of the five heavy polluted rivers, Shiwuli River, Nanfei River, Pai River and Dianbu River (Dianbu River joins Nanfei River at Cuozhen before flowing into the lake), respectively, locate at the north of western lake, with only Shuangqiao River lying at the northeast of eastern lake, as shown in Fig. 1. Hence, the north part of western Chaohu Lake should be the main source of pollution input and this is the main reason why the water is more eutrophic in the western lake than in the eastern, in the north part than in the south.

4.2.2.2 Flow field under prevailing wind condition and nutrient transportation

Based on the nutrients sources of Chaohu Lake, we can analyze the impact of hydrodynamic transportation on the formation of primary biomass distribution by numerical simulations.

Algal blooms usually occur during May to November each year in Chaohu Lake (the bloom period was June to November in 2012), when the prevailing wind is southeast wind. And the average wind speed from 2002 to 2012 is about 2.4 m/s. A sluice has been built at the east end of the lake to release water during flood period. According to the observation from Tu et al. [15], the flow field in Chaohu Lake is usually a complex one with wind-induced flow and gravity flow.

Thus, in order to understand typical flow fields of the lake, both the cases with sluice closed and open under the southeast wind of 2.4 m/s are simulated. As roughness data can not be found either in in-situ observation or in numerical experiment for Chaohu Lake, the bottom roughness height we used in this study is set to 0.01 m, referring to the numerical experiments in Taihu Lake [25]. Both lying in the middle and lower Changjiang River, the two lakes have similarity in their sediment deposition. The depth-averaged flow field is used to represent the material exchange. Moreover, in order to find out the influences of nutrient input from the heavy polluted rivers to the western lake, tracers are added at the mouths of Shiwuli River, Nanfei River (also Dianbu River) and Pai River.

Figures 5a and 5b shows the results simulated under southeast wind of 2.4 m/s with sluice closed: the depth-averaged flow field at 30 h in Fig. 5a and the distribution of tracers at 2 000 h in Fig. 5b. Figures 5c and 5d shows results simulated under southeast wind of 2.4 m/s with sluice releasing water at the rate of 900 m^3/s: the depth-averaged flow field at 30 h and the distribution of tracers at 2 000 h in Figs. 5c and 5d, respectively.

As illustrated in Fig. 5a, there are two reverse circulations existing in the western lake, both of which flows towards the northwest corner and join together there. And then, the combined-current flows from the northwest corner of western lake, passes through the north of Mushan Mountain, and enters the eastern lake with a velocity of 0.01–0.02 m/s. There are also three circulations locating respec-

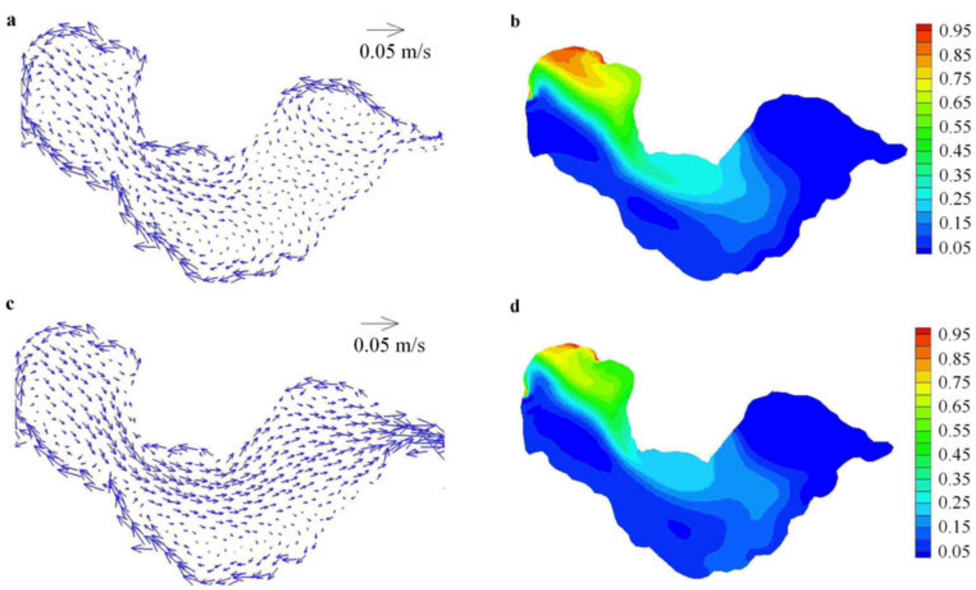

Fig. 5 Simulation results under southeast wind of 2.4 m/s. **a** Depth-average flow field at 30 h with closed sluice; **b** Distribution of tracer at 2 000 h with closed sluice; **c** Depth-average flow field at 30 h with open sluice; **d** Distribution of tracer at 2 000 h with open sluice

tively in the areas around Zhongmiao, the mouth of Zhao river and the mouth of Jiongyang river. Flows in other areas are quite slow, with very small velocity pointing towards northwest. From Figs. 5a and 5b, it is clear that the nutrient input from rivers is transported by the flow along-shore and accumulates at the northwest corner rather than at the mouths of rivers. Advected by joint-current, the nutrient enters the eastern lake through the north of Mushan Mountain, and then gets trapped by a clockwise circulation near Zhongmiao. As it is difficult to exchange material between circulation system and the surrounding, a large amount of nutrient with high concentration remains in the area around Zhongmiao, making the area a heavier accumulating place than the other areas in the eastern lake. Similarly, it is not easy for external nutrient to get into the circulations. Thus, the nutrient concentration in the south of the western lake and the area around Zhao River mouth, where there exist two circulations, is quite low.

Similar results are also obtained in the case when the sluice is open, as shown in Figs. 5c and 5d. Two reverse circulations join at the northwest corner and then the joint current, which is stronger than the one when the sluice is closed, enters the eastern lake through the north of Mushan Mountain and flows towards Chaohu Sluice. Three circulations exist respectively in the areas around Zhongmiao, Zhao River mouth and Jiongyang River mouth, all of which are smaller than those with closed sluice. Both in Figs. 5a and 5c, there are obvious currents along the shore, with much larger velocity than in the other places of the lake. This may be ascribed to the much shallower depth near the shore than that in the middle of the lake, as indicated by Fig. 1. And it is a common phenomena that places near the shore with shallower depth has larger velocity, as has be found in the Erhai Lake and Lake Michigan [26, 27]. Moreover, the most outside dots shown in Figs. 5a and 5c are not the shoreline of the lake, but about 800 m away from the shore. Vectors have been averaged in the near grids in order to have proper spacing to be shown clearly. Figure 5d shows that tracer distribution at 2 000 h is of the highest level in the northwest part of the western lake, and of high level in the area around Zhongmiao–Mushan of the eastern lake as compared with the other part of the eastern lake. It is almost the same for the case of closed sluice (Fig. 5b). This is because the water release of the sluice has an obvious impact only on the flow field in the east part of the eastern lake, and the nutrient concentration there is too low to identify significant difference.

To conclude, because of the combined effect of pollution sources and hydrodynamic transportation driven by the prevailing wind, the present distribution of eutrophic level in Chaohu Lake is formed, which is characterized by higher eutrophic level in the western lake than in the eastern lake with comparatively high concentration of nutrient in the northwest part of the western lake and the area around Zhongmiao–Mushan of the eastern lake. Moreover, previous researches showed that the distribution of phytoplankton would coincide with that of nutrient [28], and the biomass in Chaohu Lake was positively correlated with nutrient concentration [16, 29]. Hence, the spatial distribution of biomass should be similar to that of nutrient, which means that biomass would aggregate in the northwest part of the western lake and the area around Zhongmiao–Mushan. Besides, phytoplankton from other areas would be advected by currents, as shown in Figs. 5a and 5c, to gather at the places mentioned above. Obviously, the regions with high levels of nutrient and phytoplankton are consistent with the primary biomass distribution deduced from remote sensing images shown in Fig. 4a.

4.3 Adjustment of the algae distribution by the wind of the day

As aforementioned, the location of pollution sources and hydrodynamic transportation under prevailing wind determine the primary distribution of biomass. However, according to the remote sensing images shown in Fig. 6, the regions of algal blooms are not identical with the high level regions of biomass, but on the downwind side of them, with the wind direction of the corresponding days at 22.11°, 113.37°, and 220.08° respectively. The same viewpoint has also been pointed out in Sect. 3.1 that algae tends to occur on the downwind side under the wind of the corresponding day. And it is clear that the wind of the day plays an important role in adjusting the distribution of algal bloom.

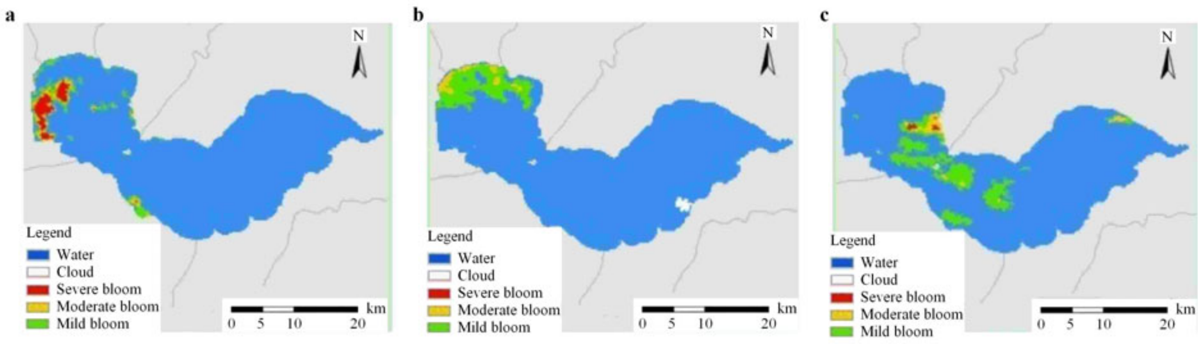

Fig. 6 Different distribution of algae in Chaohu Lake taken by MODIS (from the Institute of Meteorological Science of Anhui Province)

There exist two different mechanisms for algae moving in water under the action of wind. For granule cells dispersing in the water, phytoplankton cells are transported by the flow induced by wind and move at the same speed of water flow. For mat-shape algae accumulating on the surface of water, they drift faster than water flow under the direct driven force of wind [30]. Previously, we established a simplified drift model for mat-shaped algae horizontal drift, which indicates that algae would move towards the downwind side at a speed that changes in a quadratic function with the wind speed [31]. Thus, in this section we mainly focus on the transportation of granule plankton cells in the water to see the reason and the process of the transportation towards the downwind side.

As Deng et al. [32] reported based on the field observation, the concentration of Microcystis (the dominant phytoplankton) in the upper water is significantly higher than that in the lower layer at daytime in Chaohu Lake. Moreover, microcystis is a kind of floating phytoplankton that will go up and accumulate at the water surface when blooms happen under proper weather condition. Therefore, to study the transportation process of microcystis on the day when blooms happen and to correlate with the remote sensing data taken between 10:00 am and 12:00 am, the flow field in the upper layer is discussed here. Simulated results with closed and open Chaohu Sluice under different wind conditions are shown in Figs. 7 and 8, respectively.

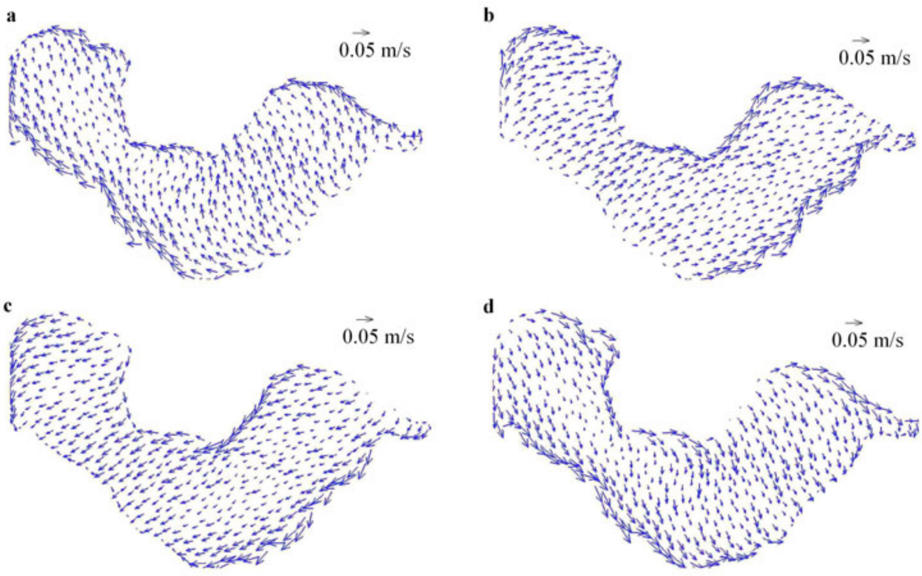

Fig. 7 Flow field of upper layer water under different wind conditions with sluice closed. **a** Southeast; **b** Southwest; **c** Northeast; **d** Northwest

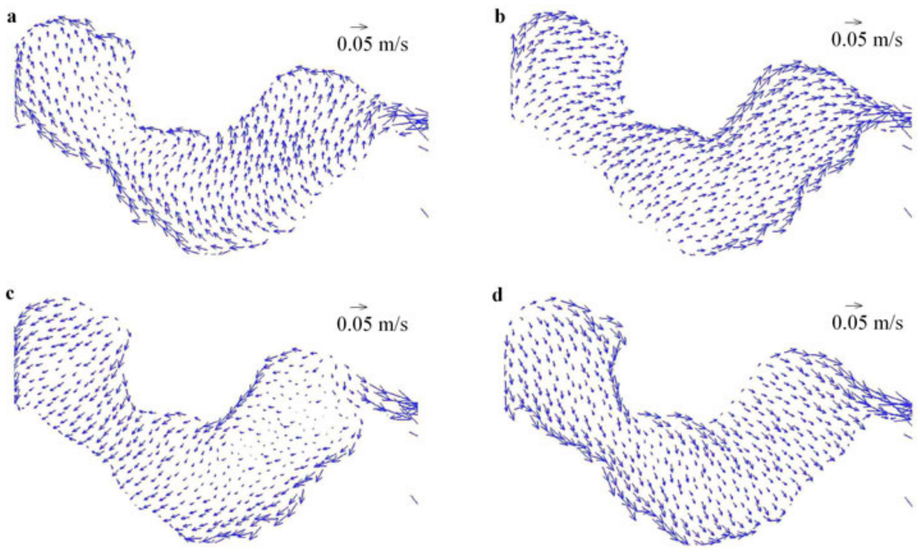

Fig. 8 Flow field of upper layer water under different wind conditions with sluice open. **a** Southeast; **b** Southwest; **c** Northeast; **d** Northwest

The simulation shows that when the sluice is closed water in the upper layer flows in the same direction of wind under all wind conditions (Fig. 7). Meanwhile water in the east part of the eastern lake would flows towards the Chaohu Sluice when the sluice is open (Fig. 8). However, as illustrated in Fig. 3, algal blooms mainly happen in the western lake and the west part of the eastern lake, where the flow field is not much influenced by sluice's releasing water. Hence, algae transported by currents would move towards the downwind side no matter the sluice is closed or open.

Therefore, the algae, either driven by wind or advected by currents, would move downwind from the original aggregation places, and reach the places where the blooms actually take place. That is to say, the wind of the day, either by driving the mat-shaped algae directly or by inducing current in the upper layer to transport disperse cells, adjusts the horizontal distribution of algae towards the downwind side.

4.4 The two-time scale formation process of algae horizontal distribution

It is widely accepted that abundance of biomass is a prerequisite for algal blooms in the water. But algal blooms are not caused by the rapid growth of biomass in water. Instead, it is about the rapid accumulation phytoplankton on the surface of water [33, 34]. That is to say, in the growth period from April to September, biomass increases steadily and remains of high level in the water, and on the day of bloom under appropriate weather, phytoplankton cells would quickly float up and assemble on the water surface [34]. Based on this understanding of algal bloom, we conclude that, determined by the locations of pollution sources and hydrodynamic transportation under prevailing wind, Chaohu Lake exhibits the present distribution of nutrient with high level regions in the north of the western lake and around Zhongmiao–Mushan. During the growth period, phytoplankton biomass increases a lot in these regions and phytoplankton from other area would be transported and accumulated there. When the weather condition is suitable, the algae, either transported by currents or driven directly by wind, would move from the primary aggregation regions towards the downwind side and reaches the place where the blooms actually take place.

Take the blooms in 2012 as an example. During the bloom season in 2012, two circulations jointed together at the northwest corner of Chaohu Lake, then flew into the eastern lake through the north of Mushan Mountain and joined the circulation at Zhongmiao. Thus, the nutrient from the rivers was transported by the circulations in the western lake and gathered at the northwest corner instead of the river mouths. Then the nutrient was brought into the eastern lake through the north of Mushan Mountain by the flow, got trapped by the Zhongmiao circulation and formed the distribution shown in Figs. 5b and 5d. As explained above, the biomass would form a similar distribution like the nutrient, with severe aggregation in the north of the western lake and the area around Zhongmiao–Mushan. On the day of October 10th 2012, when the weather condition was appropriate, phytoplankton cells floated up and assembled in the upper water layer. Being driven directly by the northeast wind (22°) or transported by the flows as shown in Figs. 7c and 8c, the algae moved to the middle-west of the western lake, as illustrated by Fig. 6a. Similarly, on the day of June 12th and November 21th when it blew southeast wind (113.37°) and southwest wind (220.08°) respectively, algae moved from the original gathering places to the northwest or the southeast of the western lake, as shown by Figs. 6b and 6c.

To summarize, the formation of horizontal distribution of algae in Chaohu Lake is a two-time scale process. That means, on the longer time scale, during bloom season, the primary distribution of biomass is determined by the currents induced by prevailing wind; while on the shorter time scale, on the day when blooms happen, the primary distribution of algae which forms on the longer time scale is adjusted by the wind of the day to result in the actual distribution of algal bloom. Consequently, understanding the whole two-time scale formation process is required to better explain and describe the formation mechanism of the horizontal distribution of algae in Chaohu Lake.

5 Conclusions

The present work uses a combined technique of satellite measurement and numerical simulation to reveal the whole formation process of algae horizontal distribution. We not only show the frequency and suspicious places of algal bloom in Chaohu Lake under different wind conditions, but also adopt a two-time scale process to explain why the algal bloom would happen at the detected places from the aspects of original distribution of nutrient and biomass, which capture the formation process of algal bloom from initiation. In detail, the following conclusions are drawn:

(1) Based on the remote sensing images, we show that algal blooms mainly occur in the western lake, with the northwest corner the most severe place. Phytoplankton biomass mainly aggregates in the north part of the western lake and the area around Zhongmiao–Mushan in the eastern lake, which accords with field observations in previous works.

(2) Shiwuli River, Pai River, Nanfei River, and Dianbu River, all of which lie to the north of the western lake, are the main pollution sources of Chaohu Lake. Under the prevailing southeast wind during bloom season, the nutrients input from these rivers are transported by the flow along-shore and accumulates at the northwest corner rather than at the mouths of rivers. Advected by joint current, the nutrient enters the eastern lake through the north of Mushan Mountain, and then gets trapped by a clockwise circulation near Zhongmiao. The primary distributions of nutrient and biomass are determined by the hydrodynamic process and form two high level regions in the north part of the western lake and the area around Zhongmiao–Mushan.

(3) Upper water layer of the western lake and the west part of the eastern lake, where algal blooms mainly happen, flows in the same direction as the wind under both conditions with sluice closed and open. Therefore, either transported by wind-induced current or driven directly by wind force of the day when blooms happen, the primary distribution of biomass is adjusted towards the downwind side, which finally results in the actual distribution of algae in Chaohu Lake.
(4) Considering the different effect of the prevailing wind and the wind of the day on algae distribution, we develop a two-time scale formation process of horizontal distribution of algal bloom in Chaohu Lake. Specifically speaking, on the longer time scale, i.e., during the bloom season, the primary distribution of biomass is determined by the flow field induced by prevailing wind; and on the shorter time scale, i.e., on the day when bloom occurs, the distribution of algae is adjusted by the wind of the day, and the algae reaches the places where the blooms actually take place.

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