Dynamic criterion for the formation of surface water-blooms

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Abstract Surface water-blooms (SWBs) is usually explained as a buoyant migration of blue-green algae to the water surface under the conditions of reduced turbulence. Wind-induced turbulent mixing can cause considerable heterogeneity in the vertical concentration distribution of algal cells. There exists a criterion below which cell buoyancy can overcome the turbulent mixing. Former researchers regarded a certain wind speed as this criterion, but this wind speed differs in value. In this research, we propose a new criterion, nondimensional entrainment number (En), which represents the ratio of the intrinsic velocity of algal cells relative to the characteristic velocity of wind-induced mixing. Observation in Taihu Lake demonstrates that this new criterion is more suitable for the description of hydrodynamic effect on the formation of surface water-blooms. [doi:10.1063/2.1304203]

Keywords SWBs, microcystis, turbulent mixing, wind speed, entrainment number

"Water-blooms" is a term of convenience applied to an outbreak of phytoplankton cells well above average for a given water body, while "surface water-blooms" is restricted to the dense aggregations of buoyant phytoplankton cells that accumulate at the water surface on occasions.[1] Numerous algal cells discolor the water, form scum, produce unpleasant tastes and odors, affect shellfish and fish populations or otherwise create a nuisance and seriously reduce water quality.

Surface water-blooms (SWBs) formation is explained as a buoyant migration to the water surface under conditions of reduced turbulence.[2–4] The algae principally responsible for SWBs are mostly gas vacuolate cyanobacteria (blue-green algae), for example microcystis. Algal cells are uniformly distributed in the water column with the action of turbulent mixing, but migrate to the water surface to form dense surface scums when mixing stops (as shown in Fig. 1).

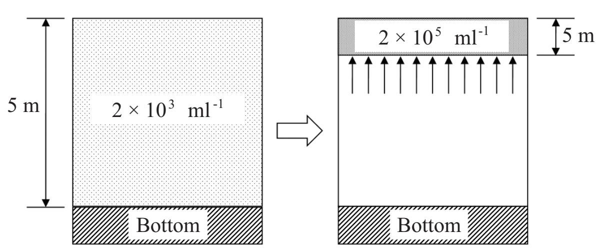

Fig. 1. Scheme of the formation of SWBs.

Turbulent mixing in the upper water column is induced mainly by wind. It has long been recognized that wind speed plays a key role during the formation of SWBs.[5–7] Only if the wind speed is low enough can the SWBs appear. Figure 2 shows a reduction of coefficient of variance CV of the vertical concentration distribution of microcystis at different depths in Taihu Lake with the wind speed increases.[8,9]

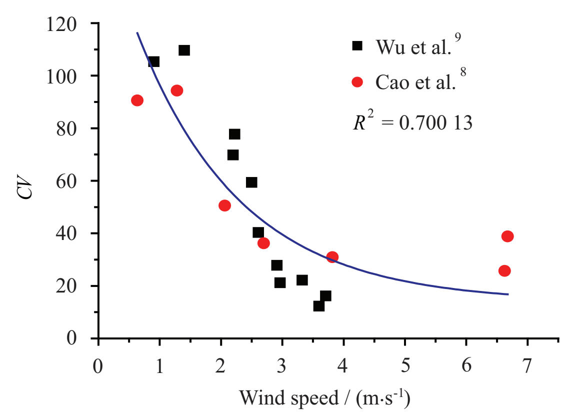

Fig. 2. Effect of wind speed on CV of the vertical distribution of microcystis.

Field studies suggest that winds having speed higher than 2–3 m/s are required to mix floating phytoplankton cells (or colonies) away from the water surface.[10] But the value of this critical wind speed is still not a consensus. Observations in Eglwys Nynyd indicate that local concentrations of blue-green algae only appeared at wind speeds below 4 m/s,[11] data from Lake Mendota shows the highest daily average wind velocity observed during a surface bloom was 2.68 m/s,[12] and the study in Taihu Lake suggests 3.1 m/s is a critical value.[8]

In this study, CV of microcystis colonies with different size is analyzed on the basis of an investigation taken in Taihu Lake.[9] It is found that colonies with larger size have a higher value of CV at low wind speeds, and with the wind speed increases, CV of all colonies decreases to a relatively low value (as shown in Fig. 3). The result indicates that colony size might be the reason why critical wind speed is different in previous observations.

Wind-induced mixing that fully entrains a phyto-

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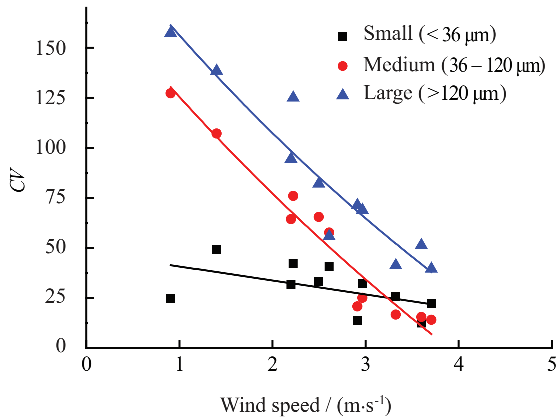

Fig. 3. Effect of colony size on CV of the vertical distribution of microcystis.

plankton population will homogenize its vertical distribution, but the degree of entrainment varies depending on the intrinsic velocity of the phytoplankton relative to the velocity of the turbulent motion. In a detailed consideration of this relationship, Humphries and Imberger[13] introduced a quotient ($\Phi = U/(15V)$, where U is the characteristic velocity of turbulent eddies that transport the cells in the upper water column and V is the modulus of the sinking or floating velocity of the phytoplankton unit) to distinguish the extent of entrainment. However, they did not give the detailed expression of this parameter Φ. Previous research used $\Phi = 1$ as the entrainment criterion, borrowing ideas from sand settling study.[13] But algae cell is different from sand particle. Bloom-forming cells are usually buoyant while sand particles are heavier than water. Moreover, the velocity of sand particle is constant while the velocity of algae cell is regulated by light.[14] In previous studies, the intrinsic velocity of the phytoplankton is treated as a constant value, which is not suitable for the description of the bloom-forming algae. The aim of this research is to give a more accurate expression of this entrainment quotient for bloom-forming algae.

Firstly, we rewrite the nondimensional parameter which is used to distinguish the extent of entrainment (hereafter, called entrainment number, En)

$$En = \frac{U}{V}. \tag{1}$$

In the gas-vacuolate microcystis the presence of intracellular gas-filled space lowers average density below that of the surrounding water so that the organisms are positively buoyant. The intrinsic floating velocity is indicated by the expression of Stokes' Law[3]

$$V = \frac{2gr^2\Delta\rho}{9\phi\eta}, \tag{2}$$

where g is the acceleration due to gravity, r is the radius of a sphere of identical volume and density, $\Delta\rho$ is the density difference between the organism and water, ϕ is the coefficient of form resistance, and η is the viscosity of the water.

When wind speeds are moderate to low and the lake is not loosing heat, the characteristic velocity of turbulence (U) in the upper water column can be equated to the water friction velocity (U^*) estimated from the wind speed as[15,16]

$$U \propto U^* = U_{10}\sqrt{\frac{C_a\rho_a}{\rho_w}}, \tag{3}$$

where ρ_a is the air density, ρ_w is the water density, C_a is wind stress drag coefficient, and U_{10} is the wind speed at a height 10 m above the surface.

By substituting the Eqs. (1) and (2) into Eq. (3), the entrainment number can be expressed as

$$En = \frac{9\phi\eta}{2g}\frac{U_{10}}{r^2\Delta\rho}\sqrt{\frac{C_a\rho_a}{\rho_w}}. \tag{4}$$

The definition of entrainment number indicates that when En is large, water velocities are large relative to the intrinsic floating velocity of microcystis to entrain the cells within the water motion so that turbulence homogenizes the vertical distribution of the population. When En is small, then the intrinsic floating velocity of microcystis plays an increasing role in the population distribution. En can be used to be the dynamic criterion for the formation of SWBs.

To verify the relationship between SWBs formation and this new criterion, Fig. 3 is revised by substituting En for wind speed as the x-coordinate (as shown in Fig. 4). Comparing with that in Fig. 3 where wind speed is the criterion, the points in Fig. 4 are more concentrated suggesting that CV is more related with En. Moreover, CV decreases to a constant value with the increase of En, showing the existence of a critical value over which SWBs are not likely to appear.

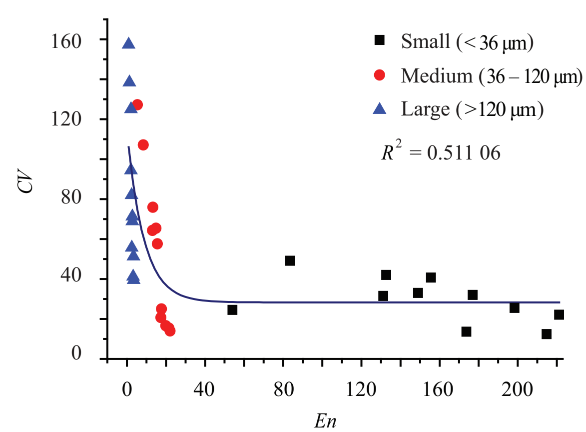

Fig. 4. Effect of En on CV of the vertical distribution of microcystis.

In summary, entrainment number is a better dynamic criterion for the formation of SWBs. Usually blooms appear at low value of En when wind-induced mixing is weak. In essence, the larger is the algae and the greater its intrinsic flotation velocity, then the greater is the turbulent intensity required to entrain it. Large colonies of fast floating velocity are more likely to accumulate at water surface to form a hazardous bloom in lakes.

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