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Effects of hydrodynamics processes on phosphorus fluxes from sediment in large, shallow Taihu Lake

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Abstract

The turnover of phosphorus (P) in lake sediments, a major cause of eutrophication and subsequent deterioration of water quality, is in need of deep understanding. In this study, effects of resuspension on P release were studied in cylindrical microcosms with Y-shape apparatus. The results indicated that there was a positive correlation between flux of suspended substance across sediment-water interface (F_{SS}) and the wind speed, and an increasing F_{SS} during each wind process followed by a steady state. The maximal F_{SS} under light, moderate, and strong wind conditions were 299.9±41.1, 573.4±61.7, and 2093.8±215.7 g/m^2, respectively. However, flux of P across sediment-water interface (F_P) did not follow a similar pattern as F_{SS} responding to wind intensity, which increased and reached the maximum in initial 120 min for light wind, then decreased gradually, with maximal flux of 9.4±1.9 mg/m^2. A rapid increase of F_P at the first 30 min was observed under moderate wind, with maximal flux of 11.2±0.6 mg/m^2. Surprisingly, strong wind caused less F_P than under light and moderate wind conditions with maximal flux of 3.5±0.9 mg/m^2. F_{SS} in water column declined obviously during the sedimentation process after winds, but F_P varied with wind regime. No obvious difference was detected on F_P after 8 h sedimentation process, compared with the initial value, which means little redundant P left in the water column after winds.

Key words: hydrodynamic process; resuspension; sedimentation; phosphorus flux; Taihu Lake

Introduction

The hydrodynamic process, an important physical phenomenon is a key factor that affects transportation and transformation of nutrients, especially at the level of sediment-water interface. Much attention has been paid to dynamic process of sediment-water interface (Suk *et al*., 1999; Gleizon *et al*., 2003; Kersten *et al*., 2005; Michaud *et al*., 2003). There are several important principles related to sediment resuspension. Firstly, it will affect boundary layer structure and re-distribution of surface sediments and the enrichment of dissolved and particulate nutrients in water column (Cozar *et al*., 2005). Secondly, it will increase nutrient concentrations in water body and delay the revival of the aquatic ecosystem, especially in shallow lakes (Voulgaris and Collins, 2000; Horppila and Nurminen, 2001). Finally, the suspended substance (SS) may have significant influence on water transparency, light attenuation, and bio-species and their abundance associated with primary production (Bubinas and Repeeka, 2003; Hawley, 2000), which will also affect the behavior of nutrients in the water body.

Many methods have been proposed on hydrodynamic processes research. For instance, *in situ* observation of sediment resuspension and nutrient changes were achieved under different wind conditions (James *et al*., 2004; Horppila and Nurminen, 2005; Hu *et al*., 2006); Flow chamber experiments (Laima *et al*., 1998), annular tan (Li *et al*., 2004), and flume experiment (Zhu *et al*., 2005a) were also used to simulate sediment resuspension. But there are still some disadvantages in these methods. The *in situ* observation is hard to duplicate under same environment condition; and it is difficult to retain the sediments intact in a classical simulative experiment, which includes the flow chamber experiment, annular tan, and flume experiment, with little chance to fit the condition *in situ*. New techniques should be brought forward to further understand the hydrodynamic process on sediment-water interface.

However, most existing researches focus only on sediment resuspension process, and researches on sedimentation effects in relation to wind processes are still poorly

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understood. In order to reveal the entire effects of nutrient behavior under hydrodynamic condition, the resuspension and sedimentation processes should be simulated together. Based on the relationship between simulated hydrodynamic condition and wind speed, an innovative apparatus is used to reveal the rules of P concentration changes in water column and P flux across water-sediment interface in the winds processes, with water depth, dissolved oxygen concentration, and temperature maintained as close to the *in situ* conditions.

1 Methods

1.1 Core sediment sampling

Sediment cores were collected from Meiliang Bay (31.50864°N; 120.17528°E), a semi-enclosed large bay in Taihu Lake, China, in April 2006 with a water depth of 2.3 m, which is severely polluted by industrial wastewater and ship transportation. The sediment is sandy, silty soil with a mean grain diameter of 17.1 μm, TP of 0.71 g/kg, and TN of 1.28 g/kg. Dissolved oxygen in overlying water was 8.8 mg/L, temperature was 15.4°C, ammonia concentration was 1.81 mg/L, and SRP was 0.005 μg/L.

Sediment samples were taken with Plexiglass tubes (11 cm I.D., 50 cm in length) by cylindrical sampler (Rigo Co. Φ 11 cm × 50 cm). Several plastic barrels (25 L) were used to collect water samples in situ, which were taken as overlaying water in the experiment. All the samples were transferred to the laboratory within a few hours and kept in room temperature of 4°C.

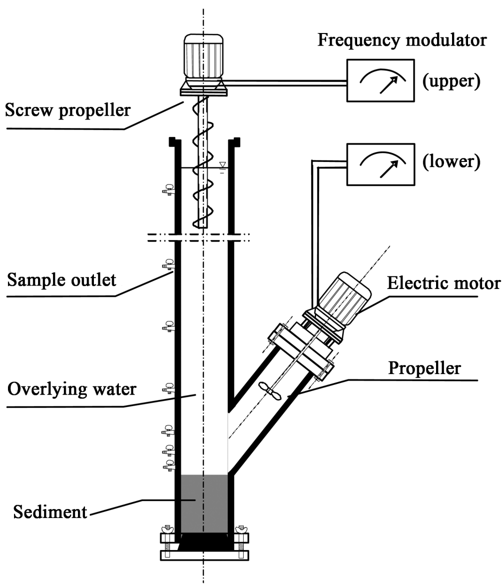

Fig. 1 Sketch of Y-shape apparatus to resuspend sediments.

1.2 Resuspension apparatus

Y-shape apparatus (Chinese National Invention Patent (CN 200410014329. X, Open No: CN 1563928). A method and apparatus indoor simulating benthic resuspension status. Inventor: Fan Chengxin) was used to simulate sediment resuspension process and to study P fluxes from intact sediments under different stirring velocities (Fig.1). Sediment cores were carefully transplanted into lower Plexiglass tube of Y-shape apparatus, and water collected at the station was injected over sediment surface slowly without disturbance. The length of sediment core and overlaying water column were 20 cm and 160 cm, respectively. One screw propeller was placed at 120 cm above the sediment surface to mix the water vertically. Another screw propeller was placed 15 cm above the sediment surface in Y tube with an angle of 55° from horizon to offer sediment resuspension force. The rotation of two propellers were controlled by different motors with frequency modulation (0–20 Hz) and actuating frequency of 3.5 Hz. Water samples were simultaneously taken from water column at 5, 25, 55, 105, 155 cm from the outlets above the sediment surface at a given time, then filtered by 0.45 μm cellulose acetate filters, and stored at 4°C until analysis. P concentrations of water samples were measured spectrophotometrically with molybdenum blue by flow injection analyzer (SKALAR-SA3000/5000, Netherlands).

1.3 Resuspension experiment

Wind-wave forces were simulated by rotation of propellers. Sediments were resuspended when the bottom shear produced by propeller exceeded the critical shear stress, and the upper propeller impelled vertical blend of water in column. Therefore, upper and oblique propellers controlled vertical distribution of suspended substance (SS) and flux of suspended substance across sediment-water interface (F_{SS}), respectively. Previous studies showed that vertical distribution of SS in water column was close to its *in situ* situation measured by Hu *et al*. (2006), when the upper propeller run at 10.0 Hz. According to statistics record on wind regime of Taihu Lake (Nov. 2004–Oct. 2005), accumulative frequency of wind speed was divided into four segments and four mean values were calculated for each segment (Table 1). Integrating with total suspended substance in water column per unit area (T_{SS}) by invariable rotation frequency of Y-shape apparatus and spot T_{SS}, the following relation between wind speed (v, m/s) and rotation frequency (n, Hz) was acquired as $v = 2.667n - 13.8$. Four values of 5.8, 6.4, 7.1, and 8.4 Hz, closely represented background, light, moderate, and strong winds, respectively.

The mean duration of moderate and strong winds in Taihu Lake was 120 and 155 min, respectively. In this

Table 1 Weighted mean of wind speed in Taihu Lake (Nov. 2004–Oct. 2005)

Accumulative frequency	< 31.67%	31.67%–63.33%	63.33%–95.00%	> 95.00%
Wind regime	Background wind	Light wind	Moderate wind	Strong wind
Wind speed (m/s)	1.7	3.2	5.1	8.7

study, 180 min was selected as duration of light, moderate, and strong wind. Wind-wave induced resuspension was simulated by gradual increases of rotation frequency, and the wind dynamic processes are shown in Fig.4.

1.4 Calculation method

The concentration of suspended substance (C_{SS}) was measured by a suspended substance detector (740 Monitor, PARTECH Ltd.) which was placed into water column at a designated water depth and corrected by standard measure, and by classical water loss methods dried at 105°C after filtration by glass fiber filters. Compared with the wind-wave forces, the advection transportation of suspended particulate made by lake current in Taihu Lake can be neglected. F_{SS} (g/m^2) at a certain time can be calculated by formula as below:

$$F_{SSt} = T_{SSt} - T_{SS0} \tag{1}$$

where, F_{SSt} is F_{SS} at the time of t (g/m^2); T_{SSt} is T_{SS} at the time of t (g/m^2); T_{SS0} is T_{SS} at the initial period of wind process (g/m^2). In which

$$T_{SS} = \sum_{i=1}^{n} C_{SSi} \times \Delta h_i \tag{2}$$

where, T_{SS} is the total suspended substance in water column per unit area (g/m^2); C_{SSi} is the concentration of suspended substance in layered (i) water (g/m^3); and Δh_i is the thickness of water column layer i (m).

Flux of P (F_P) across sediment-water interface (mg/m^2) within certain duration can be calculated by formula as below:

$$F_{Pt} = T_{Pt} - T_{P0} \tag{3}$$

where, F_{Pt} is F_P at the time of t (mg/m^2); T_{Pt} is T_P at the time of t in wind process (mg/m^2); T_{P0} is initial T_P at the initial period of wind process (mg/m^2). In which

$$T_p = \sum_{i=1}^{n} C_{Pi} \times \Delta h_i \tag{4}$$

where, T_P is the total dissolved P in water column per unit area (mg/m^2); C_{Pi} is P concentration in layered (i) water (mg/m^3); and Δh_i is the thickness of the water layer i (m).

2 Results

2.1 Effect of wind process on vertical distribution of SS

Heterogeneous vertical distribution of SS in the water column was observed. The C_{SS} in the middle and upper water column was closer to those in the surface water, while C_{SS} in the bottom layer was much higher (Fig.2). Moreover, the lines of vertical distribution of SS in Fig.2 were parallel to each other for different wind processes. Similar case was observed *in situ* in Taihu Lake (Hu *et al*., 2006). The C_{SS} under strong wind condition were much higher than those under moderate and light wind conditions, which demonstrated that the wind-wave force was a key factor that impacted the sediment resuspension in large shallow lakes.

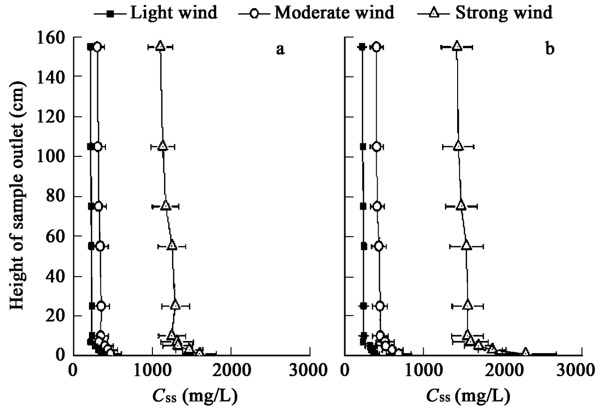

Fig. 2 Vertical distribution of SS at the 2nd and 4th hour in wind process. C_{SS}: concentration of suspended sediment; (a) at 2nd hour; (b) at 4th hour.

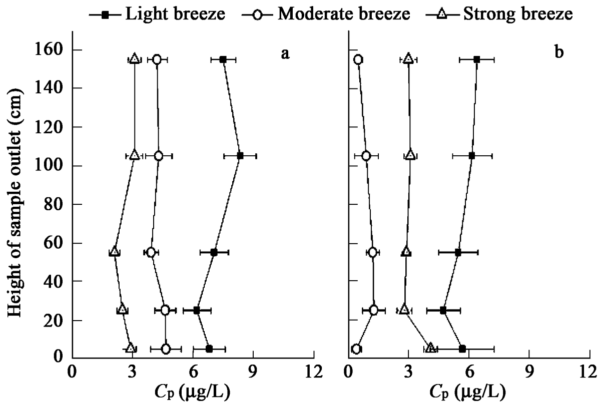

Fig. 3 Vertical distribution of P at 2nd and 4th hour in wind process. C_P: concentration of phosphorus; (a) at 2nd hour; (b) at 4th hour.

2.2 Effect of wind process on vertical distribution of P content

P concentration in the middle and upper layer of water column was close to those in the surface water layer, while P concentration in the bottom layer fluctuated in wide range, especially at the 4th hour of the three winds processes (Fig.3). Compared to the case of the 2nd hour, the lines for concentration of P at 4th hour in moderate wind declined markedly. Little difference was observed between light and strong wind processes (Fig.3). It can be concluded that P concentration was impacted by sorption and desorption of suspended matter (Zhou *et al*., 2005a; Huettel and Gust, 1992), but homogeneous P concentration at different water depth illustrated that hydrodynamics was the key factor controlling P distribution after resuspension.

2.3 Effect of wind process on flux of suspended substance F_{SS}

Remarkable increase of F_{SS} during the wind process was observed for all wind processes, and the increment of F_{SS} depended on wind velocity. The F_{SS} between the 3rd hour and 4th hour was stable (Fig.4), which suggested that the F_{SS} reached equilibrium. But equilibration time was extended on stronger hydrodynamic forces. Generally, the maximal flux of SS appeared at the 4th hour. There was a positive correlation between hydrodynamic forces

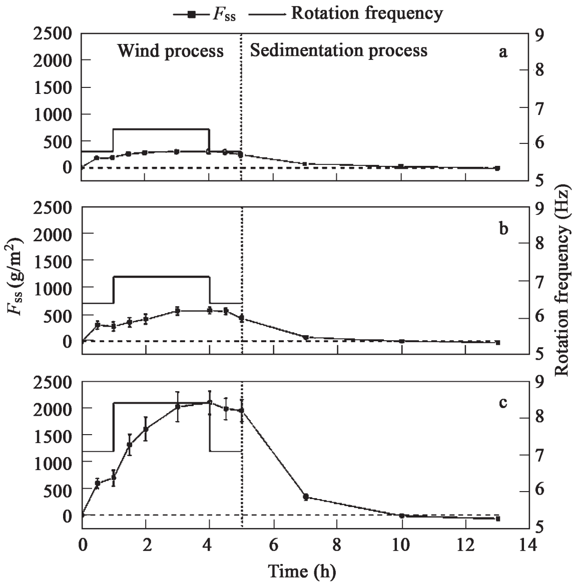

Fig. 4 Effect of light, moderate, and strong wind processes on F_{SS}. F_{SS}: flux of SS across sediment-water interface; (a) light wind; (b) moderate wind; (c) strong wind; 0 Hz in sedimentation process.

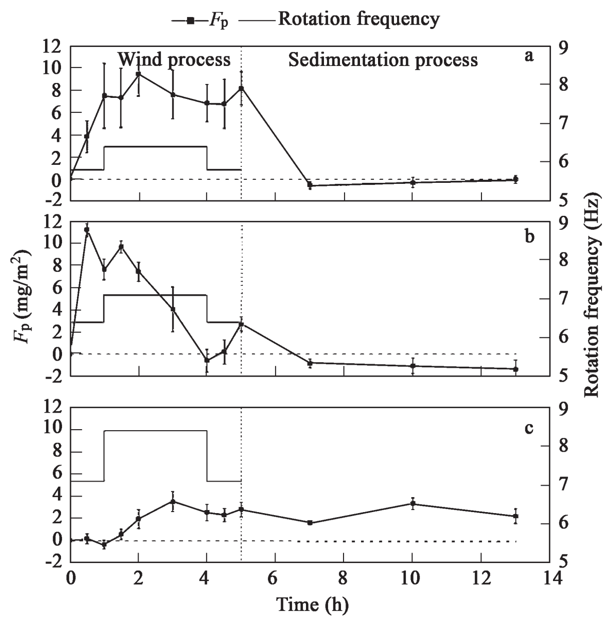

Fig. 5 Effect of light, moderate, and strong wind processes on F_P. F_P: flux of phosphorus across sediment-water interface; (a) light wind; (b) moderate wind; (c) strong wind; 0 Hz in sedimentation process.

and fluxes of suspended substance across sediment-water interface.

It can be observed that the T_{SS} was ranged from 86.5±14.2 to 2404.9±228.9 g/m^2 during wind process (Table 2), and the T_{SS} was ranged from 86.5±14.2 to 384.9±46.0 g/m^2 during the light wind, with an average of 299.6 g/m^2 and from 311.1±23.9 to 2404.9±228.9 g/m^2 during the strong wind, with an average of 1498.8 g/m^2, respectively.

It can be concluded that the surface sediments resuspend rapidly as soon as the wind force increased, and settled down to the lake bottom as the winds and waves calm down. The quantity of the resuspended sediment from surface sediments can be calculated by subtracting the value of T_{SS} after the wind process from before the wind process, which ranged from 299.9 to 2093.8 g/m^2 under different wind conditions, with an average of 989.0 g/m^2 (Table 2).

2.4 Effect of wind process on flux of phosphorus F_P

It could be observed that there is a more intensive increase of F_P in water column during light and moderate wind processes than strong wind process (Fig.5). There was a continuous increase of F_P under light wind condition, with maximal flux of 7.5±2.9 mg/m^2, before peak concentration was reached 90 min later, and then decreased gradually. Rapid increase of F_P in the first 30 min was also found during moderate wind process, with peak flux of 11.2±1.9 mg/m^2, followed by a decline in the sedimentation processes. Compared to light and moderate winds, strong wind induced less flux, with a peak flux of 3.5±0.9 mg/m^2.

3 Discussion

3.1 Sediment resuspension

Sediment resuspension occurred continuously when the bottom shear exceeded the critical value, which was sufficient to disrupt the cohesion of the bottom materials (Evans, 1994; Bloesch, 1995). Stronger wind produced more powerful shear than moderate and light winds, and caused more increment of SS and bigger granularity of suspended particles (Fan *et al.*, 2004; Luo *et al.*, 2004). After resuspension, the particulates were mixed continuously in the water body of the whole lake, with constant concentrations in the mixed region and even deposition on the entire bottom layer. The more intensive wind made less

Table 2 Fluxes of SS and P across sediment-water interface in wind process

Matter	Wind regime	T_{SS0}	T_{SSf}	F_{SSf}	Max F_{SSt}
SS (g/m^2)	Light	86.5±14.2	384.9±46.0	298.4±44.3	299.9±41.1
	Moderate	116.1±18.3	689.5±72.5	573.4±61.7	573.4±61.7
	Strong	311.1±23.9	2404.9±228.9	2093.8±215.7	2093.8±215.7
Matter	Wind regime	T_{P0}	T_{Pf}	F_{Pf}	Max F_{Pt}
P (mg/m^2)	Light	2.4±0.3	9.2±1.5	6.8±1.6	9.4±1.9
	Moderate	1.6±0.5	1.5±0.2	–0.6±1.0	11.2±0.6
	Strong	2.4±0.4	4.9±0.9	2.5±0.7	3.5±0.9

T_{SSf} and F_{SSf} denote T_{SS} and F_{SS} at the 4th hour in wind process (g/m^2), respectively; T_{Pf} and F_{Pf} denote T_P and F_P at the 4th hour in wind process (mg/m^2), respectively.

difference on SS concentration in water column. However, power of hydrodynamics faded with depth of water (Hu *et al*., 2006; Luo *et al*., 2004; Qin *et al*., 2004), and little exchange occurred between bottom and upper levels of water. Therefore, C_{SS} in the hypolimnetic water was much higher than in the middle and surface water.

3.2 Release mechanism of P

Hypolimnetic P concentrations were probably affected by mineral solubility, sorption and desorption processes of sediment and suspended particulate (Mahler and Lynch, 1999; Zhou *et al*., 2005b; Huang *et al*., 2004), and microbial mineralization on oxic condition, and by redox potential during anoxic conditions (Haggard *et al*., 2005). Hydrodynamic disturbance caused by strong wind plays an important role in the internal release of P (Zhu *et al*., 2005b). Surface sediment was suspended into overlaying water in wind course, and abundant phosphorus was released from the suspended sediment and its pore water, and thus caused increment of internal phosphorus budget.

3.2.1 Light wind and moderate wind

Release from pore water and surface sediment, and desorption of suspended sediment were main factors contributing to the increase of P concentration in water column. The pore water release could increase 8.5% of P concentration in water (Sun *et al*., 2006), so pore water is not the major source of release. There was an oxic microlayer above sediment controlling release rates of P (Penn *et al*., 2000). A possible explanation for rapid increase of P concentration at the beginning phase (0–2 h) of light and moderate wind was due to the broken oxic microlayer.

Both suspended sediment and dissolved oxygen (DO) were enhanced in wind process. Laima *et al*. (1998) found a smooth increase of O_2 concentration in chamber water up to the point of resuspension. Zhu *et al*. (2005a) reported that concentration of DO increase 2 mg/L after 2 h wave disturbance. P removal under oxic conditions is usually attributed to binding with ferric iron (Fe^{3+}), forming insoluble complexes (Miao *et al*., 2006). Soluble manganous (Mn^{2+}) will oxidize to the more insoluble manganic (Mn^{3+}) forms when exposed to oxygenated conditions. Consequently, strong adsorption of dissolved P to solid iron or Mn oxyhydroxides led to the decrease of P concentration in light wind (2–4 h). Similar trend appeared for moderate wind, but P concentration reached peak flux and decreased early, because intensive hydrodynamics force accelerated its deoxygenating process.

3.2.2 Strong wind

Maximal F_{SS} during strong wind process was about 5 times higher than moderate wind process (Table 2), and more P was released into water. At the same time, higher concentration of SS created higher sorption ability. Reoxygenation process of strong wind was at a fast pace, thus P adsorption on iron or Mn oxyhydroxides particulates was accelerated.Therefore, adsorption of suspended sediment was the master effect impacting the P concentration probably in strong wind, and little increment of F_P was observed in suspension course (Fig.5).

3.3 Reliability comparison

In large shallow lakes, primarily the lake currents and wind-waves induce the dynamic force of sediment suspension. While under strong winds, only wind-wave is the dominant dynamic force of sediment resuspension (Qin *et al*., 2004). When the propeller rotated with 8.4 Hz, the shear stress at the sediment-water interface was equivalent to under wind speed of 8.7 m/s. T_{SS} of 1700 g/m^2 in Meiliang Bay was observed *in situ* when wind speed ranged from 5.7 m/s to 8.0 m/s (Hu *et al*., 2006),which indicated that the T_{SS} of 689.5 g/m^2 and 2404.9 g/m^2 during moderate wind (5.1 m/s) and strong wind (8.7 m/s) respectively in this experiment was reasonable, compared to the *in situ* data.

Sediment resuspension and P release processes under controlled hydrodynamic condition are still poorly understood. Zhu *et al*. (2005a) used flume experiment to simulate sediment resuspension, and inferred that P concentration was weakly influenced by wind disturbance. The maximal P concentration (20 μg/L) was only 25% higher than that of static condition (16 μg/L), and P decreased slightly after wave height was maintained for 50 min, which was in accordance to the result in this paper.

4 Conclusions

Hydrodynamics contributed to the sediment P flux and the control of P vertical distribution in water column. Flux of P and suspended substance in waters exhibited different behaviors under hydrodynamic conditions. Flux of suspended substance increased gradually with augmented wind speed, but little positive correlation between the wind speed and the P concentration in water was observed. Light and moderate winds caused more fluxes of P than strong wind condition. No obvious difference was detected on fluxes of P after sedimentation process, compared to the initial value.

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