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Waves-waves collide induced by different wind directions caused high exchanged in the water level at the open area Shallow Lake, China

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Wind from different directions induce waves-waves to collid at the central zone of Taihu Lake. It causes exchange in water bodies and release of internal nutrients which increases algal bloom. This study aims to analyz the impact of the interactions between waves-waves collision from different directions and different sources such as traveling ships and explored factors, causing sediment resuspension. The results were achieved to collect high-frequency data for measuring wind speeds, currents, waves, and suspended solid concentration (SSCs). The results indicate that the water exchange and the turbidity highly escalated when wind speeds reached 5 m/s. The surface flow velocities are very high, about 80 cm/s or more according to the raw data after calibrating the instruments. This finding is very important in the processes of sediments dynamic. Maybe in these wide area, high waves –waves collide leading to constructive interference from different sources generate waves. Sediment processes were categorized into three period A, B, and C corresponding to three shear-stress thresholds. Period A: Sediment bottom particals was stable with $τw < 0.01$ N/m^2. It did not change through this period and the averaged suspended solid concentration (SSCs) was approximately 50 mg/L. Period B: Sediment resuspension was small with a range between $0.01 ≤ τw < 0.1$ N/m^2. It jumped up slowly and the averaged was in the range of 50 to 70 mg/L. Period C: Sediment resuspension was moderate with shear stress $0.1 ≤ τw < 0.8$ N/m^2. The form of the sediment bed was changed at the second period, this shows that increase of the shear stress activated the sediment in this period. The bottom SSCs increased quickly from 60 to 350 mg/L in average. Outcomes of this paper presents the main factor causing sediment resuspension, which may assist further studies and estimate the real reasons for internal nutrient release from different waves induced waves-waves to collide in Lake Taihu.

Key words: Eutrophication, central zone, shear stress, different direction wind, waves-waves collide, constrictive interference.

INTRODUCTION

Excess nutrient loading in shallow lakes, reservoirs as well as freshwater bodies have become a critical

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environmental issue which is resulting in increased algal blooms and affects the water quality negatively (Paerl et al., 2001; Paerl and Huisman, 2008; Qin et al., 2010). The factors effect on water eutrophication include nutrient enrichment, hydrodynamics, and environmental factors. The prevalence of water eutrophication is actually a difficult function to evaluate amongst the affecting factors (Martin et al., 2008; Yang, 2008). Excessive nutrient loading into surface water system is considered to be one of its main factors (Fan et al., 2004; Tong et al., 2003; Xiao-e and Yang, 2008; You et al., 2007). Eutrophication phenomena are excessive nutrient loading especially in shallow lakes. It is considered as a result of internal nutrients release from sediments (Qin, 2009; Qin et al., 2006; Zamparas and Zacharias, 2014).

Sediment resuspension by waves-waves collides that work on the water-sediment results in internal nutrient release. The main dynamic steps considered to be the key of transporting solid particles and nutrients. Wind-induced waves are the forces which sediment re-suspension in shallow water bodies (Li et al., 2017; Qin et al., 2006; Stone, 2011; Wang et al., 2014). The changes in habitat of aquatic organisms may be attributed to a few storm events, waves-waves collide from different sources influence on transmission, nutrient and sediment transport (Barros, 2005; Davis et al., 1982; Mazumder and Ojha, 2007; Skilleter, 1996).

In addition, other research used numerical experiments to analyze the impact of hydrodynamic force on the sediment resuspension in lakes (Qin et al., 2004; You et al., 2007). Other researchers have worked on the impacts of currents and waves on sediment resuspension processes (Li et al., 2017; Pu et al., 2000). Observations on sediment dynamics resuspension were carried out in open-channels, rivers resuspension, and the results showed that it is primarily caused by current-induced shear stress (Jin and Ji, 2004; Li and Sheng, 2011). However, it is clear that the sediment resuspension consider a result of wind-induced waves in shallow lakes, ponds, and nearshore of the lakes (Chung et al., 2009; Ji and Jin, 2014; Qin et al., 2004; Mian and Yanful, 2004). The shear stress is responsible for sediment resuspension in shallow lakes (Hamilton et al., 1996; Sheng and Lick, 1979).

The current study about sediment resuspension in shallow lakes, for example Lake Taihu in China assistance to sediment resuspension is from current and waves, mainly associating to wind effects, were not measured (Qin et al., 2004; Qin et al., 2006). In the present study, real-time measurements of high-frequency sediment concentration and hydrodynamics data from Lake Taihu were achieved under complex actions of wind-induced waves and currents. The aims of this study were to: (1) explore the changes of the current speed, wave parameters and nutrients loads under different wind speeds and directions in Taihu Lake; (2) establish the relationships between winds, current, wave, and suspended solids concentration (SSC); and (3) estimate the effects of sediment dynamics processes to critical shear stress. The outcomes of this paper will contribute to realizing the factors and mechanisms of sediment resuspension such as waves-waves collide from different direction in the open area of Lake Taihu.

MATERIALS AND METHODS

Study site

Lake Taihu is located in the lower Yangtze River Delta in China between 30°56′-31°33′ N and 119°53′-120°36′ E in the south part of Jiangsu province. The depth ranges from 1 to 2.5 m with a mean of 1.9 m and the total water surface area is about 2,338 km^2. It is an essential source of drinking water for local cities around the lake, and has experienced severe eutrophication and harmful algal blooms. Sediment resuspension has caused nutrient released, which is one of the most important factors of algal growth in the lake. It has been continually monitored until now. Field observations were conducted in Pingtaishan, the central part of the Lake with depth 2.7 m (Figure1).

Instruments pattern

Synchronous, high-frequency measurements of wind, currents, waves, and SSC were carried out in this study. The observation tools included a RBR duo T.D wave tide gauge, PH-II Handheld weather stations, PHWD wind direction sensor, a bottom-mounted holder equipped with an Acoustic Doppler current profiler (ADP Argonaut-XR), Acoustic Doppler Velocimeter (ADV Ocean, Son Tek Inc.), and Optical Backscatter Sensor (OBS) turbidity meter. The wind parameters were measured using PH-II Handheld weather stations and a PHWD wind direction sensor fixed on a bracket 5 m above the surface of the lake (Figure 2). The records gathering interval was 5 min and it used automatic wind speed with direction recorder (10 meter above the water surface, 10 min monitoring interval). Also, the vertical velocity profile was measured using an ADP Argonaut-XR (operating frequency of 1500 kHz) fixed above the sediment-water interface (Figure 2). The ADP blind height was 50 cm and the instrument height was 30 cm, so the first layer of the monitoring cell was 80 cm above the lake bottom. The water bodies was classified into four diffision. The ADP measured the variance in every 10 min, average current profile at a resolution of 0.1 cm/s, signal-to-noise ratio (SNR) in the water profile, correlation coefficient, and echo intensity (EI).

Velocity was measured at two fixed points using two ADVs. The First was 5 cm overhead the lakebed. The second was 50 cm under the water surface. Surface ADV had an operating frequency of 10 MHz a monitoring frequency of 10 Hz (Figure 2). Temperature wave tide gauges RBR duo TD wave was used for measuring 3-D velocities. The instrument was fixed 50 cm below the water surface (Figure 2). It measured significant wave height and wave period. OBS-3A instruments were used for measuring Turbidity.

Analysis methods

Laboratory analysis of SSC

The turbidity (NTU) measured by the OBS was calibrated with SSC samples, and measuring the concentration (in mg/L) according to Luo, (2004) method.

Wave data gathering

The Equation 1 showing wave parameters was used:

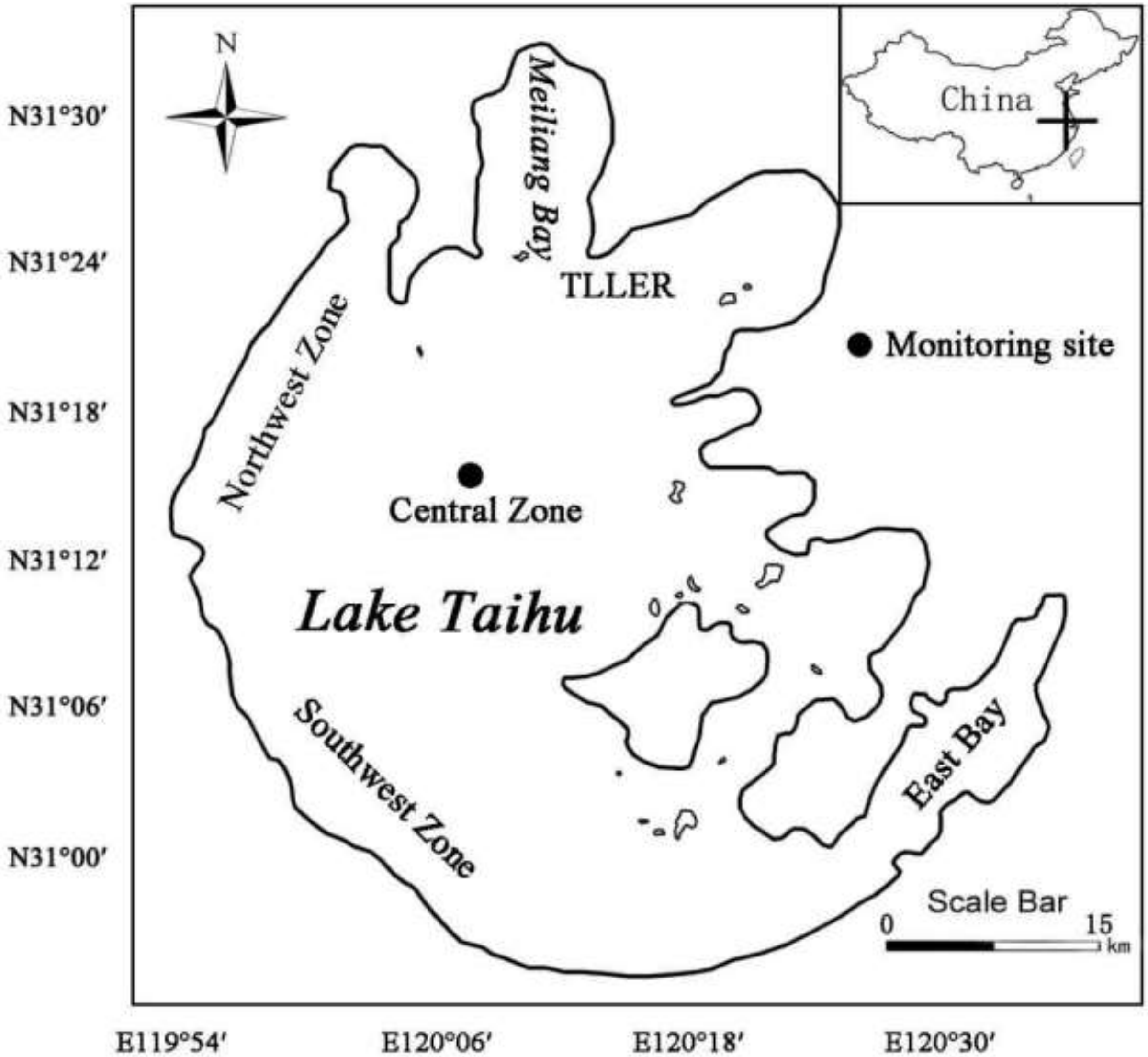

Figure 1. Location of the monitoring site at central zone in Taihu Lake.

$$L_s = (\frac{gT_s^2}{2\pi})\tanh(\frac{2\pi h}{L_s}) \quad (1)$$

L_s referes to the significant wavelength, T_s means the significant wave period, and *h* means the depth points we observed.

The maximum orbital velocity of wave near the bottom layer u_w (m/s) can be expressed as (Madsen, 1976; Whitehouse, 2000):

$$u_w = \frac{\pi H_s}{T_s \sinh\left(\frac{2\pi h}{L_s}\right)} \quad (2)$$

The letters refers to the following: H_s means the effective wave height (m), L_s the wavelength (m), T_s is wave period, and *h* is the depth pionts in meter.

Shear stress gathering

Shear stress produced by wave-current interactions consider the dynamic force for sediment resuspension in the Lake (Chung et al., 2009). To differentiate the different contributions of waves and currents, the shear stress generated by waves and currents at the water-sediment interface was calculated based on the linear wave theory and Karman-Prandtl logarithmic velocity distribution law.

Shear stress produced by waves can be calculated by the following equation (Li et al., 2017; Grant and Madsen, 1979) :

$$\tau_w = 0.5\rho f_w u_w^2 \quad (3)$$

The abbreviation τ_w is shear stress (N/m^2), ρ indicated to the density of water (kg/m^3), u_w the maximum wave orbital velocity near the bed (calculated by Equation 2), and f_w the wave friction coefficient related to the lake bottom roughness and Reynolds number. The f_w was calculated as follows (Jiang et al., 2000):

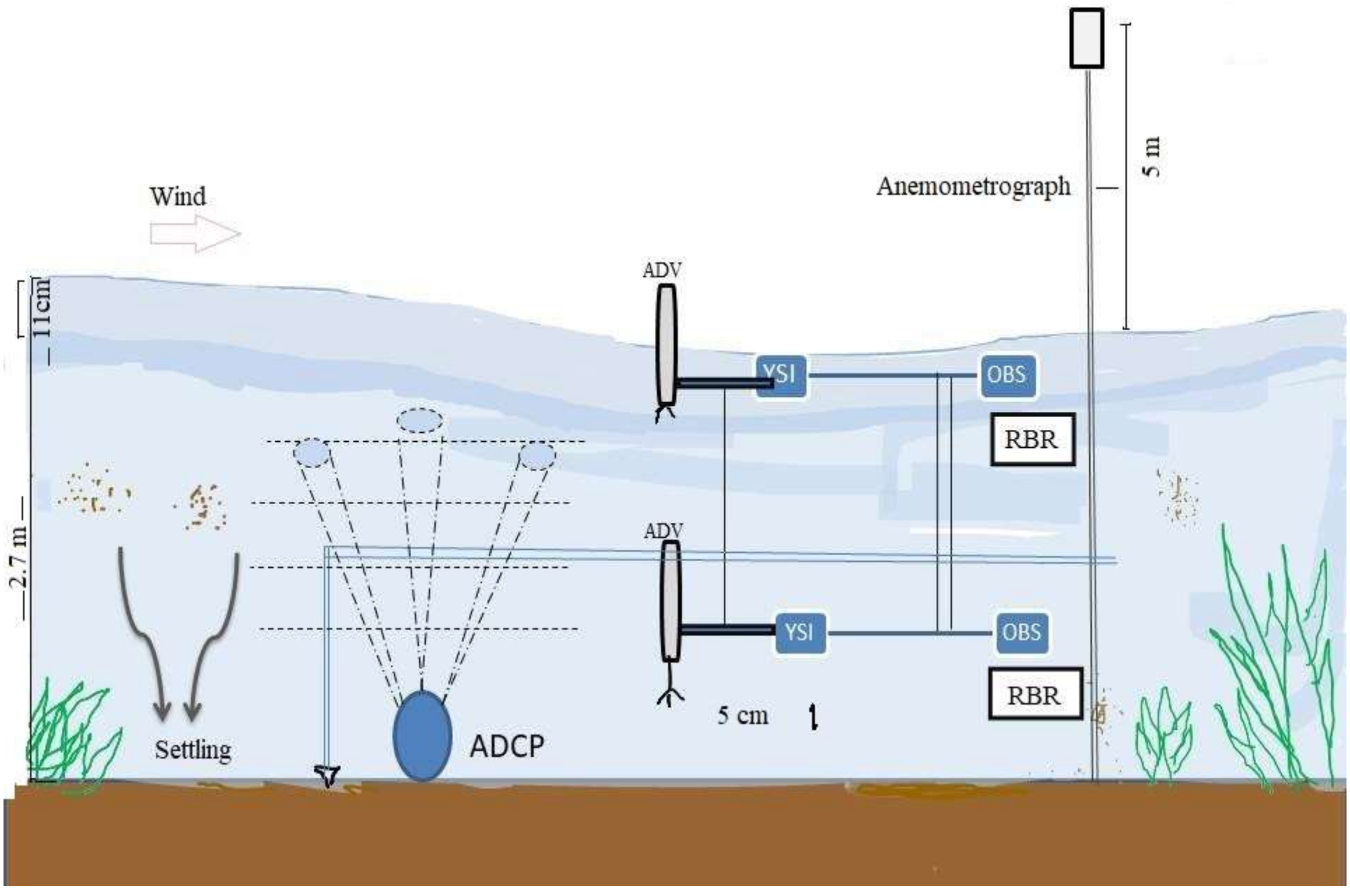

Figure 2. Diagram of the instruments layout for field observation in central zone.

$$f_w = \exp\left[5.2(A_\delta / K_s)^{-0.19} - 6.0\right]$$
$$f_{w,\max} = 0.3 \text{ if } A_\delta / K_s \leq 1.57 \quad (4)$$

The abbreviation Ks is the physical roughness of the lake bed and A_δ is the amplitude of wave-particle (m), which is determined by the linear wave theory. A_δ is calculated as follows:

$$A_\delta = \frac{H_s}{2\sinh\left(\frac{2\pi}{L_s}h\right)} \quad (5)$$

The shear stress caused by current at the water-sediment interface calculated with the following (Hawley, 2000; Sheng and Lick, 1979) methods:

$$\tau_c = \rho u_b^* u_b^* \quad (6)$$

$$u_b^* = \frac{ku_z}{\ln\frac{z}{z_0}} \quad (7)$$

The abbreviation τ_c indicates the shear stress affected by currents (N/m^2); u_b^* is friction velocity (m/s); k is the Kaman constant (0.4); u_z represents the velocity, which is the height, z, above the bottom; and z_0 is the bottom physical roughness (0.2 mm) (Li et al., 2017 ; Hawley, 2000; Nielsen et al., 2001).

RESULTS AND AND DISCUSSION

Physical characteristics of wind, wave and flow velocities

Wind field analysis

From 23rd to 31st July 2014 the wind variances in the observation period is recorded in Figure 1. The range of wind speed was from 0.7 m/s to 9.6 m/s with mean 3.7 m/s. The statistical analysis of the wind direction frequencies is shown in Figure 4. The frequencies moving clockwise from North to West and a little South were 14.67, 5.84, 5.71, 3.78, 4.66, 3.29, 4.07, 3.28, 4.66, 3.28, 4.07, 6.80, 4.86, 4.86, 2.77, 6.24, 3.03, 2.85, 2.465, 11.44 and 16.42%. During the observation period, the main high percent wind directions were North-north West, North, and Northwest and West-Northwest. The opposite wind directions are Southeast and Southwest. The directions of wind variables and the high percent are f the north. The result indicates the generated waves from different directions and the high waves from the north. This finding is very important to a view point on different waves from different wind directions, which should be in considered by researchers in Lake Taihu.

Physical appearance of waves

From 19:00-6:00 during July 23-31, 2014, the significant wave height ranged from 0.005 to 0.817 m with a mean value of 0.289 m; the significant wave period varied from 1.72 to 3.952 s with a mean value of 2.613 s, and the significant wavelength ranged from 0.000267 to 45.75 m with a mean value of 8.95 m. Varying tentative movements of significant wave height and period were in harmony with wind speeds (Figure 3). Wind speeds significantly influences generated wave in the Lake. Besides, the wind direction is also an important factor. Figure 4 demonstrates that there were different wind fetch lengths and wind energies which may be caused by variances in the height generated. The wave height generated by North West winds is larger than wave heights generated by South-Southeast winds with same wind speed (Li et al., 2017). Additionally, the wind fetch length is an index of wave height. The wind subdues in a forward movement to dash across the water body. (Green and Coco, 2014; Li et al., 2017; Luo, 2004). Different wave's height is very important as the waves meeting in the central zone, which is indicated for variable, collides in this area.

Physical appearance of flow velocities

At the Central Zone, the flow velocities ranged between 2.81 cm/s to more than 80 cm/s during the summer season. This is not consistent with the findings (Jalil et al., 2018; Li et al., 2017;) at Meiliang Bay, where the flow velocities ranged between 2.75 cm/s to 21.58 cm/s with a mean velocity of 13.23 cm/s. The surface flow velocities were found to be higher than the lower water layers flow velocities. Upper middle, middle, and lower current of the flow were in the same direction during wind speeds as shown in Figure 6. The current direction changed markedly in each layer, which maybe as a result of the location of the observation. In open areas, the waves maybe induced differently from diverse sources such as waves induced by different wind directions and traveling ships in the lake. The monsoon weather is characterized by southeasterly winds in the summer and northwesterly winds in winter (Qin, 2008). In the lake, surface water current flows from SE to NE and from NW to SE at the bottom of the lake, and the transition area is at the middle layer. At wind speed ranging from 5-6.5 m/s, all currents from the surface to the bottom followed the wind direction; consequently, the wind-induced water movement and energy dispersal downwards, right to the bottom of the lake. The flow velocities in the surface were unstable and greatly influenced by surface waves induced by wind. Wind directions in the central zone during the filed observation were North-northwest, North, and Northwest and West-northwest. The opposite wind directions are Southeast and Southwest. Conversely, the water flooded from Meiliang Bay to the Lake center with SE or SW winds. Maybe this flowed water exchange in this area was produced by the water level alteration. Waves caused high currents in the central zone of shallow lake Taihu.

Wind wave conditions

Important conditions of wind wave

Wind-induced resuspension of sediments was studied in the shallow. Sediment resuspension was mostly motivated by wind-induced waves. Wind-induced waves were conciderd the main energy for variations in turbidity (Li et al., 2017). Many wind speeds impact on wave factors (Figure 5). The significant and maximum wave heights were 0.34 m to 0.40 m and 0.52 to 0.45 m. In Taihu Lake, the significant wave height ranged from 0.3 m to 0.5 m when wind speed was between 1 m/s and 6 m/s. In South Taihu Lake where the wind speeds ranged between 1 m/s to 6.2 m/s, the significant and maximum wave heights were 0.2 to 0.28 m and 0.04 to 0.46 m (Wu et al., 2013; Zheng et al., 2015). In central zone, the wind speed ranged between 1.2 m/s to 8.1 m/s. The results indicated that when the wind speed increased, the wave height increased. Figure 5 shows that when the significant wave height was less than 0.3 m, the wave energy density was lesser, especially on 26, 27 of July. The mean wave periods show that the significant wave period varied around 2 s, and the mean wave periods were less than 2 s. The result is similar to that obtained by Qin et al. (2003), who described that the mean wave periods were around 1.1 to 2.6 s in the Lake. Figure 5 shows that the mean direction of wind-waves spread under different wind directions. The wave directions varied between 90 to 180 degrees, which established with the direction of the dominant wind Figure 4.

Effect of wind speed on turbidity

The turbidities in the water layers were accompanied by wind speed. Significant wind speeds conduct energy to hydrodynamic. It obstructed the constancy of suspended solids and encouraged sediment move in the water layers. The turbidity in the bottom is higher than in the surface layer. It is about 100 to 710.4 NTU and in the surface is about 50 to 254.4 NTU. The background turbidity is about

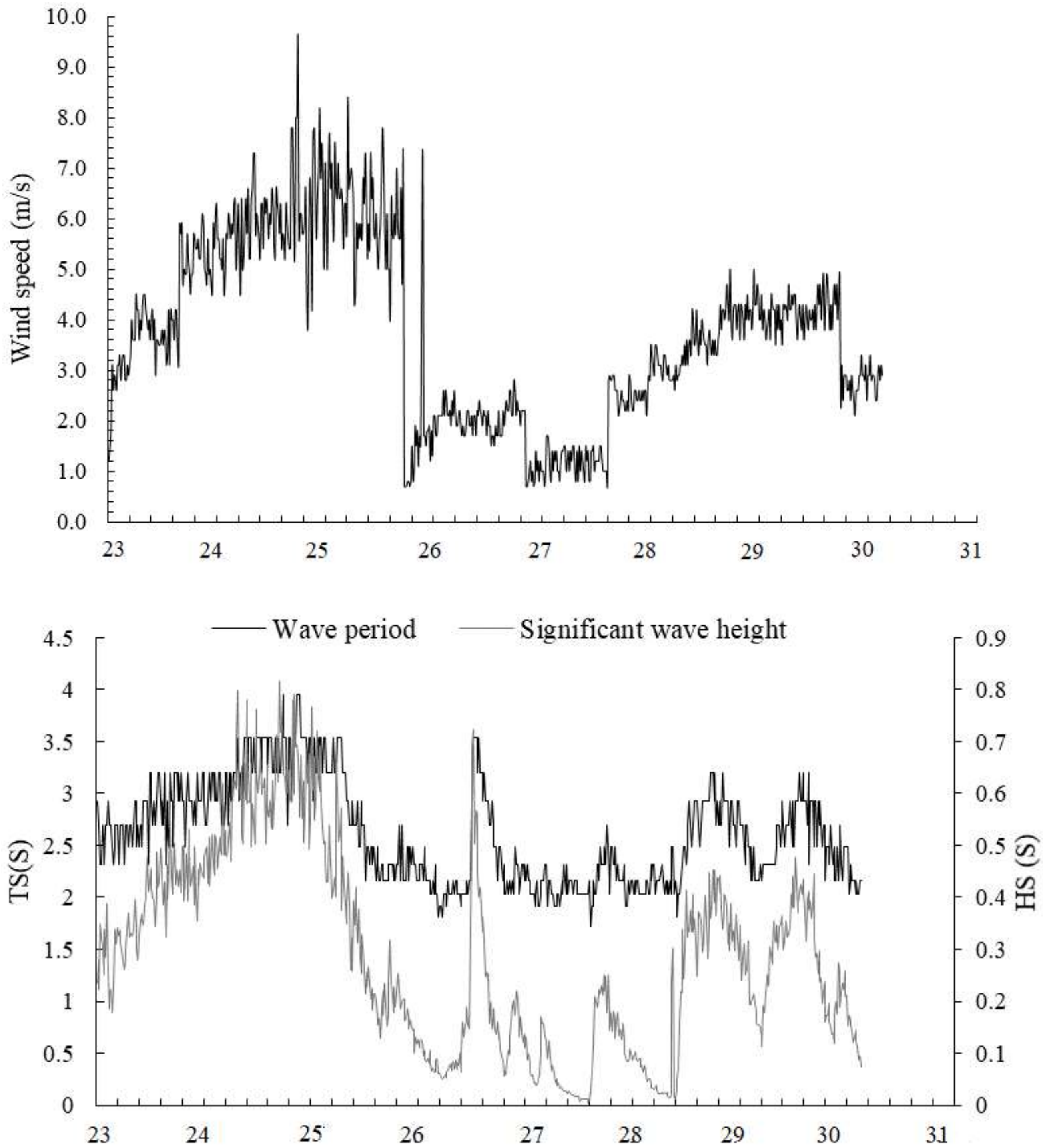

Figure 3. Varying trends of wind speed significant wave height and wave period 23-31/07/2014 19:00.

100 to 150 NTU and the surface is about 50 to 100 with a slow wind speed. Relating to Meiliang Bay during the small speed, the variance between turbidity in the surface and bottom layer was slight and the turbidity before was about 25 to 30 NTU. This finding shows that the suspended solids, which contain 50 of organics substances, can move to the surface easily of light thickness, also in the relaxed winds and hydrodynamics (Qin et al., 2000). When the wind speed increases, the bottom sediment continues to resuspend increasingly, resulting in variances in turbidity in water bodies. The realtionship between turbidity and wind speed in the

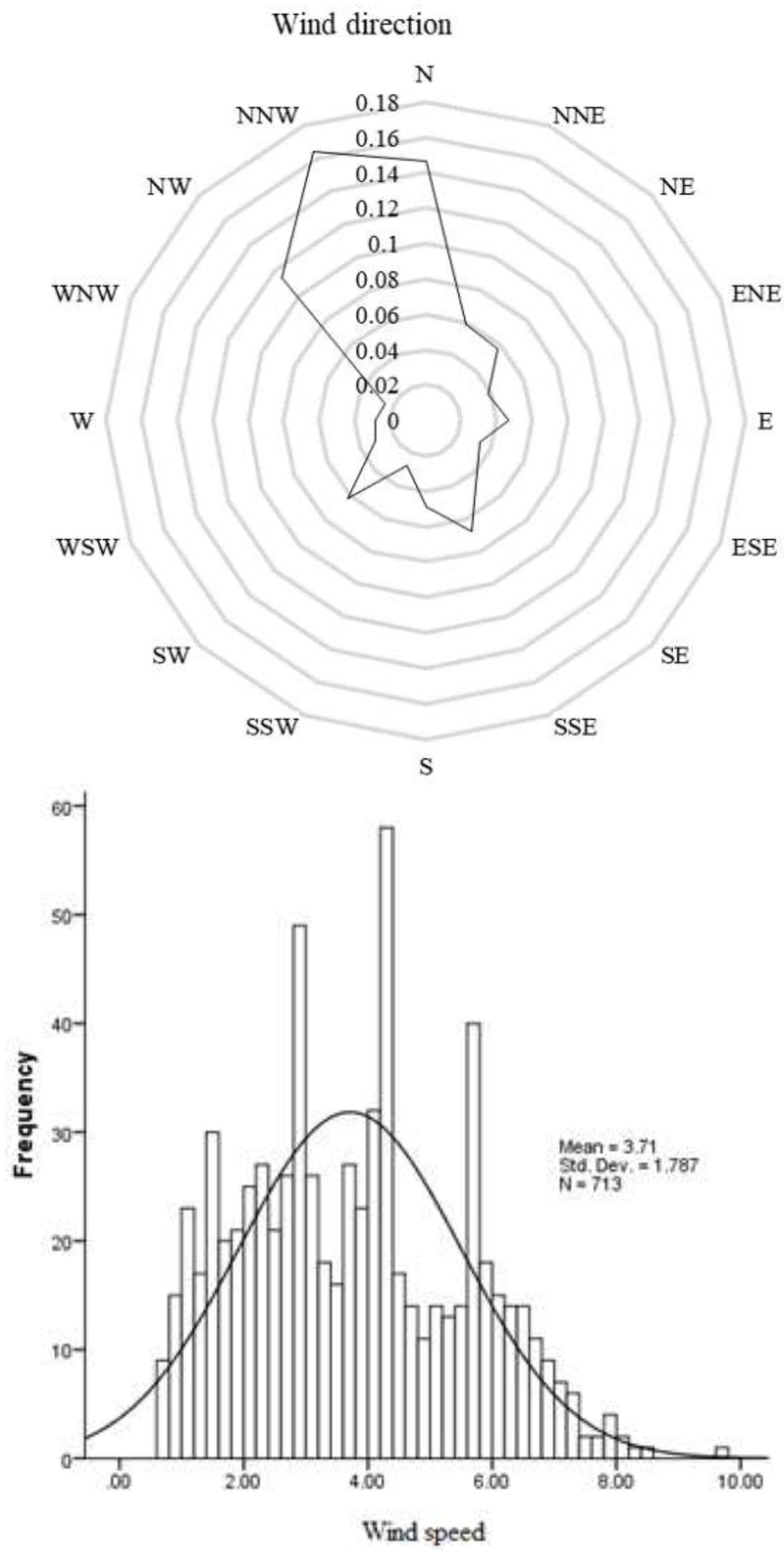

Figure 4. Wind direction and frequency of wind speed (m/s).

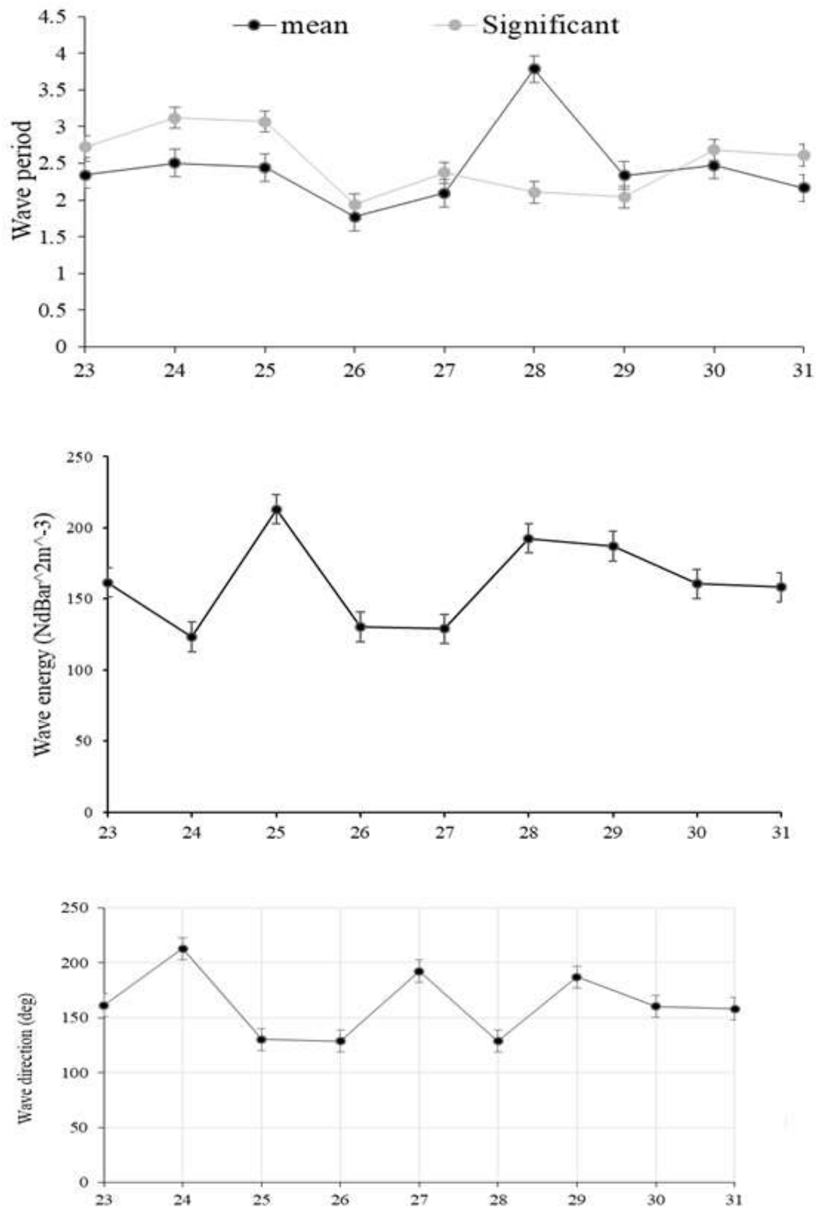

Figure 5. Mean wave energy density (a) wave period (b) and wave direction (c) under different wind disturbances.

surface and bottom layers is shown in Figure 7. The results displayed that a wind speed of 5 m/s was a point for sediment resuspension. Turbidities in the surface had moderate fluctuations, 50 to 100 NTU with wind speed 3.5 m/s; while in the bottom layer, they had large fluctuations, 100 to 200 NTU, with wind speed 4.5 m/s. Turbidity in the water column increased significantly and more unstable when wind speed ranged between 5~8 m/s. For instance, it increased in the bottom 7 to 8 times, and the surface 3 to 4 times (Figure 7). Also, these may occur because of different wind directions which generated different waves, leading to production of waves-waves collide. Hence this the main factor for sediments resuspension processes in the lake.

Impact of shear stress on the renewed suspension of sediment

The factors mechanisms influenced by sediment dynamics in open-area lakes are waves and currents (Bloesch, 1995; Li et al., 2017; Qin, 2008). They induced shear stress which influenced the SSC (Li et al., 2017; Qin, 2008). The sediment resuspension processes in

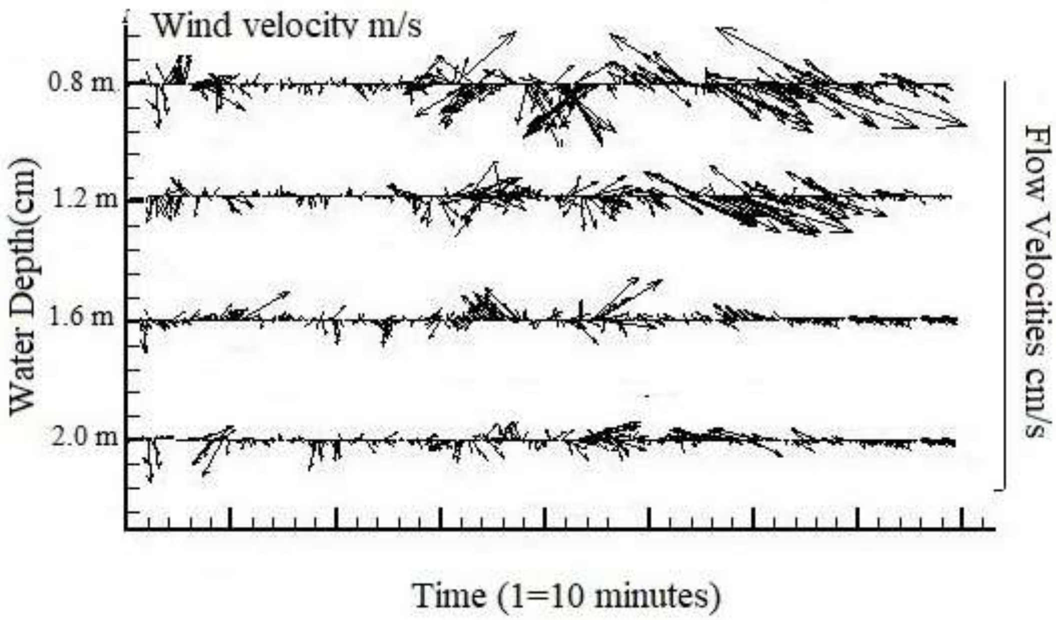

Figure 6. Comparison of wind velocities and Vertical flow velocity profiles during the present study field observations.

boundary was studied according to the bottom shear stress (Li et al., 2017; Qin, 2008).

During filed observation, the bottom shear stress generated by waves and currents displayed dissimilar tentative differences. The shear stress caused by waves was significant between 0.0008 - 1.908 N/m^2, with a mean value of 0.471 N/m^2. The bottom shear stress produced by currents was small, between 0.030 - 0.354 N/m^2, with a mean value of 0.030 N/m^2. These results given basically suggests that the total shear stress induced by waves was dominant. In most cases, in Lake Taihu, the shear stress created by waves is considered the main role in sediment resuspension. This result is close to Qin (2008) as well as Zhang and Xu (2003). The shear stress caused by wave are greater than those generated by currents. In some cases they are the same or greater than those generated by wave, when the winds or wind fetch is very small (Li et al., 2017; Qin, 2008). The bed shear stress produced by currents and waves is shown in Figure 8. There is a affirmative relationship between bed SSC and wave shear stress (Figure 8), while there is no relationship between SSC and current shear stress (Figure 8). This result indicate that waves are the main factor for sediment suspension in the Lake. The association between wave shear stress and SSC was analyzed to find out the critical shear stress value during sediment dynamic processes (Figure 8). The results revealed that the appropriate equation between Sedemint suspension concentration and shear stress generated by wave was $SSC_{OBS} = 38.161e^{1.56\tau_w}$, with R^2=0.6225. The trend appeared as three shear stress thresholds (shown as red dots in Figure 8) and sediment suspension progression divided into three phases: Phase A: Sediment remained was stable and $\tau_w < 0.01$ N/m^2. The bottom SSC was unaffected with average of about 50 mg/L; Phase B: Sediment was slightly activated and $0.01 \leq \tau_w < 0.1$ N/m^2. It increased with an average between 50 - 70 mg/L; Phase C: A sediment was moderately damaged and $0.1 \leq \tau_w < 0.8$ N/m^2. It shown that sediment and shear stress increased together and the average SSC was between 60 -350 mg/L.

The sediments in the bottom resuspended into the water column when both velocity and shear stressed exceeded the critical value. Results from this study indicate that measured influences of waves and currents depended on wind conditions; in the presence of wind speed conditions (< 4.5 m/s). in some cases, the bed shear stress was contributed equally; but this did not result in sediment resuspension process. In others cases, 95 was as a result of wave-induced shear stress. Some studies indicated that the piont of shear stress value which is important in sediment suspension ranged between 0.01 - 0.1 N/m^2 (Fang, 2004; James et al., 1997; Li et al., 2017; Lick, 1994; Lijklema et al., 1994; Sheng and Lick, 1979).

Conclusion

The present study eludicated that the factor of sediment resuspension processes during interactions between currents and waves is generated by wind. The results

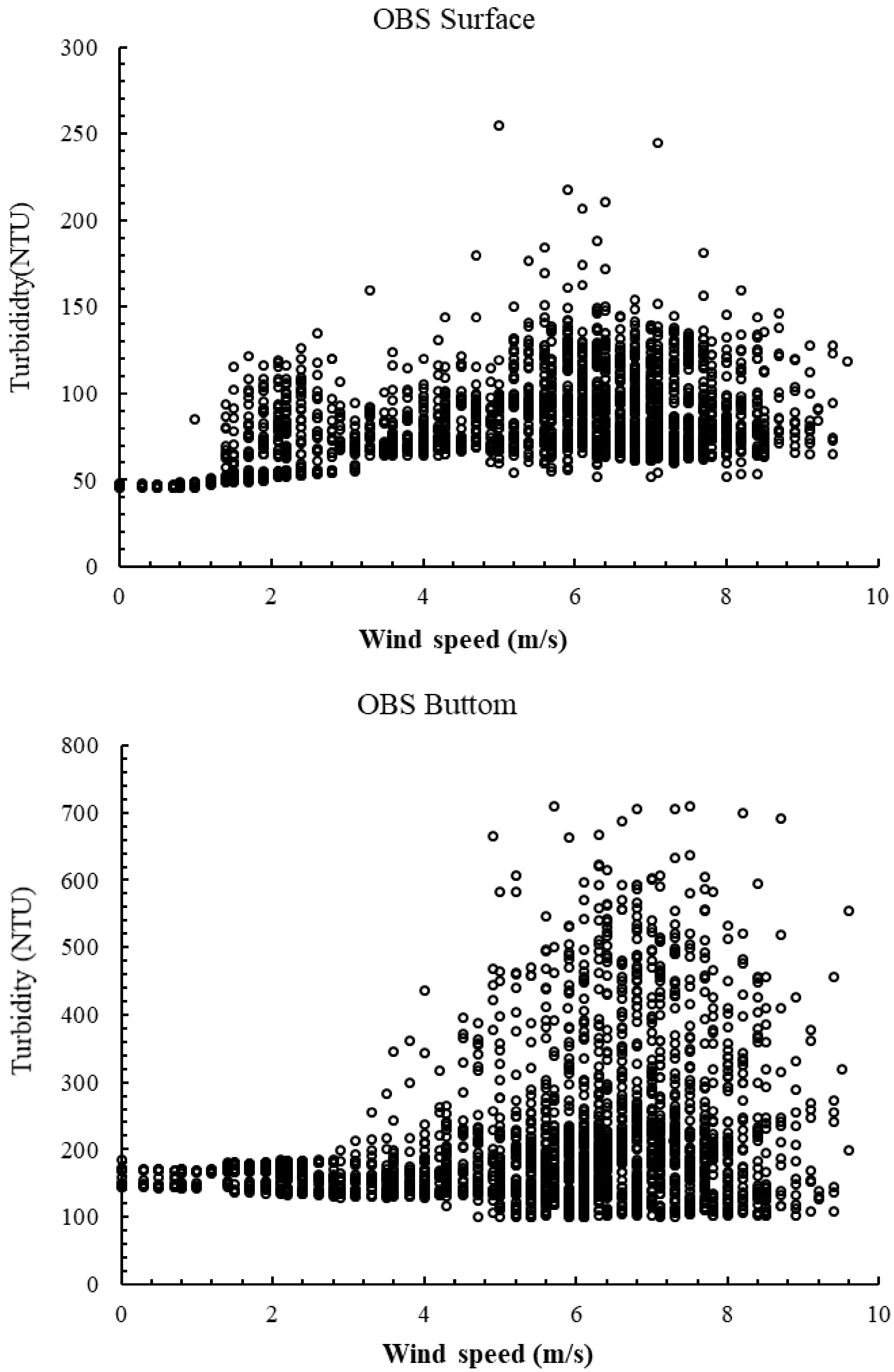

Figure 7. The relationship between turbidity in the surface and bottom with wind speed.

demonstrate that the turbidity has a relationship with wind speed and increases when wind speed reaches 5 m/s and more. In most cases, different waves induced by different wind directions collides in central zone and are resposable for the processes. The correlation between SSC and shear stress was determined using the formula

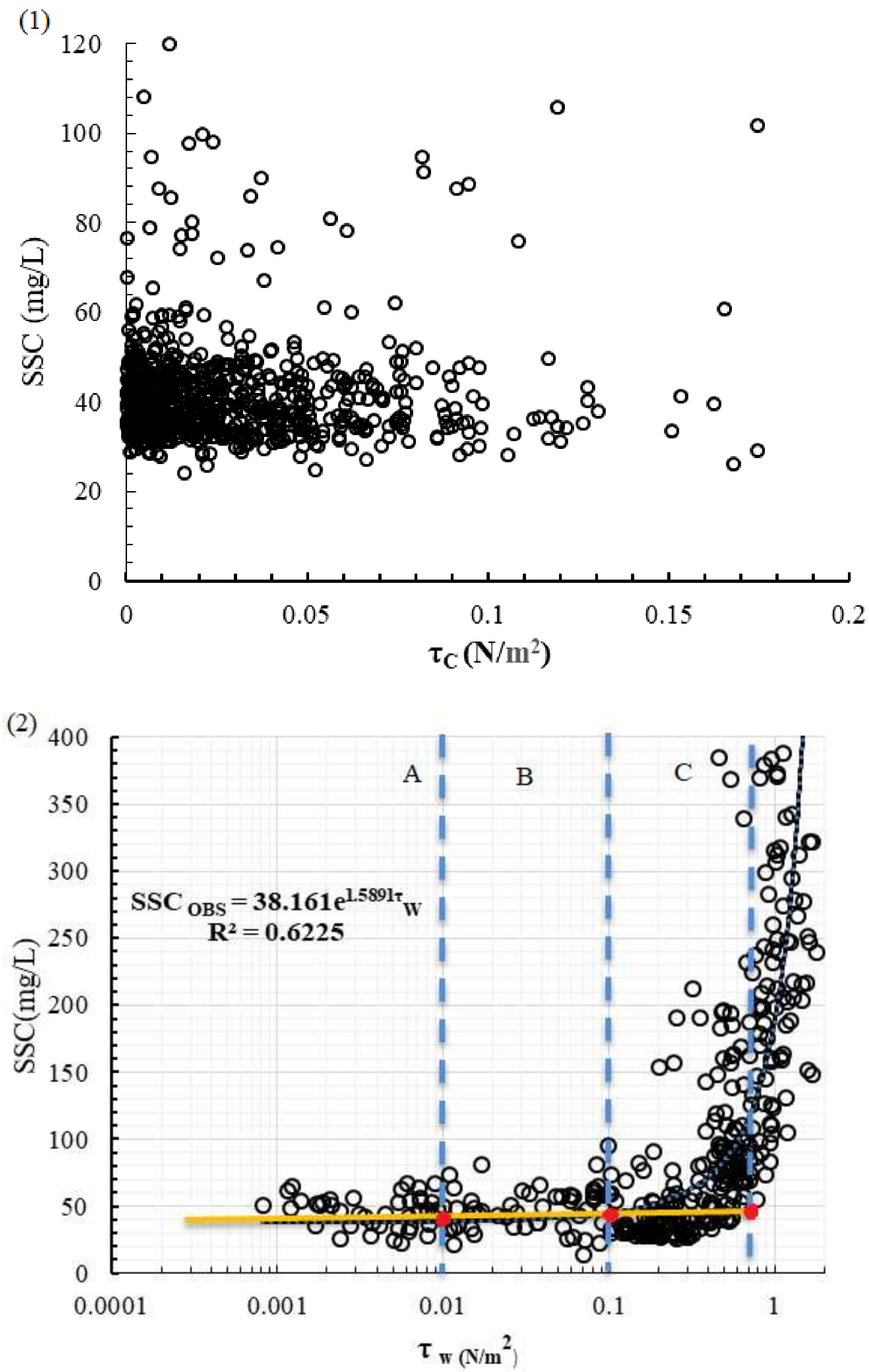

Figure 8. The relationship between SSC in the bottom layer and current-induced shearstress (1) and wave-induce shearstress (2).

SSC_{OBS}=38.161$e^{1.56\tau_w}$. The sediment movement process was classified into three stages. Stage A, SSC is constant with value 50 mg/L and τ_w was less than $\tau w < 0.01$ N/m^2. Stage B, SSC increased from 50 to 70 mg/L, and τ_w was in the range of 0.01 ≤ τw < 0.1 N/m^2. Stage C, a moderate quantity of sediment resuspension between 60 - 350 mg/L with 0.1 ≤ τw < 0.8 N/m^2. The outcomes of this paper opines that surface flow velocities may be very high in central zone of Taihu lake. This finding indicates different waves generated by different forces in the lake. When the waves-waves collided, they caused sediment resuspension processes at the bottom of Lake Taihu. Further studies should focus on the types of wave's interactions from different recourses, which encourages Algal blooms.

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CONFLICT OF INTEREST

The author has not declared any conflict of interest.

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