STUDY ON TURBULENT STRUCTURES IN TYPICAL REGIONS OF LAKE TAIHU, CHINA

YIPING LI(1), JIN WEI(2), CHUNYAN TANG(3) & KUMUD ACHARYA(4)

(1,2,3) Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes, Ministry of Education, College of Environment, Hohai University, Nanjing 210098, China
liyiping@hhu.edu.cn; weijin@hhu.edu.cn; 825976526@qq.com
(4) Division of Hydrologic Sciences, Desert Research Institute, Las Vegas, NV 89119, USA
Kumud.Acharya@dri.edu

ABSTRACT

Turbulence bursts play an important role in turbulence production and transportation. Turbulence structures in turbulent boundary layers show various bursting phenomena and make different contributions to momentum flux and sediment turbulent flux in natural geophysical flows, so this paper study the differences in two sites of Lake Taihu, using data collected from Acoustic Doppler Velometer (ADV). Statistical and quadrant analyses reveal the anisotropic and intermittent nature of momentum flux and turbulent sediment flux. In current-wave main region, the occurrence probability in time of four types of bursting motions were almost the same, but ejection and sweep make large contributions to Reynolds stress. It’s sweep and outward interaction make sediment suspension and transport. The waves increased the vertical fluctuations and sediment suspension. However, in current-main with many plants region interactions make large contributions to Reynolds stress. Interactions occur more than ejection and sweep motions, and make large interactions of momentum flux. For the turbulent sediment flux, it’s ejection and interactions make large contributions. Ejection stripe in East Taihu Bay can cause less sediments suspension, in central zone sweep caused sediment suspension, but outward interaction contributes to sediment transport more in both conditions. It is an important step for turbulence constructers and sediment suspension study to understand the spatial, temporal and frequency characteristics of sediment suspension events in relation to turbulent fluctuations, both in structural form and in temporal distribution.

Keywords: Turbulence burst; sediment suspension; quadrant analysis; Lake Taihu.

1 INTRODUCTION

Sediment resuspension is one of the main processes that control the suspended sediment transport, and is also an important effect on water eutrophication (Yuan, 2009; Qin et al., 2006; Qin, 2009; Wu et al., 2016). Hydrodynamically induced sediment suspension can affect internal nutrient release (Qin et al., 2004; Cooke et al., 2005; Stone, 2011; Lürling and Oosterhout, 2013), the underwater light field (Liu et al., 2013) and the formation of buoyant cyanobacterial blooms (Wu et al., 2013) which exacerbate the water quality, such as turbidity, dissolved oxygen deficiency, smelled and fish kills especially in lakes (Paerl and Huisman, 2008; Conley et al., 2009). For large shallow lakes, like Lake Taihu, is suffer from sever algae bloom these years because the internal nutrient release. Therefore, sediment resuspension study is important to understand the sediment transport which is main form for internal sediment loading, then to help suppress eutrophication in lakes.

Many researchers study sediment suspension by shear stress, but it’s problematic to define a single value for a bed shear stress in the presence of a strong horizontal pressure gradient (Guard, 2011). Shear stress is from sediments averaged state view to judge sediment resuspension condition, that can’t analyze root causes leading to sediment suspension. Yuan (2009) suggested that it was small-scale turbulent processes mainly controlled the instantaneous suspension of sediment near the bottom boundary layer. In fact, researchers have study on the wall turbulence with sediment resuspension for decades. Turbulence, which is also called coherent structures is generated intermittently by burst cycles near the boundary (Willmarth and Lu, 1972). And Wang (2000) agreed that turbulence played an important role on the motion of particles in sediment-water interface. Jackson (1976) reported that upward momentum flux provides the vertical anisotropy in the turbulence which is sediment resuspension needed. It was accepted that bedload transport of coarse sediments was driven by sweep-type events, while suspended load transport of finer sediments was dominated by the ejection events in the near wall region (Heathershaw and Thorne, 1985; Cellino, 2004). Liu (2012) revealed that the relationship
between passing coherent energetic structures and sediment resuspension was complex by sediment suspension model. Barman (2016) revealed that the contributions to the total shear stress due to ejection and sweep are dominant at the wake region for single and double hemisphere near the bed, while towards the surface outward and inward interactions show significant effect for wave-current interactions which is largely different from that over the flat-surface case.

Recent papers mainly study the turbulence and sediment suspension in flume, estuary, sea or using sediment suspension models, lacking the spatial and scale relationships between boundary layer turbulence and sediment suspension events in lakes, even how sediment particles respond to turbulence at current-main and wave-current main areas in large, shallow lakes remain unclear. The relations between the turbulent structure and either the topographic features of the underlying erodible bed or the dispersion of sediment also remain unclear. The present paper analyzed the continuous and high-frequency field-observation data collected by Acoustic Doppler Velocimeter (ADV) and Optical Backscatter Sensor (OBS) in the bottom of the lakebed. The aim of this paper is to: (1) understand the characteristics of turbulent bursts at current-main area and wave-current main area based on the analyses of horizontal and vertical velocity and SSC; (2) illustrate the relationship between turbulence structure and sediment suspension at the boundary layer; (3) provide some new views for water managers to control eutrophication. It is an important step for sediment suspension study to understand the spatial, temporal and frequency characteristics of sediment suspension events in relation to turbulent fluctuations, both in structural form and in temporal distribution.

2 STUDY AREA AND METHOD

2.1 Study area
Lake Taihu (30°55′40″–31°32′58″N, 119°52′32″–120°36′10″E), which is the third largest freshwater lake in China, is a large shallow eutrophic lake in the Yangtze Delta. It covers an area of 2338 km2 and a yearly volume around 4.43 billion m3 with mean water depths and 1.9 m. It is an important drinking water resource for some local cities, and important for the ecology and fishery production. Lake Taihu has frequent algal blooms for several decades (Qin et al., 2007; Stone, 2011; Wu, 2015). Sediment resuspension is an important driving factor for excessive nutrient loadings in Lake Taihu.

The field experiments were conducted in Two sites (Figure 1), Pingtaishan (site1) and East Taihu Bay(site2). Site1 is located in the central zone of Lake Taihu (N 31.229380°, E 120.108540°), whose mean water depth was 3.15m within thin bottom sediments during experiment time. The current-waves are strong in central zone. Site2 is in East Taihu Bay (30.998865°N, 120.443189°E), whose mean depth was 2m and many plants there. Its main hydrodynamic was current.

2.2 Field observation
The field observation was covered from July 22-31,2014 in Pingtai Shan and June 4-12, 2015 in East Taihu Bay. The field observation was equipped with SonTek ADV Ocean (5M Hz), OBS-3A, PH-II Handheld whether station (obtained a data every 1min) to get high frequency, synchronous data. ADV, which obtained three-dimensional velocity data and echo intensity (EI) with the sampling frequency of 10 Hz, and OBS-3A which got turbidity data with burst interval of 1min, were mounted at 5cm above the water bottom. At the same time, water samples were collected to get suspended sediment concentration (SSC).

2.3 Data processing
2.3.1 Data pre-processing
The 3D instantaneous flow velocity field \((u, v, w)\) represent the streamwise, cross-wise and vertical velocity. For the purpose of data quality control, it need pre-processing: initial signal check; then remove the outliers which was signal-to-noise ratio (SNR) less than 40 dB or correlation coefficient smaller than 70%; and the missing data were patched by linear interpolation using the neighboring points when the time occupied by missing data is less than 1% of the total time. To extract the turbulence component \((u', v', w')\), the instantaneous flow field of each component \((u, v, w)\) were subtract from the mean flow velocity \((\bar{u}, \bar{v}, \bar{w})\) which estimated by applying a moving average as a low pass filter (Hachem Kassem, 2015):

\[
u' = u - \bar{u}, \quad v' = v - \bar{v}, \quad w' = w - \bar{w}
\]  

where \(u', v', w'\) means the velocity fluctuation in mainstream, transverse and vertical directions respectively.

Previous studies reported a simple logarithmic relationship between near-bed SSC and echo intensity (EI) recorded by ADV (Voulgaris and Meyers, 2004; Y. Yuan, 2009). OBS mounted at the same height with ADV was used to calibrated EI. Before that, water samples were used to convert OBS turbidity (NTU) to SSC (mg/L). Figure 2 shows the turbidity values well related with SSC in the water samples with \(r=0.94\); and the correlation coefficient between log10(SSC) and EI is 0.84. This calibration procedure obtained high frequency of SSC (10Hz), which is sufficient for the study.

![Figure 2](image)

**Figure 2.** (a) Calibration of OBS turbidity (NTU) with bottle samples (mg/L); (b) Calibration of ADV EI (dB) with OBS SSC (mg/L).

2.3.2 Turbulence kinetic energy (TKE) calculation
The time series of TKE was calculated by three components of turbulent velocity \((u', v', w')\) as follows:

\[
TKE=0.5(u'^2 + v'^2 + w'^2)
\]  

Where \(u', v', w'\) were the velocity fluctuations in east, north and vertical direction respectively.

2.3.3 Quadrant analysis
The directions of three-dimensional velocity data measured by ADV were east, north and vertical, because of vintage quadrant analysis of turbulent coherent structure has its mainstream direction, we tried to redistribute three-dimensional velocity according to its mainstream and it succeeded. The bursting process were classified into four types of events depending on the velocity fluctuations in mainstream and vertical directions (Heathershaw, 1974; Liu, 2014).

The quadrant analysis categorizes the bursting events into four quadrants as follows:
1. \(u'<0, w'>0, u'w'<0\): an ejection of low-speed fluid away from the boundary
2. \(u'>0, w'<0, u'w'<0\): a sweep or inrush of high-speed fluid toward the boundary
3. \(u'>0, w'>0, u'w'>0\): a weak outward interaction of fluid away from the boundary (high-speed fluid reflected by the wall)
4. \(u'<0, w'<0, u'w'>0\): a weak inward interaction of fluid toward the boundary (low-speed fluid being pushed back)

The paper involving statistical analysis and quadrant analysis are using horizontal turbulent velocity fluctuations \((u')\) and vertical turbulent velocity fluctuations \((w')\) defined according to Eq. [1]. The mean, standard deviation, skewness and kurtosis for each time series of data were calculated.

3 RESULTS AND DISCUSSION
3.1 Raw data time series comparison in two sites
From the obtained data at site1, $u'$ was ranged from -1.5 to 1.5 cm/s with large irregular fluctuations, and averaged horizontal velocity was 4.34 cm/s. $w'$ was ranged from -1 to 1.2 cm/s, and the averaged vertical velocity was -0.24 cm/s. Comparing with $u'$, $w'$ fluctuated smaller. $c'$ was ranged from -20 to 20 mg/L, and the averaged suspended sediment concentration (SSC) was 42.67 mg/L. While at site2, $u'$ was varied from -2 to 2 cm/s with large irregular fluctuations, and averaged mainstream was 6.39 cm/s. $w'$ was ranged from -0.6 to 0.8 cm/s, and the averaged vertical velocity was 0.1169 cm/s. $c'$ was ranged from -5 to 5 mg/L, and the averaged suspended sediment concentration (SSC) was 46.83 mg/L. The $u'$, $w'$ and $c'$ fluctuated around their averaged values.

The average horizontal velocity in site2 is larger than that in site1, because site2 is an output region of Taipu River. The average vertical velocity in site1 was larger than that in site 2, and the main water down-flow in site1 while in site2 the main water up-flow in vertical. Because site1 is the center of lake, it has deep depth and high waves, leading to larger vertical velocity and vertical momentum exchange. The SSC is at the same magnitude, but SSC fluctuation is larger in site1, because the larger vertical momentum and mass transfer of sediment by waves in site1. Barman (2016) also said that the sediment was picked up by the waves. The TKE in site2 is 2 times larger than in site1, because the $w'$ fluctuations are considerably smaller than those in the other directions.

3.2 Statics analysis of large amplitude events

Coherent events are characterized by intermittent and many orders of magnitude events occur in random time and space. Intermittent coherent events of turbulence production and vertical transfer in bottom boundary layer are observed under different flow conditions, and was compared by statics analysis. The instantaneous momentum flux ($u'w'$) and instantaneous sediment turbulent diffusion flux ($c'w'$) were accompanied by irregular fluctuations and interrupted by salient excursions. The time series of $u'w'$ in site 1 varied from -0.63 to 0.52 cm²/s and the mean momentum flux were -0.00586 cm²/s² and $c'w'$ was varied from -93.4 to 78.3 mg/(m²s) and the mean sediment flux was -0.05997 mg/(m²s). The time series of $u'w'$ in site 2 varies from -0.59 to 1.2 cm²/s² and the mean momentum flux was 0.0308 cm²/s², and $c'w'$ is varied from -18.6 to 10.8 mg/(m²s) and the sediment flux was 0.0866 mg/(m²s). $u'w'$ in two sites was in an order of magnitude, and were larger than their ensemble average. The variation of instantaneous momentum flux ($u'w'$) in site2 is larger than $u'w'$ in site1, while sediment diffusion flux ($c'w'$) was smaller in site1. It suggested that although the magnitude of Renolds stress were the same, the sediment diffusion flux could be large different. Because in site2 horizontal current is the main flow and vertical velocity fluctuations were smaller so that sediments suspended less and transport mainly by advected currents; while in site1 current-waves both were strong and vertical flow fluctuations were stronger than site1, so that sediment suspension more. As Figure 3 shows, $c'$ have quasi-normal probability distribution, the distributions of $c'w'$ was characterized as high kurtosis and positive skewness which suggested upward transport of sediment in two sites. The distribution of $u'w'$ also shows high kurtosis and asymmetrical, but it is positive skewness in site1 and negative skewness in site2. That's because the ejection and sweep make more contribution relative to interactions in site1, but a totally opposite effect in site2 (analyzed in section 3.3). The symmetry of the $u'w'$ were found in Heathershaw (1974) and Yuan (2009).
Figure 3. Probability density distribution of $w'$, $c'$, $U'w'$ and $c'w'$ based on statistical analysis Pingtai Shan(a) and East Taihu Bay(b) (red line is standard normal distribution).

Contributions of large $u'w'$ and $c'w'$ events to mean sediment flux ($\bar{u}'w'$ and $\bar{c}'w'$) are summarized statistically in Figure 4. It took the two, three and four standard deviations as the large amplitude events for analysis. In site1, the large $u'w'$ events occurring outside the two, three, and four standard deviations contributed as much as 62.6%, 48.2% and 33.5% to $\bar{u}'w'$ in 5.2%, 2.3% and 1.1% of the total time, respectively (Figure 4a). In site2, the large $u'w'$ events occurring outside the two, three, and four standard deviations contributed as much as 32.4%, 23.9% and 13.3% to $\bar{u}'w'$ in 4.4%, 2.2% and 1.1% of the total time, respectively (Figure 4b). It suggested that vertical transfers of momentum occur intermittently with relatively large magnitude, short duration in the lakebed, the same conclusions found in coastal area (Heathershaw, 1974; Yuan, 2009).

Figure 4. Time occupied percent by large $u'w'$ events, and Contributions of large-amplitude events of momentum to average momentum ($\bar{u}'w'$) in Pingtai Shan (a) and East Taihu Bay (b).

The large $c'w'$ events outside the two, three and four standard deviations contributed -39.7%, -127.5% and 153% in 4.6%, 2.1% and 1% of the time to the mean sediment flux in site1, respectively. In site2, The large $c'w'$ events outside the two and three standard deviations contributed -39.7%, -127.5% and 153% in 4.6%, 2.1% and 1% of the time to the mean sediment flux, respectively (Figure 5). The results suggest that sediment transport primarily occurred in short bursts. Yuan (2009) got the same results in the sea.
3.3 Quadrant analysis and dominant structural features of different flow field

Quadrant analysis is used to quantify the intermittent instantaneous Reynolds stress signals and identify turbulence structures within a turbulent bursting sequence (Kassem, 2015). Bursts play important role in turbulence production and transportation. Coherent structures which consist of organized vortices in space and time are responsible for most of the resistance of motion and transport process (Mazumder and Ojha, 2007; Jain, 2015).

Figure 6. Quadrant statistical analyses of coherent structures. (a) Time occupied by four types of events in Pingtai Shan, (b) Contributions to momentum flux, and Contributions to turbulent sediment flux in Pingtai Shan, (c) Time occupied by four types of events in East Taihu Bay, (d) Contributions to momentum flux, and Contributions to turbulent sediment flux in East Taihu Bay.

The occurrence probability in time of these four types of bursting motions (ejection, sweep, inward interaction, and outward interaction) in site1 were 27.4%, 24.6%, 24.8% and 22.4%, respectively (Figure 6a). Four events have nearly the same occurrence probabilities, but their contributions to momentum flux and
turbulent sediment flux were various (Figure 6b). The sum of momentum flux was -30 cm²/s², which means ejection and sweep make large contributions in site1; inward interaction and outward interaction did negative contributions. The largest contributions to stress often occur through ejection and sweep motions (Robinson, 1991). Moreover, sweep and outward interaction did the most contributions when it didn’t consider its positive or negative. For the turbulent sediment flux, sweep and outward interaction did the most contributions (the sum of turbulent sediment flux was -306.8 mg/(m²s²)). It has been observed that outward interaction can be as effective as ejection and sweep, and Nelson (1995) reported the same results. Recent papers reported that ejections are associated with sediment suspension, while sweeps are effective at transporting bedload (Cao, 1997; Heathershaw, 1979; Keylock, 2007; Yuan et al., 2009). At the lakebed, sweep loosened the sediments and outward interaction took the sediment into the water, then sweep transported the sediments at the stronger wave-current flow conditions.

At site2, ejection, sweep, inward interaction and outward interaction occupied the time during 512s of 17.4%, 18.6%, 32.5% and 31.5%, respectively (Figure 6c). The sum of momentum flux is 126.1 cm²/s², and the sum of turbulent sediment flux was 354.9 mg/(m²s). ejection and sweep make contributions to Reynolds stress, but it was interactions occur more and make large contributions to momentum flux. For the turbulent sediment flux, it was ejection and interactions make large contributions (Figure 6d). it suggested that sweep just loosened the sediment couldn’t transport the sediment, it was ejection and interactions transported the sediment. Maybe because different sediment grain size and topography, ejection had different effect on sediment transport. Jackson (1976) said gradual lift-up of low-speed streaks only in the smooth-bed flow, sudden violent ejections of fluid from interstices when flow over the rough boundary. Kemp and Simon (1982) showed that the near bed velocities over the rough bed for current alone were reduced, while near bed turbulence intensities were increased due to the presence of waves.

4 CONCLUSIONS

A complex quasi-ordered flow structure which consists of a deterministic sequence of fluid motions occurring randomly in space and in time, and affected by current, waves, topography and bed-roughness (reviews in Lauder 1975; Offen and Kline 1975; Jackson, 1976). The paper analyzed the differences between turbulence structures and turbulent sediment flux in current-main region and current-waves main region. In current-wave main region, the occurrence probability in time of four types of bursting motions were almost the same, but ejection and sweep make large contributions to Reynolds stress. It’s sweep and outward interaction contributed more to sediment suspension and transport. Because waves increased the vertical fluctuations and sediment suspension. However, in current-main with many plants region, interactions occur more than ejection and sweep motions, and make large interactions to Reynolds stress and momentum flux. Ejection stripe in East Taihu Bay can cause less sediments suspension, in central zone sweep caused sediment suspension, but outward interaction contributes to sediment transport more in both conditions. The paper also has some shortcomings, it just considered the turbulence in mainstream and vertical directions, 3D data analysis should be applied in the future. And in the future study, it is important to measure the entire process of vortex from producing to breaking, and how it affects the sediment suspension and transport.

ACKNOWLEDGEMENTS

The research was supported by National Key Research and Development Program of China (2017YFC0405203), the Fundamental Research Funds for the Central Universities (2018B48214), the Fundamental Research Funds for the Central Universities (No. 2017B20514) and PAPD, the Chinese National Science Foundation (51779072, 51579071, 41323001, and 51539003), the National Science Funds for Creative Research Groups of China (51421006), the Postgraduate Research & Practice Innovation Program of Jiangsu Province (2018B672X14), the program of Dual Innovative Talents Plan and Innovative Research Team in Jiangsu Province, and the Priority Academic Program Development of Jiangsu Higher Education Institutions.

REFERENCES


