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Dynamics of settling particulate matter during typhoon Muifa in Heini Bay, China*

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Abstract Settling particulate matter (SPM) is widely used to describe the sedimentary environment. We have investigated here the SPM collected with a time-series sediment trap in the Heini Bay, Weihai, Shandong Peninsula, China, during the super typhoon Muifa (August 2011, maximum wind speed 55 m/s). Meteorological and hydrological parameters were measured for 18 days. By analyzing the particle flux, grain size, and loss-on-ignition (organic matter content) of SPM we found dramatic changes in these parameters, induced by typhoon Muifa for about 6 days. With the arrival of typhoon, the daily SPM fluxes increased sharply to the maximum at 76.4 g/(m^2·d) on the first day and this increase is about 9 times of the normal value, and after 6 days the SPM decreased to the normal value gradually. Other parameters, such as grain size of SPM and organic matter also experienced similar changes. Using these SPM parameters, we divided the settling progress by cluster analysis into three phases: strong (for 3 days), weak (for 3 days), and zero typhoon impact.

Keyword: settling particulate matter (SPM); typhoon; sediment trap; SPM flux; Heini Bay

1 INTRODUCTION

Suspended particulate matter in seawater is an important substance in various marine physical, chemical, and biological processes, and plays as an external agent in coupling and interaction among multiple elements (Kuss and Kremling, 1999; Collier et al., 2000; Silverberg et al., 2007). Settling particulate matter (SPM) in shallow sea has been applied to study the migration and transformation of nutrients or other chemical elements, change and development of seabed topography, erosion, and deposition on the continental margin, waterway, etc. (Tambiev and Demina, 1992; Aguiñiga et al., 2010; Lee et al., 2011). Occurrence of extreme weather in a shallow sea region, typically typhoon or hurricane, is often accompanied by changes in deposition rate and material composition. Understanding these changes helps the researchers in canvassing material provenance, hydrodynamic condition, and so on (Silverberg et al., 2007; Yang et al., 2011).

Time-series sediment traps make it possible to sample SPM in specific depth and period, with which the flux, composition, provenance, and environmental responses can be analyzed (Hsu et al., 2004). Although turbulence and tilting of the trap may influence the sampling (Baker et al., 1988; Honjo and Doherty, 1988; Gust et al., 1994), it is still a good method so far to record what happened in its ambience. Samples captured by this method feature good representation of the deployment period (Usbeck et al., 2003). This method has been widely used in dynamic sedimentary environment and geochemical studies (Honjo and Doherty, 1988).

In many studies, a sediment trap is moored for several months for collecting SPM. The contents and

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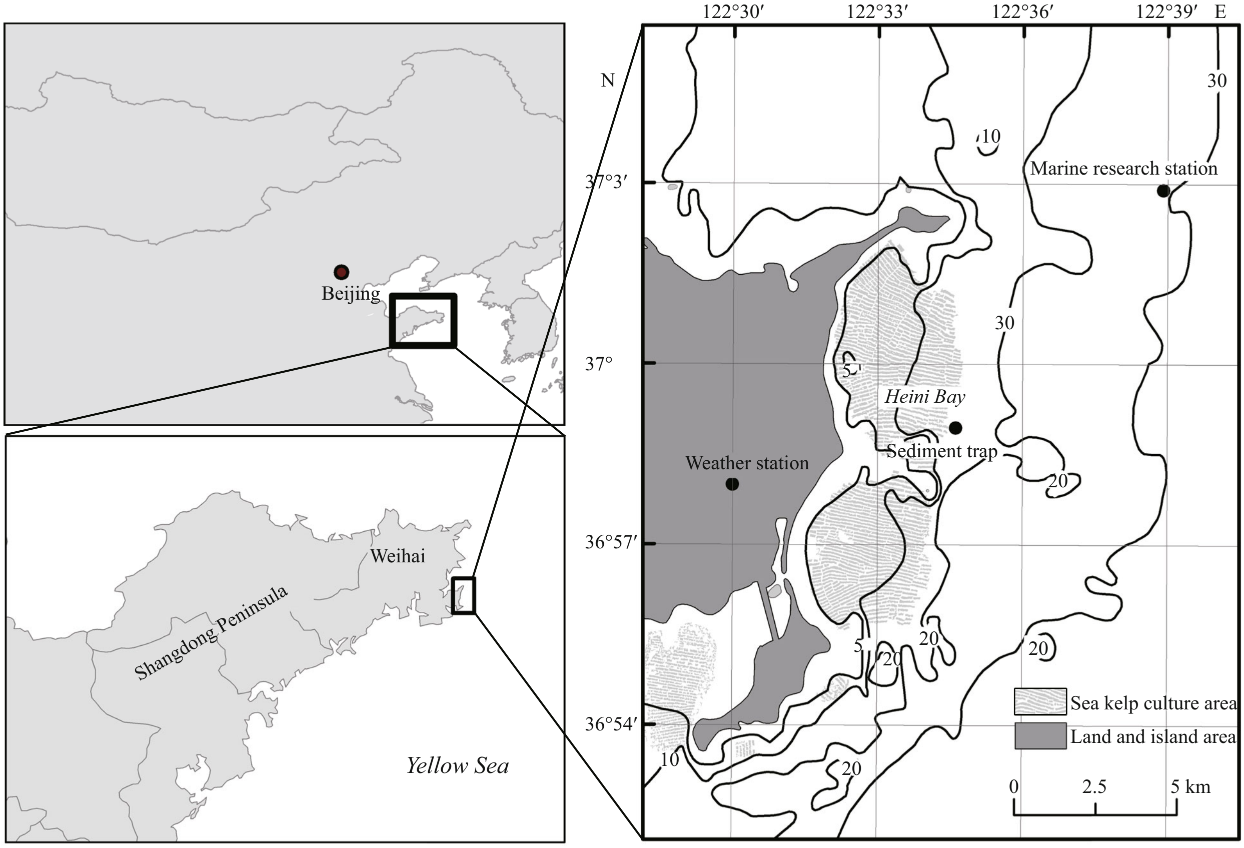

Fig.1 Geographic location of the study area and the sample station

seasonal changes of particulate organic carbon, particulate organic nitrogen, biogenic silica, ^{210}Pb and ^{234}Th, micro plankton, foraminifera, and other parameters of the samples can be investigated (Yamada and Aono, 2003; Sukigara and Saino, 2005; Yamada and Zheng, 2007; Hernández-Almeida et al., 2011; Lin et al., 2011). Since the 1970s, several experimental studies have been published in inner continental shelf sedimentary environment affected by typhoon (Liu et al., 2006; Huh et al., 2009). In these studies, simultaneous parameters of coastal winds, salinity, temperature, flow field, suspended sediment concentration, and suspended particle-size were measured, and gradient organic matter of the SPM samples was analyzed to determine the interactions of these parameters with sedimentary environment (Liu and Lin, 2004; Liu et al., 2006).

Field observations are difficult in a strong wind field. Therefore, during a windy course, in-situ observation of SPM in coastal water with a sediment trap is rare in China and other countries, especially in middle-latitude offshore zones. In previous studies, sampling gaps are often large, during which a continuous spectra of parameter changes during a storm would miss (Bishop et al., 1978; Walsh et al., 1988; Collier et al., 2000; Silverberg et al., 2007). Therefore, it cannot be used to study the entire course of sedimentation in a storm event.

In this study, we used a time-series sediment trap to collect SPM samples daily during super-typhoon Muifa, in the Heini (*heini* means *black mud* in Chinese) Bay, Weihai, Shandong Peninsula, China in a temperate zone in climate type, and recorded the meteorological and hydrological parameters simultaneously. Then SPM flux, grain size components and distribution, and loss-on-ignition (LOI) parameters of samples were measured to identify the relationship between SPM and local hydrodynamic environment. Every sample was collected with sediment trap in 24 h. This high-density observation helps greatly the study on sedimentation procedure during a typhoon event.

2 STUDY AREA

The Heini Bay is situated at the eastern tip of the Shandong Peninsula and southeast to Weihai City (36°55′–37°2′N,122°31′–122°37′E) (Fig.1). This is a small open bay facing the Yellow Sea to the east, featuring a temperate continental monsoon climate, and is of mid-latitude weather system, with more gusty winds and heavy rains. On average, 1.6 tropical cyclones occur in the study area, including 0.3 landed at the coast (Gao et al., 2008; Niu et al., 2011). Small rivers near Heini Bay flow into the sea directly, and carry only small amount of sediment into the bay. The suspended matter in the bay comes from two sources: local hills, and resuspended matter in the shore and seabed.

3 MATERIAL AND METHOD

3.1 Meteorological and hydrological observations

The Rongcheng Chudao Island Marine Research Station of China Offshore Marine Observation and Research Network is a 3-m observational buoy system. It is designed to make long-term continuous fixed-point observation on the offshore marine information and it is about 9.7 km northeast to the sediment trap (manufactured by McLane Corporation, USA) (Fig.1). The marine research station successfully recorded the meteorological and hydrological parameters during typhoon Muifa, but it stopped working on Aug. 10 after the typhoon event. The weather station locates in the west shore of Heini Bay is 7.1 km to the sediment trap, and it recorded wind speed, wind direction, barometric pressure during the typhoon, and these data are good supplement to reflect weather conditions in the bay.

The parameters such as wind direction, wind speed, wave direction, and significant wave height (SWH) were observed on the marine research station northeast to the sediment trap and are shown in Fig.2. It can be seen from Fig.2 that the SWH changed after the wind speed apparently, while the waved direction is severely impacted by sea-floor topographic and showed little relationship to the wave direction. Other meteorological parameters such as atmospheric pressure, wind speed, and wind direction were observed on the weather station located to the west of Heini Bay and are shown in Fig.3. We can see that atmospheric pressure, wind speed, and wind direction is well correlated.

3.2 Typhoon Muifa

The typhoon Muifa (International Number 1109) developed as a tropical depression in the northern west Pacific on July 28, 2011, and then became a super-typhoon for several times with maximum wind speed at 55 m/s. Figure 4 shows the path and force of typhoon Muifa, and the circels are drawn according to the diameters of Force 7 wind and Force 10 wind, but not field suvey wind speed data. In the midnight of August 7 and early morning of August 8, Muifa passed by the east of the study area. The sediment trap was at the edge of force to 10 wind radius, about 100 km to the center of the typhoon (Fig.4). The marine research station recorded the maximum wind speed of 15.1 m/s at 23:30 hours on August 7, and the maximum SWH of 5.8 m at 3:30 hours on August 8. The weather station on the west shore of Heini Bay (Fig.2) recorded the maximum wind speed of 13.32 m/s at 0:00 hours on August 8 (Fig.3).

3.3 Sampling design

We used a time-series sediment trap to collect SPM samples in the Heini Bay. The device was made by McLane Corporation, USA, model number PARFLUX Mark 78H-21. This sediment trap (164-cm high) consisted of a broad funnel (diameter 91 cm) with a collecting jar at the bottom. The funnel had baffles at the top to stop large objects that might clog the funnel and reduce the turbulence in the mouth of the trap (Usbeck et al., 2003). The sediment trap was deployed on August 5, and recovered it successfully on August 26, 2011. The observation place is to the east of the shore for about 3.5 km, in depth of 14 m at the outermost place of sea kelp culture area (Fig.1). In this season, kelp has been harvested, only a small amount of remains on the sea, which would not affect the hydrodynamic environment significantly.

The sediment trap was fixed to the sea floor with a 180-kg iron, and on the upper side was attached with three mandrel floats to keep vertical standing of the instrument (Fig.5). The instrument began sampling at 12:00 hours, August 5, 2011, each sampling bottle collected SPM in 24 hours, and then it was automatically sealed and switched to the next bottle. The sediment trap collected 21 samples in total.

During the typhoon Muifa, the sea condition was terrible and hydrodynamic conditions became more complicated. When recovering the sediment trap, the rope to recover the instrument was entangled with sea kelp shelf. Although we overcame difficulties and recovered the instrument as much as possible, the last three samples were contaminated. Only the samples from noon of August 5 to noon of August 23 were analyzed (18 samples). In this article, the samples are named by its starting day; for example, sample 8-8 is the sample functioned from 12 o'clock on August 8 to 12 o'clock on August 9. Typhoon Muifa came when the sample 8-7 was in function of collection (Figs.2, 3).

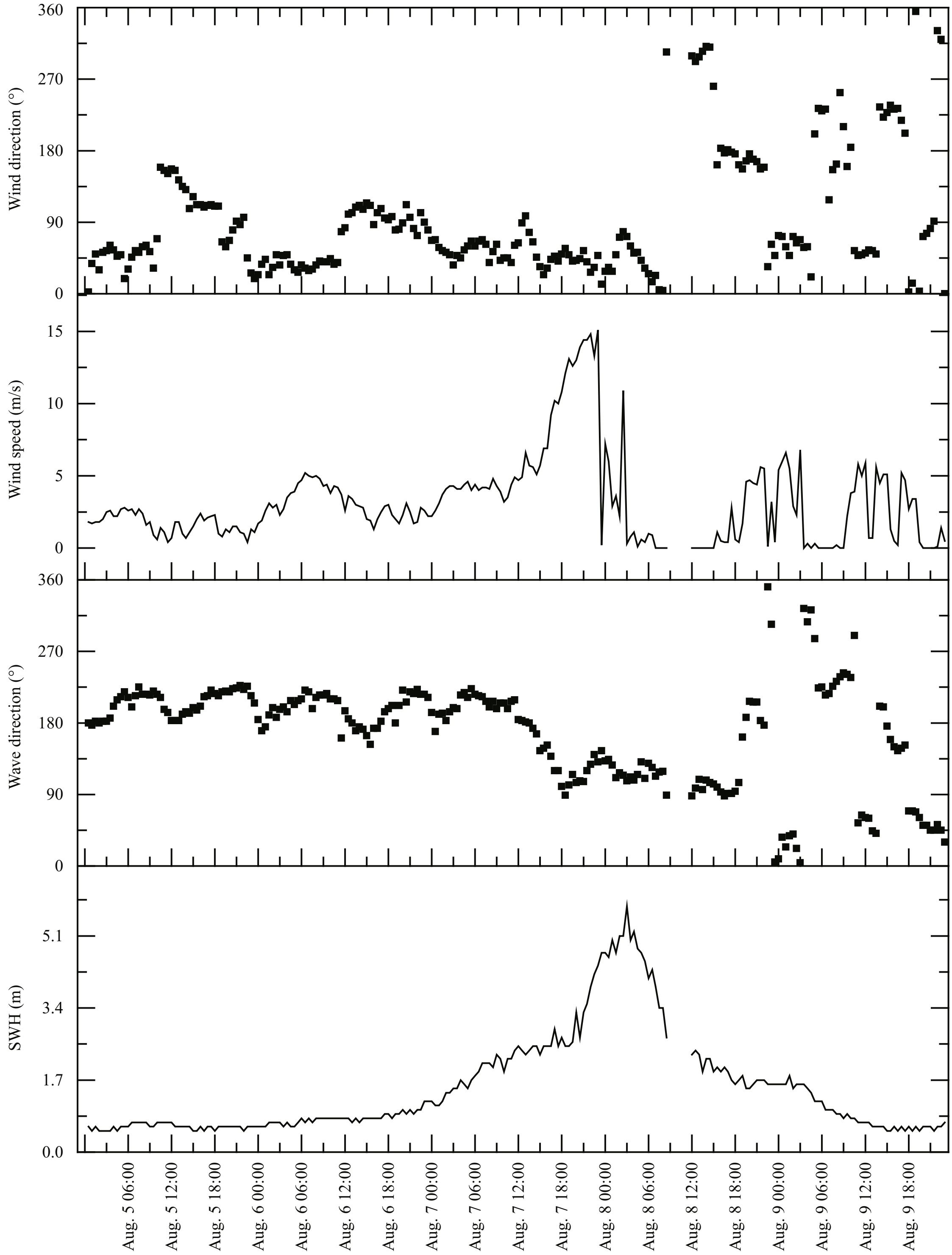

Fig.2 Wind direction, wind speed, wave direction, and significant wave height (SWH) parameters observed in the marine research station northeast to the sediment trap

3.4 Data analysis

After the sediment trap was recovered, samples were checked and cap-sealed for laboratory use. Samples of each bottle was poured into a beaker together with water. The bottle was washed several times with deionized distilled water. After 24 h of standing, the upper water was discarded by siphoning and deionized distilled water was added to dissolve the salt. This process was repeated for three times to ensure the salt in the samples was totally removed. The remaining part was placed into an oven to stove

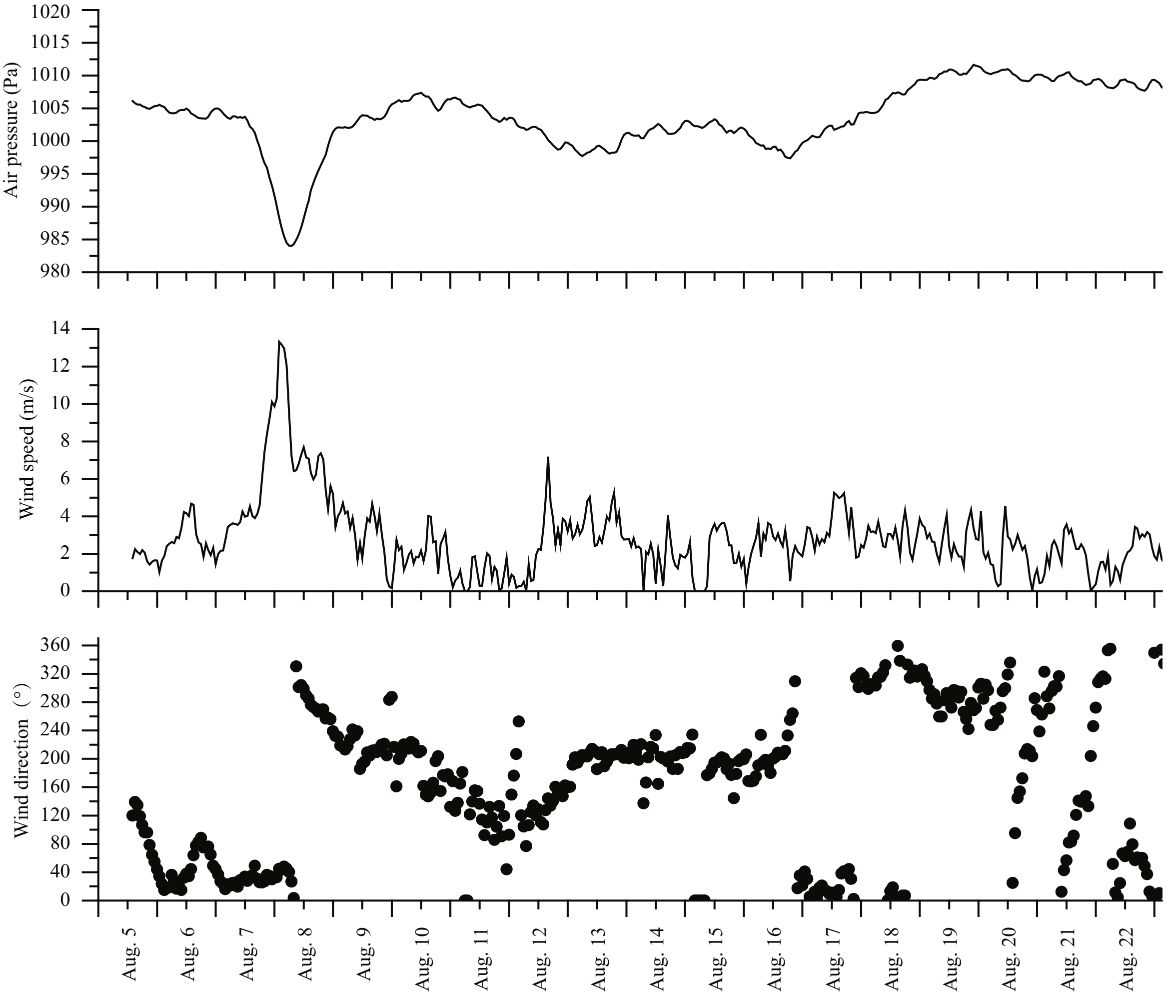

Fig.3 Atmospheric pressure, wind speed and wind direction observed on the weather station located to the west of Heini Bay

at 60°C, and then after 2-h cooling, high-precision electronic balance was used to weight the oven-dry samples. Particle flux was calculated according to the following formula:

$$F = \frac{M}{H \cdot V \cdot \cos(\theta)}, \quad (1)$$

where F stands for particle fluxes in unit of g/(m^2·d); M is the weight of dried sediment samples in grams; V is the area (m^2) of the sampling funnel; θ is the average tilt angle (°) recorded by the sediment trap during its working time; H denotes the collecting time, unit day (d) and H=1.00.

Loss-on-ignition (LOI) was measured to stand for the content of organic matter in the sample (Wang et al., 2013). Briefly, 3–5 g samples were taken out from each dried samples and was grounded with a stone pestle, and heated at 105°C for 2 h to remove water, and then weighted and recorded as W_{105}. The samples were then placed in a muffle furnace and heated at 550°C for 4 h to remove organic material. After heating, only inorganic substance was left and the weight was denoted as W_{550}. An LOI index was calculated with Eq.2 as follows:

$$\text{LOI}=(W_{105}-W_{550})/(W_{105}-W_0), \quad (2)$$

where the LOI stands for loss-on-ignition of a sample; W_{550} is the weight of the sample and the crucible after heated to 550°C; W_{105} is the weight of the sample and the crucible after heated to 105°C; W_0 is the weight of the crucible.

We took out 1–2 g from each sample, put it into a small beaker, dispersed it by ultrasonic vibration, and then used Cilas940L laser particle size analyzer to analyze the sample size. The grain size parameters were calculated with GRADISTAT software.

4 RESULT

4.1 Changes of SPM flux

Figure 6 shows the particle flux recorded during August 5 to 22. It is evident that the SPM flux

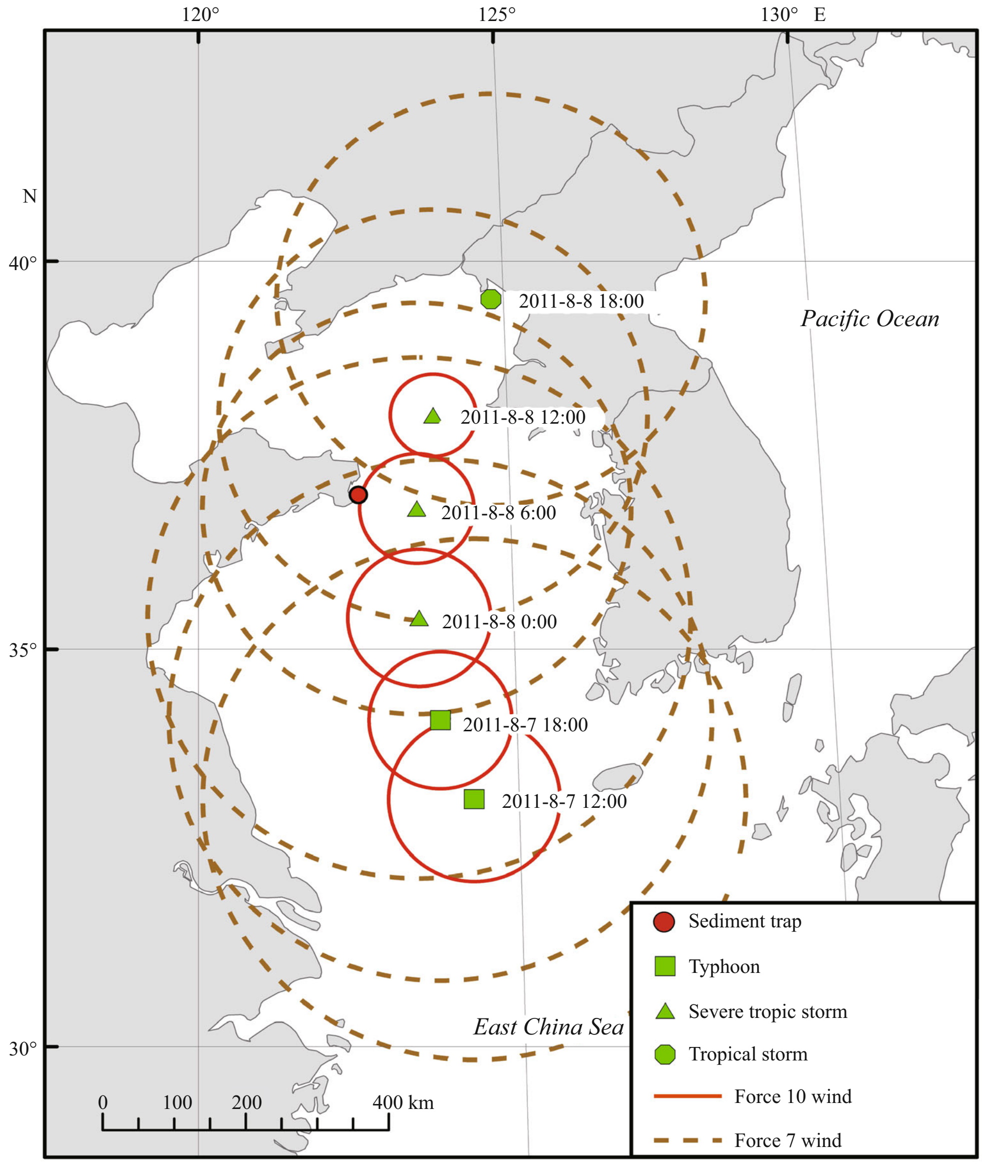

Fig.4 The path and force of typhoon Muifa

Force 7 means wind speed 13.9–17.1 m/s; Force 10 means wind speed 24.5–28.4 m/s.

showed a significant high in particle flux during the typhoon. The maximum SPM flux is 76.4 g/(m^2·d). When typhoon passed, the SPM flux restored to a normal value, except for a small-scale fluctuation in Sample 8-11. The reason is that when Sample 8-11 was collected, the wind speed weakened rapidly (Figs.2, 3), which resulted in a quick drop in SPM and then a greater particle flux at this time.

4.2 Grain size distribution

Samples collected with sediment trap were analyzed for grain size, using laser particle size analyzer. The frequency and cumulative frequency of the grain size of the samples are shown in Fig.7a, b, in which the particle sizes were <90 μm in size, and the grain size distribution under different hydrodynamic conditions showed some differences. Samples 8-5, 8-6, and 8-21 showed high-clay contents, whereas the samples 8-7, 8-8, and 8-9 showed low-clay contents and high-silt contents (Fig.7a, b).

4.3 Grain size parameters

We used GRADISTAT software to calculate the grain size parameters with Folk and Ward method (Pye and Blott, 2004; Folk and Ward, 1957), the average grain size, sorting, skewness and kurtosis parameters were calculated. The changes of these parameters over the time are shown in Fig.8. We can see all the grain size parameters are sensitive to the typhoon event, and showed regular changes on the day of typhoon Muifa arrival (sample 8-8). In Fig.8b, a white line is drawn to divide different kind of sorting, and 2–4 means very poorly sorted. In Fig.8c, a white line is drawn to divide different kinds of skewness, and -0.3– -1 means very coarse skewness, and -0.1– -0.3 means coarse skewness (Blott and Pye, 2001).

4.4 Loss on ignition

We measured LOI of the samples to see changes of organic matter due to the typhoon (Fig.9). Figure 9 shows that during the typhoon process, LOI of the samples had experienced a process of rapid decrease from 6.6%–6.3% at samples 8-5 and 8-6 to 4.3%–3.9% at samples 8-7 and 8-8, and then increase gradually to its normal level.

5 DISCUSSION

5.1 Trap efficiency in intensive hydrodynamic condition

Buesseler (1991) and Baker et al. (1988) published the trapping efficiency of bottom-tethered sediment traps. In this study, particle settling is mainly controlled by hydrodynamic conditions. Seawater near shore is more turbid than in deep sea. The sediment trap we used was made by McLane Corporation USA, which was designed in conical shape with a baffle to reduce the influence of water flow, such as advective flow (Gardner, 1980). In Eq.1, we considered average tilt value of the sediment trap. Therefore, during the working time, the sediment trap had similar trap efficiency, and the settling samples we collected should be valid and

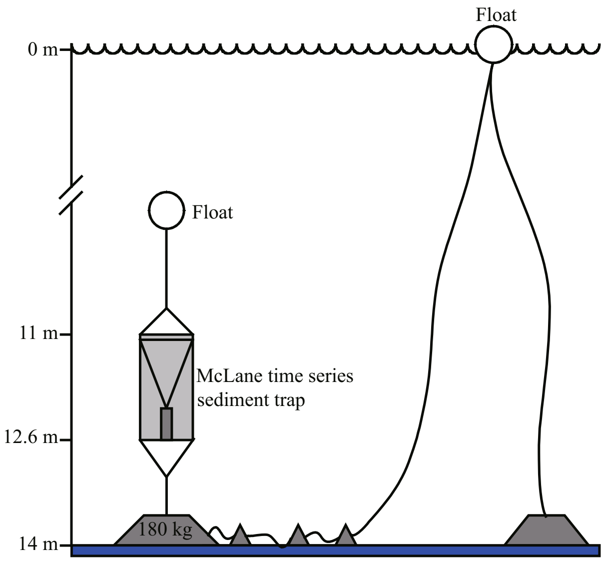

Fig.5 Sketch map of the deploy method of the time series sediment trap

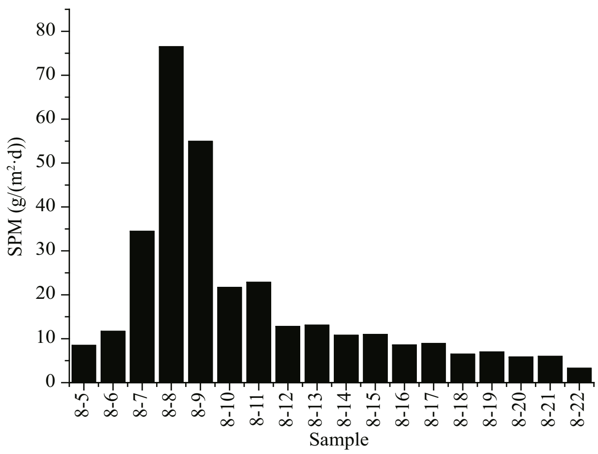

Fig.6 Changes of SPM flux by the time

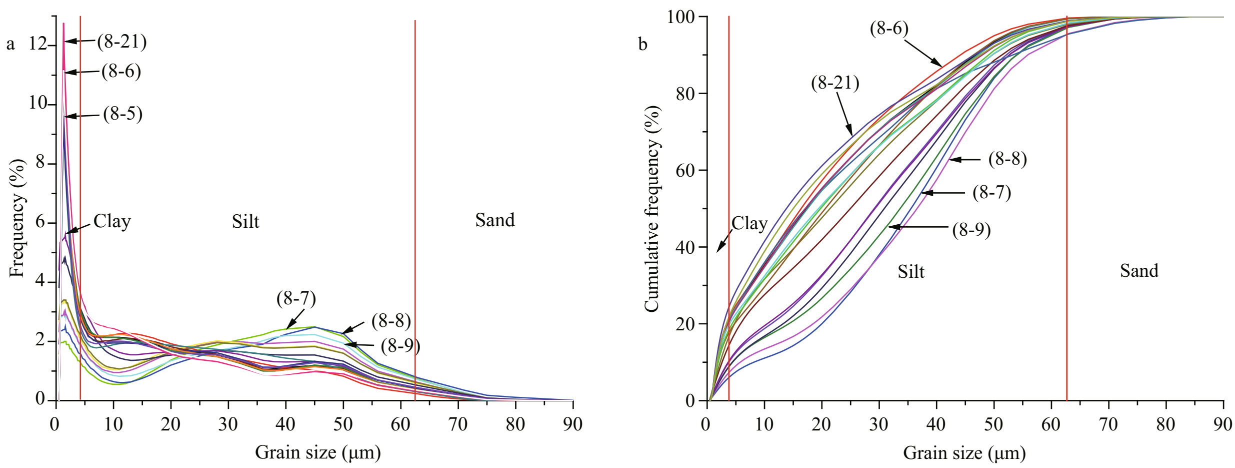

Fig.7 Frequency of grain size distribution(a); grain size cumulative frequency (b)

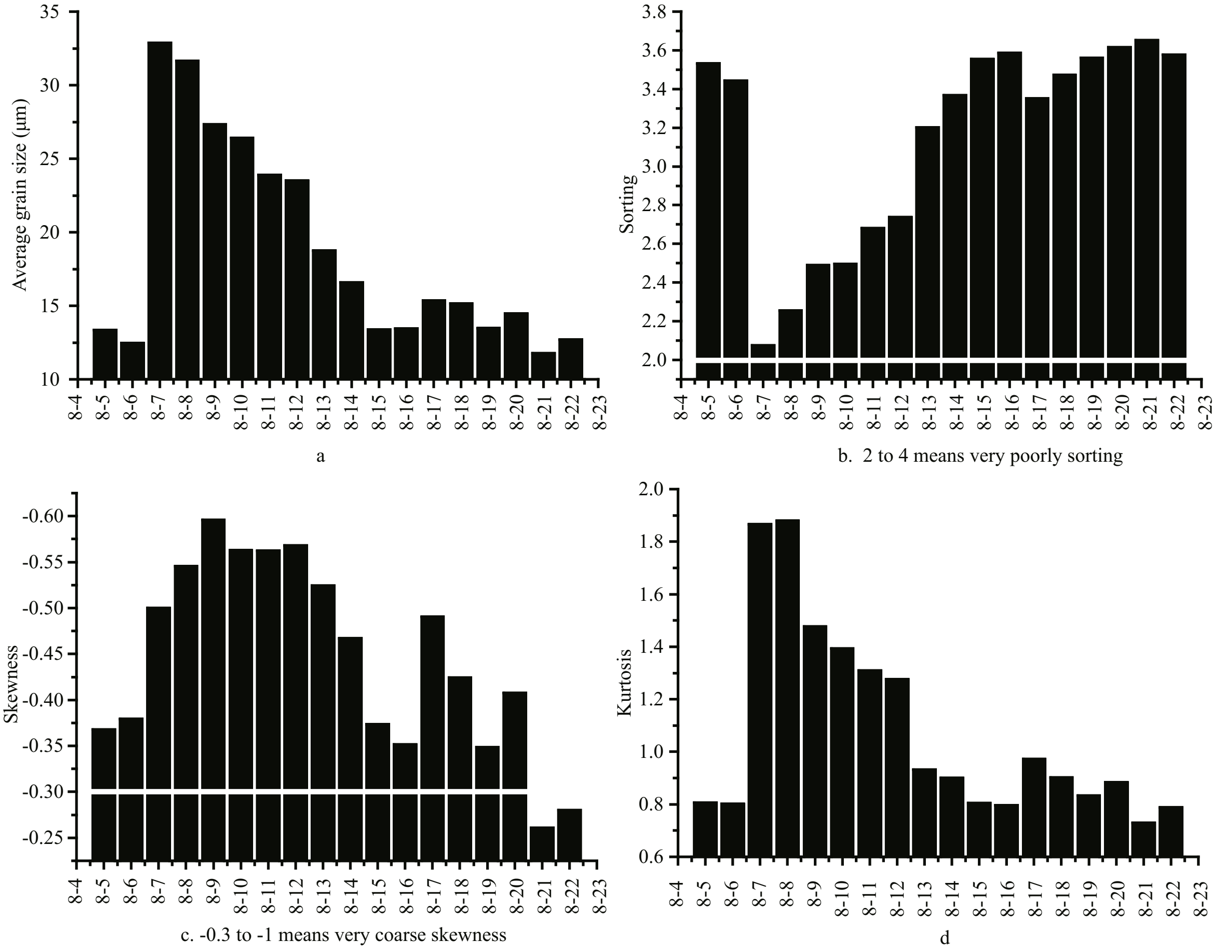

Fig.8 Changes of grain size parameters by the time

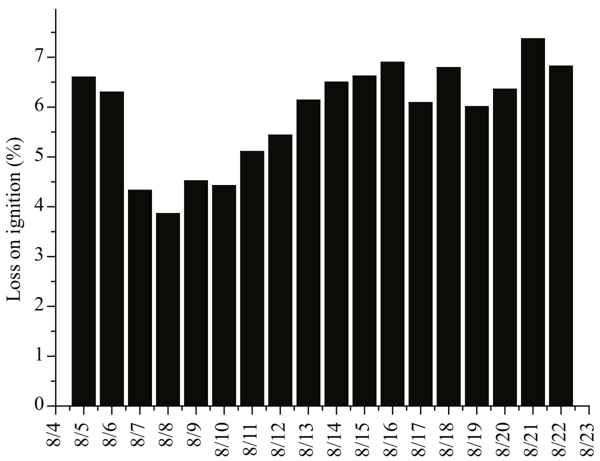

Fig.9 Changes of loss-on-ignition of the samples according to time

could be able to reflect the settling characters affected by typhoon Muifa. Several workers used these type of traps in shallow seas and collected settling samples (Liu and Lin, 2004; Fan, 2011; Lin et al., 2013).

5.2 Changes of SPM parameters according to typhoon event

5.2.1 SPM flux

As shown in Figs.2 and 3, the typhoon swiped the study area at the midnight of August 7 and early morning of August 8. Before the typhoon passed by, the SWH increased before wind speed mainly because the energy broadcasted to the study area by means of wave. The particle fluxes increased slowly with these changes from 8.5 g/(m^2·d) in sample 8-5, to 11.7 g/(m^2·d) in sample 8-6 (Fig.6). When sample 8-7 was collected, typhoon Muifa just passed by the study area. The maximum average wind speed recorded by the marine Research station was 15.1 m/s, at 23:30 hours on August 7, and the data from the weather station (on the west shore of Heini Bay) was 13.32 m/s, at 00:00 hours on August 8. The maximum value of the SWH appeared at the marine Research station at 3:30, up to 5.8 m, and was 4 hours later after the wind speed maximum time. During this time, seabed sediment was stirred up by wave and current and went into the water. When hydrodynamic environment reached its maximum value, it begun to weak gradually, and the suspended sediment began to settle largely. The SPM flux of sample 8-7 reached 34.4 g/(m²·d), 2.9 times the sample 8-6. However, as the time of collecting sample 8-7 stopped was on 12 o'clock, August 8, and the settlement time was short and so that it was missed, the SPM flux of sample 8-7 was not the maximum during the typhoon event.

During sample 8-8 collection, hydrodynamic environment had been in a process of weakening, and a large number of suspended sediments had deposited. Therefore, the particle flux of sample 8-8 amounted to the maximum value of 76.4 g/(m²·d). Then, the hydrodynamic environment weakened continuously and the SPM flux decreased until sample 8-14 for 10.8 g/(m²·d), less than the value before typhoon arrival (sample 8-6).

5.2.2 Grain size

As shown in Fig.8, the grain size increased rapidly during the course of the typhoon. It experienced a rapid increase from 13.4–12.4 μm (at samples 8-5–8-6) to 32.9 μm (at samples 8-7) and then decreased gradually to its normal level (Fig.8a). The sorting parameters decreased rapidly from 3.5–3.4 (at samples 8-5, 8-6) to 2.0 (at samples 8-7), and then increased gradually to its background (Fig.8b). The skewness parameter reflects asymmetry of grain size distribution. In this study the skewness of all samples is negative. In the typhoon event, the skewness decreased from -0.37, -0.38 (at samples 8-5, 8-6), to -0.5 (at sample 8-7), and reached the minimum value of -0.6 at sample 8-9,and then it increased gradually to the normal level. It has a longer delay time than other parameters (Fig.8c). Small fluctuations appeared after sample 8-15, and it was caused mainly by small-scale weather event. Kurtosis describes concentrated level on both sides of the average grain size. It increased from 0.81, 0.80 (samples 8-5, 8-6) to 1.87, 1.88 (samples 8-7, 8-8), and then decreased gradually, fully restored to the level of non-typhoon on the sample 8-15 (Fig.8d).

5.2.3 LOI

In Fig.9, samples 8-5 and 8-6 stand for LOI values of pre-typhoon condition. When typhoon Muifa arrived, samples 8-7, 8-8, 8-9, 8-10 were severely affected. The LOI of the seafloor sediment near sediment trap ranged from 2.9% to 5.1% (sampled on 2011.8.4, 2011.8.23), which is similar to samples 8-7, 8-8, 8-9, 8-10. Therefore, it can be inferred that during the typhoon event, sea floor sediment was re-suspended by wave and current action, and then available in the water as SPM with lower LOI value. Then, the impact of the typhoon on the depositional environment weakened gradually and the LOI of the samples increased gradually, until restored to the status of non-typhoon.

5.3 Settling phases during the typhoon event

The course of the typhoon controlled the changes in hydrodynamic environment in the study area. We could divide the whole course into several settling phases according to the changes of the SPM parameters. In this study, we used SPSS software to make hierarchical cluster analysis in terms of SPM fluxes, average grain size, sorting, skewness, kurtosis, and loss on ignition. All the variables were standardized to 0–1, and the distances of the sample were calculated by means of squared Euclidean distance. This method identifies relatively homogeneous groups of samples based on selected parameters, using an algorithm that starts with a sample in a separate cluster and combines clusters until only one is left. Distance or similarity measures are shown in horizontal axis in Fig.10. The results show that all the samples can be divided into three clusters, and each cluster stands for a phase of settling progress (Fig.10). The three phases were under strong (represented by samples 8-7, 8-8, 8-9), weak (by samples 8-10, 8-11, 8-12), and zero typhoon impact (other samples), respectively.

During the strong phase, the settling condition was severely affected by typhoon Muifa. Wind direction, wind speed, wave direction, and SWH changed greatly. This phase is characterized by high SPM flux, coarse grain size, poor sorting, less skewness, large kurtosis and low LOI.

During the weak phase, the power of the typhoon declined gradually, as seen from wind speed and SWH. All the parameters of SPM approached to normal values.

In the zero impact phase, all the parameters returned to their normal values and became stabilized, having low flux, very fine grain size, good sorting, large skewness, small kurtosis, and high LOI.

5.4 Comparison with other areas

Previous studies in other areas observed changes of SPM flux during typhoon event (Liu and Lin, 2004;

Fan, 2011; Lin et al., 2013). However, the results varied greatly because of different submarine topography and water depth. In Kaoping Submarine Canyon (southern coast of Taiwan Island), the maximum mass flux recorded by daily sampling exceeded 700 g/(m^2·d) due to delivery of lithogenic (siliciclastic) sediment from nearby Kaoping River (Liu and Lin, 2004). In Feitsui Reservoir in northern Taiwan Island, settling particles at depths of 20 m and 70 m were collected from sediment traps for a period of 406 days, during which seven typhoons visited (Fan, 2011), and the SPM fluxes were 10–120 g/(m^2·d) in 70 m, and 10–60 g/(m^2·d) in 20 m. The results reported here are in agreement with that of Fan (2011). Although in Fan's study, longer period of sediment trapping was deployed, the resolution was only a week, much lower than ours. Therefore, this research recorded a more detailed spectrum of a typhoon course in sedimentation flux in inshore area with valuable and trustable data.

5.5 Impacts on terrigenous sediment transportation

Typhoon event is very important to the transportation of terrigenous detrital sediments to deep sea and to southward in North Yellow Sea. The study area locates on the Shandong mud wedge, which extends southward from the northeast part of the Shandong Peninsula (Milliman et al., 1987; Liu et al., 2004; Yang and Liu, 2007). The Shandong mud wedge distributes along the shelf has been deposited mainly by the resuspended Huanghe (Yellow) River sediments carried down by the coastal current. Yang and Liu (2007) had studied this transportation process by remote sensing method. In typhoon events, large amounts of sea floor sediments, mainly composed of Huanghe River Sediments, resuspended into water and was transported by the currents. This transportation process differs greatly from the normal weather condition, and could explain why the Huanghe River-derived sediment could reach the -80 m water depth in the central South Yellow Sea, about 700 km from the river mouth (Yang and Liu, 2007).

6 CONCLUSION

SPM samples were collected with a well-designed sediment trap along with meteorological and hydrological parameters during super typhoon Muifa who swiped the inner shelf off Heini Bay. SPM flux, grain size component and distribution, and LOI parameters of samples were measured to reveal the

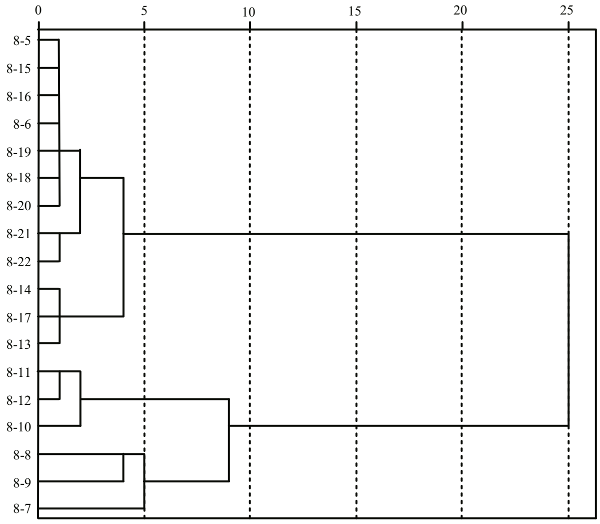

Fig.10 The division of the settling phase using cluster analysis

changing process of settling matters affected by the typhoon. Muifa disturbed local hydrodynamic environment severely, and then the settling process, of course. All the parameters changed under the typhoon condition and they are meaningful in explaining the course of sedimentation and resuspension.

During the typhoon Muifa event, all the SPM parameters changed regularly. In the first three days after the typhoon strike, SPM flux, average grain size, and kurtosis increased rapidly to the maximum; the sorting and skewness of samples became negative, LOI reduced to minimum value. In the next three days, SPM parameters decreased gradually to their normal values and then stabilized in the normal level about a week after. The average grain size, sorting, and kurtosis responded instantly to the typhoon course, while other parameters had different delay time by 1–3 days. We then divided the settling progress into three phases based on cluster analysis in terms of SPM parameters, i.e., strong (first 3 days), weak (second 3 days), and zero typhoon impact. This division was based on the results from meteorological and hydrological parameters and can be used to understand the role of these parameters in SPM flux variations.

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