Cross-shore variations in morphodynamic processes of an open-coast mudflat in the Changjiang Delta, China: With an emphasis on storm impacts

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Abstract

On the open coast of the Changjiang Delta, waves temporally play their dominant roles in shaping the tidal-flat profile, especially during typhoons. Detailed analyses are presented of the variations in grain sizes of surface sediments and bed level, measured in the summer of 1999 at Nanhui mudflats, south flank of the Changjiang Delta, China. Cross-shore variations in bed level are distinctly site-specific in response to waves. The site-specific erosion rates are related to local water depth, sediment properties, vegetation, and exposure time per semidiurnal tidal cycle. A great difference exists between the higher and lower intertidal mudflats bordered at the mean sea level (MSL): the higher section is dominated by continuous accretion, while the lower section is characteristic of dynamic changes in erosion and accretion phases. Swells play their more important roles in shaping the profile than local wind-driven waves at the study mudflat, where swells propagate onshore without great barriers’ damping and local winds are not highly strengthened by distant typhoons. Storm processes are greatly modulated by tides. The magnitude of erosion is greater by a weak storm during spring tides than a strong storm during neap tides. Significant changes in entrainment capacity of tidal currents from neap to spring tides account for the different erosion and accretion models of the intertidal mudflat.

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1. Introduction

Mudflats serve as buffers for sea defense, sinks of pollutants, nutrient traps and habitats of infauna which provide food for large communities of shorebirds. It is essential to understand and predict the response of the mudflats to accelerating rise of sea level, increasing storminess and anthropogenic activities. Although changes in mudflat profiles at different time scales have been widely studied in the past century, a reliable method to predict the effects of natural or artificial changes on the mudflat...
morphologies is still not solidly established (Roberts and Whitehouse, 2001). Several studies have recently been conducted on semi-enclosed mudflats to examine the development of long-term ‘equilibrium’ morphologies and controlling factors including physical forcing and sediment supply (Dyer et al., 2000; Kirby, 2000; Le Hir et al., 2000). Progress in numerical modeling has also recently been made to predict changes in the mudflat profiles over a relatively long term (several to tens of years) and large spatial (entire estuaries) scales (Roberts et al., 2000; Roberts and Whitehouse, 2001; Pritchard et al., 2002; Pritchard and Hogg, 2003; Yamada and Kobayashi, 2004). Simplification of external forcing is often made.

Variations in detailed small-scale morphologies over short terms are not well understood as compared to large spatial features over long terms. A better understanding of the small-scale short-term changes is crucial because of their direct interactions with intermittent wave processes, which are further complicated by tidal modulation (Ren et al., 1983; Wang, 1983; Shi and Chen, 1996; Bell et al., 1997; Green et al., 1997; Li et al., 2000; O’Brien et al., 2000; Kim, 2003). Wave-induced erosion changes significantly across shore due to variations in bed shear stress controlled by the interactions of tides and waves, bed shear strength influenced by the degrees of consolidation of cohesive fine sediments, and biological stabilization or destabilization. Recently, several field-oriented studies examined the interactions between waves and tidal currents, and their effects on the intertidal mudflat morphodynamics. The measurements continued during high-energy weather, especially during typhoons. Since the open-coast mudflats are subject to both swells and wind waves, different impacts of these two kinds of waves on the intertidal mudflats are also addressed. The bed level data are presented for each measurement sites instead of using an average over the entire intertidal zone. This is because the wave-induced erosion and accretion, also modulated by the tidal water level fluctuation, vary significantly across the shore. Surface sediment was sampled before, during and after storms to examine the sediment transport during typhoons. Our major objectives are to elucidate: (1) the effects of waves, especially typhoon-induced swells, on the open-coast, prograding intertidal mudflats with abundant riverine sediment supply, (2) the modulation of wave processes by tides, and (3) sediment transport during storms.

2. Study area and typhoon-induced swells

2.1. Study area

The Changjiang River carries an average annual sediment discharge of approximately $4.86 \times 10^7$ tons to its estuary. Nearly half of this sediment is deposited in the river mouth region to form a series
of longitudinal sand bars which bifurcate the river into four distributaries debouching into the East China Sea (Chen et al., 1999; Fig. 1). The mean tidal range is 2.6 m with a maximum of 4.6 m near the river mouth. Mean and maximum wave heights are 1.0 and 6.2 m, respectively, at Zhongjun Ship Gauging Station near the river mouth (Fig. 1), with an upstream decreasing trend (CCSA, 1997). Although the Changjiang Delta is a tide-dominated delta, both fluvial and wave processes play their significant roles in deltaic development. The delta area is significantly influenced by the monsoon, with southeasterly winds prevailing in summer and northwesterly winds in winter (Li and Wang, 1998).

Because of the abundant sediment supply, the delta front progrades seaward rapidly with the intertidal mudflats growing at an average rate of 20 km² per year in area. Land reclamation from the intertidal mudflats plays a crucial role in the mitigation of increasing land use in Shanghai. A total area of 840 km² had been reclaimed since 1950, with a mean annual rate approaching to the mudflat horizontal prograding rate (Fig. 1, CCSA, 1997). There is still about 800 km² of active intertidal mudflats fringing the delta. The seawalls constructed for reclamation are typically located at the mean high-tidal level, eliminating nearly all the supra-tidal mudflats, and part of the upper intertidal mudflats. An ambitious reclamation project has recently been carried out along the south bank of the Changjiang Delta. Alongshore seawall was constructed along the 0-m elevation contour (referred to Wusong Datum, WD), resulting in the loss of the entire natural intertidal mudflats.

Our field investigation was conducted just before this reclamation project. Variations in bed level were measured in detail along Donghai transect of Nanhui mudflats (Fig. 1). The intertidal zone extends 3.4 km from the seawall (Fig. 2). No large tidal channel exists at the intertidal mudflat, but small drainage creeks (ranging from 20 to 50 cm in depth) are common in the marshes. The mudflat can be subdivided into the upper, middle, and lower intertidal zones. The entire mudflat demonstrates an upper convex shape with a shoreward increasing trend of mean slope (Fig. 2). Approximately one-third of the area of the mudflat is colonized by vegetation. Directly in front of the seawall, Spartina alterniflora dominates a 700-m wide marsh area (M₁ in Fig. 2), follows with a Scirpus (Scirpus maritimus

Fig. 1. Mudflats flanking the Changjiang Delta and the location of the study transect.
and Scirpus triqueter) marsh of 450 m wide (M2 in Fig. 2), then gradually transits into a less-vegetated pioneer zone (M3) of about 150 m wide behind the bare mudflat. Single Scirpus stems can even survive near the neap low water elevation. The boundary between the mature marsh (M1 plus M2) and the pioneer marsh (M3) is located near the mean neap high water (Fig. 2).

2.2. Typhoons and their associated swells

Each year, an average of 28 typhoons (including tropical storms) develops over the western North Pacific Ocean and the South China Sea. The number of typhoons that have immense impacts on China’s coast reaches up to 16 annually. Roughly 7 out of 16 typhoons directly strike China’s coast with 95% of probabilities landing on the coast southwards from the Changjiang Delta. Others pass through Chinese marginal seas and hit the coasts of Japan or Korea. Typhoons usually have a lifespan of several days (Fig. 3), but sometimes can last for more than two weeks and travel a long distance before dissipation. Tropical storm-force winds can stretch out as far as 500 km from the center of a large typhoon, generating high waves over a wide area. Typhoon-induced swells can erode large amount of sediments and cause dramatic changes in the coastal morphology.

On average, two typhoons make landfall around the Changjiang Delta every year. The number of typhoons having significant influence on the deltaic coast is far beyond two, because typhoon-induced swells spread far out of their generated wind field. Nine tropical cyclones developed over the WN Pacific Ocean and the South China Sea during the field monitoring period May 24–August 28, 1999 (Fig. 3). Although none of the tropical cyclones struck the study area directly, seven of them induced waves over 2.5 m high in the inner shelf sea off the Changjiang Delta, where mean wave height is typically below 1.5 m. A maximum wave height of 5 m was reported when Typhoon Neil passed through the East China Sea (Table 1). TC2 and TC3, developed and traveled in the shelf sea off the east Japan coast, had limited impacts on the coast with a maximum wave height of 2 m.

3. Methods

Detailed bed level changes in the intertidal zones were monitored along the Donghai transect (Fig. 1).
Sixty-two graduated wooden stakes were established across the profile except the *Spartina* dominated marsh, where continuous accretion occurred without significant erosion owing to protection of high and dense vegetations. Each stake of 2 m long was struck into the mudflat sediment to a depth of 60–100 cm. Distance between two neighboring stakes was usually less than 50 m to provide information on small-scale morphodynamics. Bed level measurements were taken during daytime exposure. Not all 62 stakes were monitored every time, especially during neap tides when the upper mudflat was not inundated and the lower mudflat was not exposed. Small erosion holes were frequently observed in the vicinity of stakes, and depth and size of these scour holes varied at different stakes. During bed level measurements, a steel ruler was laid flat on the mudflat surface to serve as an average level of the adjacent sediment surface (except scour holes) relative to graduated stakes. The bed level obtained by stake scaling therefore represents an average of the nearby mudflat instead of the sediment level at the stakes. Height of each stake above the sediment surface (from the joint of the flat-laid ruler and the stake to the top of the stake) was recorded as \( H_i \) during each elevation.

### Table 1

<table>
<thead>
<tr>
<th>ID in Fig. 3</th>
<th>International name</th>
<th>Maximum wind speed (m/s)</th>
<th>Life span</th>
<th>Impact on the study coast</th>
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<td></td>
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<td>Peak wave heights and time</td>
</tr>
<tr>
<td>TC₄</td>
<td>Neil</td>
<td>25</td>
<td>7.22–28</td>
<td>5 m (7.26–7.27)</td>
</tr>
<tr>
<td>TC₆</td>
<td>Olga</td>
<td>35</td>
<td>7.29–8.04</td>
<td>3 m (8.02–03)</td>
</tr>
<tr>
<td>TC₇</td>
<td>Paul</td>
<td>28</td>
<td>8.03–09</td>
<td>3–4 m (8.05–07)</td>
</tr>
</tbody>
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Fig. 3. Passages and life-spans of tropical cyclones born in June, July and August, 1999.
monitoring. Bed level changes \((D)\) for each stake were calculated by \(\left( H_{i+1} - H_i \right)\). Erosion and accretion were denoted by negative and positive \(D\), respectively. It is worth noting that sometimes a negative \(D\) may result from consolidation instead of erosion at the upper mudflat. Resolution of the scaling ruler is 1 mm, but a higher error should be incorporated by averaging a wavy-bedformed area, especially after storms. Bed level data by individual stake measurements were smoothed by three point adjacent average to represent a general trend of mudflat’s profile changes.

The bed level measurements, with an interval of 1–3 days, continued from May 24 throughout August 28, 1999. Daily measurements were conducted from June 21 (ahead of the neap tide on June 23) to July 2 (just after the spring tide on July 1). This period was characteristic of calm weather in the summer monsoon season. Bed level was measured every two days from July 23 (neap tide) to August 13 (spring tide), spanning one and a half neap-spring cycles. This measurement period was characteristic of rough weather. Five tropical cyclones produced swells that had various degrees of impacts on the study area during this period. Except the above two measurement periods, bed level was monitored at intervals of 2–3 days. One measurement was always conducted during every neap and spring tides. Therefore, bed level changes over a 7-day (neap to spring tides or spring to neap tides) and 14-day (a spring-neap cycle) period can always be calculated from the present measurements. Here, \(D_{2–3}\), \(D_7\), and \(D_{14}\) were used to represent bed level changes over time intervals of 2–3 days, 7 days and 14 days, respectively.

Average bed level changes, i.e., average \(D_{2–3}\), \(D_7\), and \(D_{14}\), were calculated for each intertidal zone. These data were further used to calculate the activity \(\left( A \right)\) and preservation coefficient \(\left( K \right)\) based on the equations developed by Allen and Duffy (1998a), where \(A\) equals to \(\sum |D|\), and \(K\) is the ratio of \(\sum D\) and \(\Sigma D_+\) (the sum of the positive changes, i.e., accretion). The variations of \(A\) and \(K\) over different morphological zones and different monitoring intervals are discussed below.

Surface sediment samples were collected from four locations, at the middle of \textit{Scirpus} marsh (\(M_2\)), the pioneer marsh (\(M_3\)), the middle bare mudflat (\(B_{1/2}\) near the mean sea level), and the upper section of the lower mudflat (\(B_3\)). The sediment sampling was conducted typically several days before or after typhoons and also immediately after typhoons.

Carbonate and organic materials were removed by treatment with excess HCl and H\(_2\)O\(_2\). The suspension solution was repeatedly washed away with deionized water to neutral, and then dispersed for about 10 min in an ultrasonic vibrator. Grain size compositions of all pretreated samples were analyzed by a laser-diffracted size analyzer (LS230), with a measurement range of 0.4–2000 \(\mu\)m.

Wind speed and direction, and tidal elevations were obtained from the Zhongjun Ship Gauging Station (Fig. 1). The mean wind speed and dominant direction every 6 h at 2:00 am, 8:00 am, 14:00 pm, and 20:00 pm, were calculated based on measurements at a 10-min interval. The study coast trends in NW–SE. Therefore, northeasterly to southwesterly winds generate onshore flows. The wind direction in summer is dominantly onshore. A maximum wind speed of 16 m/s was recorded, but wind speeds seldom exceeded 10.8 m/s even during the passage of a distant typhoon.

Wave propagation over the intertidal mudflat was randomly observed visually to get general information for wave breaking and decaying, and wave height and period were only sporadically estimated. No other measured wave data were available from the nearby tide gauging stations. Routine daily forecasted waves \(\left( H_{1/10} \right)\) for the Changjiang delta-front area at depth of 5–20 m were therefore employed to discuss wave-climate changes during the study period, which can be accessed at the following internet address: http://dell1500sc.nmefc.gov.cn/sz/qh1.asp. A third generation wave prediction model developed by Key Laboratory of Geophysical Fluid Dynamics and Numerical Modeling, SOA, China, namely LAGFD-NWM, is applied to wave forecast, and the root mean square error (RMSE) for the predicted wave heights is meanly 16% (Yuan et al., 1992; Liu et al., 2002).

4. Short-term (1–2 days) variations in bed level

4.1. Daily bed level variations during calm weather

The monitoring from June 21 through July 2 in 1999 was performed during calm conditions between typhoon Maggie (TC\(_1\) in Fig. 3) and a tropical depression (TC\(_2\) in Fig. 3). Wave heights were generally less than 2 m (Fig. 4). Onshore winds dominated with wind speeds generally below 11 m/s except June 30 when a southeasterly wind of 13 m/s was measured. Offshore winds were subdominant but wind speeds up to 16 m/s were recorded at the
late night of June 29 and in the early morning of July 2, respectively (Fig. 4).

Bed level of the middle mudflat was monitored every two semidiurnal tides, except two visits: one tidal cycle between two continuous daytime low tides on June 30 and July 1, and four tidal cycles with a two-day interval between June 26 and 28. The upper and lower sections of the bare middle mudflat ($B_2$ vs. $B_1$), divided by the mean sea level (MSL), usually displayed different behaviors in accretion or erosion. Different erosion/accretion patterns were also measured between $M_3$ (the pioneer marsh) and $B_1$ (Fig. 5). The following discussion focuses on these three morphodynamic zones: $B_2$, $B_1$ and $M_3$.

$B_2$ was characterized by frequent alterations of erosion and accretion. Typically, accretion was measured when wave heights were less than 1.5 m (Figs. 5a, d, g, h and J), and erosion occurred when wave heights exceeded 1.8 m (Figs. 5b, c, e, f and i). The erosion rate demonstrated an apparent link to the tidal ranges. The profile was lowered by an average of 1.7 and 0.9 cm in the periods June 22–23 and June 23–24, respectively, during neap tides (Figs. 5b and c). An average thickness of 4.0 cm and 3.3 was eroded in the periods June 26–28 and June 30–July 1, respectively, near or during spring tides (Figs. 2f and i). Waves remained at 2 m high during these four separate events (Fig. 4). It was therefore inferred that erosion by large waves was modulated by tides in that larger tidal ranges resulted in greater erosion. No apparent relationship between wind conditions and bed-level changes was found at $B_2$. The daily maximum erosion and accretion rates reached up to 9.2 and 8.2 cm, respectively, at individual stake measurements, while a cumulative change of bed level was −0.9 cm during the study period. The erosion events were followed by accretion and vice versa, indicating that an “equilibrium” profile was maintained during the calm period.

An overall accreting trend was measured at $B_1$, with an average sedimentation rate of 5.7 cm during the monitoring period (Fig. 5). Waves were found not to be responsible for erosion except during June 23–24 (Fig. 5c). Erosion event during June 29–30 (Fig. 5h) might result from waves generated by local onshore winds with a peak speed of 13 m/s during the daytime high tide (Fig. 4). An offshore wind (southwesterly, perpendicular to the shoreline) with a maximum speed of 15.7 m/s might be the cause of erosion at both $M_3$ and $B_1$ during July 1–2 (Fig. 5j). However, another strong offshore wind (northwesterly, nearly parallel to the shoreline) with a maximum speed of 16 m/s did not induce extensive erosion except at two stakes where apparent erosion was measured (Fig. 5f). Erosion or accretion rates were found to increase from neap toward spring tides.

The pioneer marsh, $M_3$, had a similar trend of bed level variations as $B_1$ except with a smaller
Fig. 5. Daily changes in bed level of the middle intertidal mudflat (left column) during a relatively calm period June 21–July 2, 1999, with mean tidal ranges and wave heights in each monitoring period listed in right column. A smoothed curve was created by three point adjacent average, denoting a general trend of erosion and deposition across the profile. Three zones of the pioneer marsh, the upper and lower bare middle mudflats ($M_3$, $B_1$, $B_2$) had different accretion/erosion trends. Average daily changes in bed level over three morphological zones were calculated and marked above or below the curves.
magnitude (Fig. 5). A decrease in bed level typically resulted from erosion by offshore wind driven currents. Sometimes, consolidation accounts for the decrease in the marsh bed level due to exposure during neap tides. Fig. 5b provides an example of consolidation. The pioneer marsh was visited after a several-hour exposure to summer sun at noon. The daytime low water occurred at 2:00 pm on June 23 (Fig. 4). Also, a small magnitude (a few millimeters) of bed level changes can be associated with measurement errors.

4.2. Bed level variations in stormy conditions

During the monitoring period July 23–August 13, 1999, five tropic cyclones were developed in the WN Pacific Ocean (TC4–TC8 in Fig. 3). TC5 was a tropic storm with a maximum wind speed of 23 m/s and decayed rapidly after landing in Guandong Province (south China). TC8 was a tropic depression with a maximum wind speed of 15 m/s and dissipated rapidly after landing on Taiwan Island. These two tropical cyclones had limited impacts on the study coast. The remaining three tropical cyclones traveled north or northwest and hit the Yellow-Sea coasts of China or Korea (Fig. 3). Their wind speeds reached a maximum of 25, 35 and 28 m/s, respectively (Table 1). Because a new tropic cyclone came out before dissipation of the previous one waves remained higher than 2 m from July 24 to August 12, 1999 (Fig. 6). The largest waves were developed when these tropic cyclones were traveling across the East China Sea directly off the study coast (Table 1). However, local winds were not significantly strengthened by these distant typhoons (Table 1 and Fig. 6).

Significant variations in bed level were measured during this high-energy period (Fig. 7). Dramatic erosion occurred when the typhoon-induced swells entered the study area. When a peak swell of 5 m high, induced by typhoon Neil, hit the study area on July 26, the upper section of the lower mudflat (B3), M3 and B1 underwent erosion. Slight accretion was measured at B2 and M2 then (Fig. 7b). When swells decayed to 2.5 m from July 27 to August 1, the above erosion areas underwent accretion, and the previous accretion areas experienced erosion (Figs. 7c and d). These alternations of erosion and accretion were also measured during the following two typhoons. When swells induced by typhoon Olga peaked on August 2 with a maximum height of 3 m, erosion was measured at B1, B2 and B3, with a maximum at B2. The lower section of the lower mudflat (B4) accreted 2.5 cm on average, and M3 and M2 accreted 1.8 cm and 1.3 cm, respectively (Fig. 7e). This accretion/erosion trend was reversed during the following wave-decaying period August 3–5 (Fig. 7f). When waves were strengthened again by typhoon Paul and reached a maximum height of 4 m on
Fig. 7. Short-term (2–3 days) changes in bed level across the transect profile (left column) during a stormy period July 23–August 13, 1999, with mean tidal ranges and wave heights during each monitoring period listed in right column. Individual stake measurement data were analyzed by three point adjacent average to generate a smoothed curve, representing a general trend of erosion and deposition across the profile. Six morphological zones had different trends in response to typhoon-induced swells. Mean changes in bed level over these six zones were calculated and marked in the figures.
August 6, an erosion/accretion trend similar to that of typhoon Neil was measured (Fig. 7g). It was followed by a reverse trend of accretion and erosion when the swells decayed on the following days from 7 to 9 August (Fig. 7h). Accretion was measured over the entire intertidal mudflat except at a few stakes, when swells gradually decreased to below 2 m high (Fig. 7i). The above repeated data suggested that site-specific accretion and erosion at the mudflat were sensitive and responsive to typhoon-induced swells. Certain areas tended to be erosive during high-energy events, while other areas tended to be accretional. The rapid reversals of accretion and erosion by typhoons indicated that the intertidal mudflat maintained a ‘quasi-equilibrium’ state.

It was worth noting that wave processes were site specific and changed significantly among the three storm events. An accretion zone at $B_2$ was clearly measured during typhoon Paul at neap tides, separated in turn by the two erosion zones (Figs. 6 and 7g). Similar trend was also measured during typhoon Neil at intermediate tides (Fig. 6), but the transition was much smoothed out with an average bed-level change of nearly zero (Fig. 7b). Peak erosion occurred at $B_2$ with corresponding erosion zones at $B_3$ to $B_1$ during typhoon Olga just after the spring tide (Figs. 6 and 7c). Wave processes by typhoon Olga were the most intense in terms of the erosion rate, following with typhoons Paul and Neil. The heights of the swells, however, decreased from typhoons Neil, Paul to Olga (Table 1). Local winds were not sufficient to induce these seemingly reversed morphodynamical changes because they were not substantially strengthened by the distant typhoons and did not change significantly during these three storm events (Fig. 6, Table 1). The intense erosion by a relatively weak storm might be related to tidal modulation of wave processes. Strong spring tidal currents tended to transport more sediment farther out of the erosion sites than weak neap tidal currents, resulting in greater erosion.

The duration of high-energy conditions also played a role in the intensity of erosion/accretion events. Typhoon Paul caused two days of peak waves above the baseline height of 2.5 m, while one day for typhoon Neil (Fig. 3). The differences in peak wave sustaining periods might partly account for the slightly more erosion by typhoon Paul during neap tides than by typhoon Neil during intermediate tides (Figs. 7b vs. g).

5. Medium-term (fortnightly) variations in bed level

Bed level measurements were conducted at every spring tide during the period May 25–August 28, 1999. Especially, all 62 stakes were measured during the last three visits. Spatial variations in bed level at a spring-neap-spring cycle interval were shown in Fig. 8. The six zones defined by changing vegetation and tidal elevations had distinct patterns of erosion and accretion. Generally, the higher mudflat above the MSL was dominated by accretion, while erosion dominated the lower mudflat below the MSL. $M_2$ experienced continuous accretion regardless of wave climates. $B_1$ was dominated by accretion with only one exception of the six visits. Erosion played a dominant role at $B_2$ and $B_3$. The erosion rates were related to the intensity of swells and their peak time in the tidal regimes. Higher erosion rates were measured when the swells peaked just ahead of the spring tides. An example was shown in Fig. 8d. Less erosion was measured in other three cases when peak swells occurred up to five days ahead of the spring tides (Figs. 8a, e, and f). Accretion was sometimes measured when the mudflat has recovered to a ‘quasi-equilibrium’ profile after storms, such as $B_3$ during the period July 30–August 13. The lower section of the lower mudflat ($B_4$) seemed to be dominated by accretion suggested by the three measurements.

Bed-level variations at a fortnightly interval demonstrated somewhat similar erosion/accretion patterns of short term (1–2 days), but were much smoothed. The magnitude of erosion or accretion can be intensified by several superimposing erosion/accretion events, or mitigated by the tendency of the mudflat to maintain a ‘quasi-equilibrium’ profile.

6. Seasonal variations in bed level

Three morphological zones of $M_3$, $B_1$ and $B_2$ exhibited different erosion/accretion trends in response to hydrodynamic changes over daily to fortnightly scales (Figs. 5, 7, and 8). Seasonal changes in bed level were also quite different across these three zones (Fig. 9). The pioneer marsh ($M_3$) had much smaller bed level variations than the bare mudflat ($B_1 + B_2$). A general accretion trend was observed before July at $M_3$, while alterations of erosion and accretion in similar magnitudes were measured after July when the stormy season began. $B_1$ and $B_2$ demonstrated a similar pattern of bed level variations before July 6, with a higher
magnitude at $B_2$ than $B_1$. The accretion at $B_1$ and $B_2$ was 9.4 and 9.7 cm from May 25 to June 6, respectively. These two zones showed completely different patterns of erosion and accretion after June 6. $B_1$ underwent a general trend of accretion (accreting 3.6 cm), while $B_2$ suffered significant erosion and was on average lowered by 10.7 cm from July 6 to August 13. The dramatic changes in bed level before and after July 6 were related to seasonal variations in wave climates. There was only one distant typhoon that produced swells of 2–2.5 m high offshore the study coast from May 25 to June 6. On the contrary, seven tropical cyclones were generated and three of which produced peak waves of 5 m high from June 6 to August 13 (Fig. 3). Erosion by the swells occurred mainly below the MSL, which was exposed to strong waves for a longer time than above the MSL.

It was worth noting that mean bed-level changes of the bare middle mudflat ($B_1 + B_2$) demonstrated a similar trend as that of $M_3$. They both showed a weak average response to large waves. The reason for $M_3$ was that waves were greatly attenuated by bottom friction and the vegetation (Shi et al., 2000).
However, the decreased bed-level changes of the bare middle mudflat are caused by the cancellation while averaging the bed-level changes over two zones $B_1$ and $B_2$, which have completely opposite responses to large waves. The site-specific patterns of erosion and accretion should be emphasized when studying mudflat morphodynamics especially during stormy conditions.

Net changes in bed level from May 25 to August 28 showed that the upper and lower ends of the mudflat underwent accretion, while the middle sections ($B_2$ and $B_3$) were dominated by erosion in a stormy season (Fig. 10). The maximum accretion sites were located just seaward of $M_3$. The elevated $B_1$ favors seaward colonization of pioneer plants *Scirpus maritimus* and *Scirpus triqueter*, which in turn attenuate incoming waves to promote accretion. A high and convex cross-sectional shape was maintained even during the stormy season, facilitating the mudflat as a sediment sink where waves were greatly attenuated by bottom friction (Kirby, 2000).

7. Spatial and temporal variations in the sedimentary activity

The activity ($A$) and preservation coefficient ($K$) were calculated over the 3-month period at the different monitoring intervals of 2–3 days, 7 days and 14 days. Overall, they are quite site-specific and related to the monitoring intervals (Fig. 11).

Activity has its highest value over the 2–3 day monitoring interval, and declines as the monitoring intervals extend (Fig. 11). In a spring-neap cycle (14 days), there are typically 5–7 visits with a 2–3 day interval. These 5–7 visits record some erosion events by large waves together with some accretion events during calm conditions. $|D_{14}|$, equals $\sum |D_{2-3}|$, as expected, should be much less than $\sum |D_{2-3}|$ at a 14-day interval due to cancellation of some positive and negative $D_{2-3}$. $A_{14}$, sum of $|D_{14}|$, is therefore much less than $A_{2-3}$, sum of $|D_{2-3}|$, over the 3-month monitoring period. The time-scale attribute of Activity demonstrates that the mudflat is dynamic and responsive to wave climates over a short term, and becomes inactive and links to tidal cycles and sediment supply over a longer term. Changes in Activity over different time intervals are slight at $M_2$, because where sedimentation is mainly controlled by tides, and waves play their limited roles due to great wave damping by vegetation.

Spatial variations in Activity are marked over time intervals of 2–3 days and 7 days, and become slight over a fortnightly scale (Fig. 11). $A_{2-3}$ and $A_7$ have their highest values at $B_2$, and decrease landward and seaward. The trends link to short-term wave activities, which should have great impact on $B_2$ and decrease landward and seaward.

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Fig. 9. Cumulative changes in bed level of different zones in the middle mudflat with the monitoring intervals of 2–3 days (upper), and daily variations in wave heights from May 25 to August 13, 1999 (lower).
with tide modulation. $A_{14}$, mainly related to tidal activities, changes slightly over four bare-mudflat morphodynamical zones ($B_1$ to $B_4$), but decreases toward $M_2$ which is not flooded during neap tides.

Value $K$, the ratio of $\sum D$ and $\sum D_+$, is positive at $M_2$, $M_3$ and $B_1$ where net changes in bed level are positive, while $K$ and $\sum D$ are both negative at $B_2$ and $B_3$ (Figs. 10 and 11). The absolute values of $K$ increase as the monitoring time intervals increase, approaching to their maximum value of 1.0 at a fortnightly interval (Fig. 11). Preservation coefficient $K = 1$ represents that the study morphologic zones undergo continuous accretion, while $K = -1$ denote that continuous erosion occurs in the monitoring period. Value $K$ approaches to zero at $B_2$ and $B_3$ over the monitoring interval of 2–3 days, indicating that frequent alternations of erosion and accretion occur with the roughly identical magnitudes of accretion and erosion.

$B_4$ was monitored only at spring tides. It was accretional during the period, so value $K$ is positive (Fig. 11).

8. Spatial and temporal variations in grain sizes of surface sediment

Generally, surface sediments at the intertidal mudflat demonstrate a uni-modal grain-size distribution (Fig. 12). No terrigenous grains are coarser than coarse sand. The bare mudflat is mainly composed of very fine sand and coarse silt (3–5 phi). Slightly more sand was found at the lower mudflat, while slightly more silt was measured at the middle mudflat (pie charts $B_1$ and $B_3$ in Fig. 12). The mature marsh has much finer sediment than the bare mudflat, and is dominated by fine-to-coarse silt (4–7 phi). The pioneer marsh ($M_3$) has a grain size distribution much closer to the bare mudflat ($B_{1/2}$ and $B_3$) than to the mature marsh ($M_2$), but with silt as the dominant fraction. The modal size decreases landward from 3.91 phi at $B_3$ to 5.26 phi at $M_2$ (Fig. 12).

The grain size distributions were compared at four locations across the intertidal mudflat under five different wave conditions (Fig. 13). Five different wave conditions were (1) July 16, 10 days before typhoon Neil peaked; (2) July 28, one day after Neil; (3) August 3, immediately after Olga; (4) August 8, immediately after Paul; and (5) August 13, 5 days after Paul. Overall, the grain size distributions at the same location remained a similar shape over the different wave conditions (Fig. 13).

At $M_2$, the clay fraction remained the same after the storms (Fig. 13a). The sand fraction showed a slight increase from July 16 to 28 by 0.3%, and from July 28 to August 3 by 2.16%. The mean size and modal size showed little change before and after the typhoons.
At \( M_3 \), the modal size is nearly 4.5\( \phi \). Percentage of the sediments coarser than the modal size decreased from July 16 to August 13, 1999, compensated by an increase in finer sediments (Fig. 13b). \( M_3 \) generally became muddier after the typhoons. One exception occurred after Olga when \( M_3 \) became slightly sandier like \( M_2 \). The reason for this coarsening was that Olga occurred during spring tides and strong tidal currents entrained the coarser sediments resuspended from the bare mudflat shoreward.

\( B_{1/2} \) showed more complicated variations in grain size over the study period (Fig. 13c). Surface sediments became slightly muddier after Neil, but turned sandier after Olga and Paul. Sediment samples were taken near the MSL, where different phases and magnitudes of accretion and erosion occurred during the typhoons (Fig. 7). The muddier middle mudflat was related to a slight accretion during Neil (Fig. 7b). An increase in the sand fraction was related to the increasing erosion magnitude by Olga and Paul (Fig. 7e and g). The middle mudflat turned accretional and became muddier again after Paul. Grain size distribution on August 13, 5 days after Paul, was identical to that of July 16 (Fig. 13c), indicating the mudflat having a high resilience to normal conditions.

\( B_3 \) was slightly sandier during the typhoons than before or after the events (Fig. 13d). A small fluctuation in grain size parameters was examined to link to the erosion magnitudes. An decrease in the grain size fractions from 4.5\( \phi \) to 7\( \phi \) was compensated by an increase in the 3–4.5\( \phi \) fractions after the typhoons.

9. Discussions

9.1. Predominance of swells over local wind driven waves at the open coast mudflats

The study mudflat, facing the East China Sea, is exposed to offshore wave impacts. During the monitoring period, no tropic cyclone struck directly on the Changjiang Delta. Typhoon Olga has a closest tract to the study area, but the typhoon center was still several hundred kilometers away (Fig. 3). These distant typhoons did not result in any significant strengthening of local winds, but their swells had reached a maximum wave height of 5 m. These large swells were not greatly dissipated before shoaling on the intertidal mudflat. Our measurements showed that variations in bed level of the intertidal mudflat were highly responsive to swell heights. Under the relatively calm conditions,
Fig. 13. Temporal and spatial variations in surface sediment over a stormy period for the locations of $M_2$ (a), $M_3$ (b), $B_{1/2}$ (c), and $B_3$ (d). Sediment samples were taken on July 16 (10 days before typhoon Neil), July 28, August 3 and 7 (immediately after typhoons Neil, Olga and Paul), and August 13 (a week after typhoon Paul), respectively. Sampling locations described in Fig. 12.
the lower mudflat was dominated by erosion when wave heights exceeded 1.5 m. Under the stormy conditions, the mudflat was greatly lowered in the period of 1–2 days during typhoon peak stages. The zones of erosion turned rather rapidly into accretion after typhoon decaying even if wave heights remained above 1.5 m. Local winds and drainage processes might have limited impacts on the higher mudflat.

Our findings here are significantly different from semi-enclosed mudflats, where swells are substantially damped in the vicinity of the entrances of tidal basins (Ridderinkhof, 1998). Waves in the tidal basins are mainly generated by local winds blowing over the surface and enhanced by increased fetch as tide rises (Green et al., 1997; Christie et al., 1999; Le Hir et al., 2000; Roberts et al., 2000). Erosion and accretion of the semi-enclosed mudflats are close related to the local-wind driven waves, especially on a seasonal scale (Anderson et al., 1981; Anderson and Mayer, 1984; West and West, 1991; Allen and Duffy, 1998b).

9.2. Spatial variations in intertidal morphodynamic processes

Studies of seasonal erosion/accretion on intertidal mudflats were usually based on bed level monitoring data at a monthly (or longer) interval (e.g., Anderson et al., 1981). This paper focused on the impacts of intermittent waves on the mudflat at short-term intervals (usually 1–3 days) and fine spatial resolution. Our results showed that the mudflat’s response to waves was significantly site-specific. Based on cross-shore variations in accretion and erosion, together with changes in the vegetation cover and tidal elevations, the intertidal mudflat is subdivided into six zones. They are the mature and pioneer marshes ($M_1+M_2$ vs. $M_3$), the upper and lower sections of the middle bare mudflat ($B_1$ vs. $B_2$), and the upper and lower sections of the lower mudflat ($B_3$ vs. $B_4$). These different zones behaved in their respective ways no matter what wave climates were (Figs. 5 and 7). Cross-shore variations in accretion rates were obvious at all monitoring intervals from daily to seasonal scales (Figs. 5 and 7–10). In the long term, the mudflat demonstrated remarkable differences in annual vertical accretion rates among the higher and lower marshes, and the bare intertidal mudflat (Yang et al., 2001). The difference in accretion rates between the marshes and the bare mudflats was also reported at semi-enclosed mudflats, like the Severn Estuary (Allen and Duffy, 1998b).

A significant difference in morphodynamic processes exists between the higher and lower intertidal mudflats divided by the MSL. The higher intertidal mudflat, consisting of $M_1$, $M_2$, $M_3$, and $B_1$, is dominated by accretion events. So these zones have positive $K$ values (Fig. 11). $K$ approaches to its maximum value of 1.0 at $M_2$ when examined at a neap-spring tidal scale, indicating that the mature marsh is a continuous accretion environment. The maximum accretion rate was present at $B_1$, where a few erosion events were linked to typhoon-induced swells, strong offshore winds, and heavy raining (Fan et al., 2004). A high and accretional bare mudflat directly seaward of the pioneer marsh is crucial for sustaining seaward colonization of the pioneer plants, especially in the typhoon season from June to October each year, which coincides with the growing season for the pioneer plants Scirpus maritimus and Scirpus triqueter.

Large swells induced erosion at $B_2$ and $B_3$. Over a stormy period, negative net changes in bed level were measured, although areas of erosion rapidly became sites of accretion after the passage of peak typhoons (Fig. 9). Positive net changes in bed level were measured during calm weather. Net changes for the 3-month monitoring period were negative at $B_2$ and $B_3$, where value $K$ was also negative. At the monitoring interval of 2–3 days, $K$ approached to zero, indicating that the mudflat maintained a dynamic equilibrium during the typhoon season. In the non-typhoon season, the bare mudflat were accretional from October, 1999 to April, 2000 at another cross-section of Nanhui mudflats, 5-km north of the Donghai transect (Zhu et al., 2001). Both $B_2$ and $B_3$ are therefore characteristic of seasonal alternations of erosion and accretion with a positive annual sedimentation rate, contributed mostly from the non-typhoon season.

The lower section of the lower mudflat ($B_3$) was monitored only by a few visits when it was exposed during the spring low tides. These limit measurements suggested that net bed level change and $K$ value were positive. They are different from the changes measured at $B_2$ and $B_3$.

It is noteworthy that both $A$ and $K$ are not only different across six morphological zones, but also vary as the monitoring intervals change (Fig. 11). A seasonal alteration of $K$ in the study area was determined by Zhu et al. (2001). In the Severn Estuary, both $A$ and $K$ changed from one transect to
another along the bare mudflats and the marshes (Allen and Duffy, 1998a). The coefficients of $A$ and $K$ were considered to be important factors in simulation models of mudflat-marsh growth (Allen, 1990; French, 1993; Allen and Duffy, 1998a). Selection of $A$ and $K$ values for the numerical modeling should include their temporal- and spatial-scale attributes. Our findings here confirm the conclusions of de Vriend (1991, 1998) that time and space tend to be linked. Routine and/or periodic sampling strategies addressed to certain objects should be made based on the linkage between space and time scales.

9.3. Effects of wave-and-tide interactions on morphodynamics and sediment transport

Wave processes in the study mudflat were greatly related to tidal fluctuations. Wave breaking is considered to be a depth-dependent process, and the breaking limit is typically set at $H/h=0.8$, where $H$ is wave height and $h$ is water depth (Weggel, 1972; Wells and Kemp, 1986; Le Hir et al., 2000; Kim, 2003). For a gentle-slope muddy coast, waves experience strong damping by passing energy to the liquefied mud layer (Wells and Kemp, 1986; Li and Mehta, 1997), and it tends to have a lower $H/h$ value than that of a steeper beach profile (Le Hir et al., 2000). The study transect has a very gentle ($<0.001$) and wide subtidal zone (Figs. 1 and 2). Surface sediments are mainly composed of silt and fine sand. Bottom fluid mud layer was frequently observed even under small wave conditions. Offshore swells were therefore significantly damped after propagating over the gentle and muddy subtidal zone (Fig. 14). Assuming depth-limited breaking, wave heights on the intertidal mudflats should be maintained at a constant fraction of the local water depth regardless of incident wave heights (Black and Rosenberg, 1992; Le Hir et al., 2000). The intensity of wave processes within the wave-breaking zone could therefore be related to the water depth controlled by the fluctuating tidal levels, regardless of the intensity of storms. Our findings that the erosion rate was greater for a weak storm during spring tides than a strong storm during neap tides confirmed the concept of depth-limited breaking (Fig. 14). Similar results were observed by Kim (2003) in a Korean macrotidal mudflat.

Based on field measurements, Chen et al. (1989) suggested that wave erosion occurred mainly within the wave-breaking zone, and the suspended sediments were dispersed out of the wave-breaking zone by tidal currents (also see Shi and Chen, 1996). The wave-breaking zone shifted several to tens of hundred meters up and down slope in the study coast as the tides flooded and ebbed during a tidal cycle (Mao, 1987; Yang, 1997). Generally, there were two accretion zones and one erosion zone, located at the higher intertidal mudflat (above the MSL), the subtidal zone, and the lower intertidal mudflat, respectively (Fig. 14). Chen W (1991) gave a similar morphodynamic model for storm wave impacts on the mudflats in the Hangzhou Bay (also see Shi and Chen, 1996). Sediments at the erosion zone after typhoons were slightly muddier because finer sediments were inputted from the erosion zone.

Local winds were not significantly strengthened by distant typhoons, and the coastal setup was limited. Moreover, high turbulence by wave processes could prevent formation of returning flows at the bottom in the shallow water. Therefore, the proposed offshore-directed currents by wind-induced circulation or turbidity currents during storms (Swift et al., 1983; Walker, 1984; also see Fig. 11.5 in Boggs, 2001) were supposed to be absent or at least insignificant in the shallow gentle coast. The redistribution of suspended fine sediments out of the wave-breaking zone was considered to be mainly controlled by tidal currents. Onshore sediment transport by flood currents could be augmented by onshore wind forcing and wave propagation. The existence of the inner muddier accretion zone indicated onshore sediment transport occurred during the typhoons. Laboratory experiments by Van Rijn (1985) and Mehta (1996) showed that the fluid mud layer could also be transported shoreward (upslope) against gravity under wave action (also see Van Rijn, 1998). Offshore transport occurred in the ebbing tidal regime. Vertical current circulation predicted by the geostrophic model could not develop in the shallow water and should not account for offshore transport (also see Gagan et al., 1990; Keen and Slingerland, 1993).

Entrainment capacity of onshore currents differed greatly from neap to spring tides. Such might result in different erosion/accretion models in the intertidal mudflats. Resuspended sediments tended to settle quickly out of high turbidity current near the wave-breaking zone with weak flood currents.
during neap tides, forming a middle accretion zone in the lower section of the middle mudflat ($B_2$). Reforming waves might break again and produce an inner erosion zone in the upper section of the middle mudflat ($B_1$). Accretion in the inner accretion zone was limited (Fig. 14b). The middle accretion zone during neap tides was displayed by a neutral accretion/erosion zone during the intermediate tides with increasing entrainment capacity by flood currents (Fig. 14c). This middle accretion zone disappeared toward spring tides, and the erosion zone also shifted upslope due to increasing tidal ranges (Fig. 14d). Strong spring tidal currents seemingly transported more sediment farther out.
of the erosion zone, resulting in higher magnitudes of both erosion in the lower mudflat and accretion in the higher mudflat.

It was also noteworthy that the eroded materials could be replenished just in a few days after the typhoons with the erosion zone turning into an accretion zone. In the Changjiang Delta, the flood season coincides with the typhoon season. Huge riverine sediment input could make it possible for the mudflats recovering to their ‘quasi-equilibrium’ profile to normal wave conditions in several tides after the typhoons, even if some resuspended sediments had been taken by ebb currents far away from where could be transported back easily.

10. Conclusions

Intertidal mudflats can be exposed to swells or local wind-driven waves. Meso-tidal mudflats in the Changjiang Delta, facing the East China Sea without barriers, are subject to great impacts of offshore swells especially during the summer monsoon season. Variations in bed level of the intertidal mudflat have a strong relationship with wave heights. Erosion switches on when waves exceed 1.8 m high during non-typhoon conditions. Serious erosion takes place during typhoon peak periods. Erosion zones rapidly turn into accretion sites after the typhoons’ dissipation. Except annual average of two typhoons making landfall on the study coast, several distant typhoons potentially induce large swells in the study coastal sea, producing major morphological changes and sediment transport in the mudflat. Local winds are usually insignificantly strengthened by distant typhoons, and have limited impacts on the mudflat.

Consequences of wave processes tend to have small spatio-temporal features. Our interpretations are based on single stake measurements with short-term intervals and small distance between two adjacent stakes. Results show that cross-shore variations in bed level are distinctly site-specific in response to waves. The site-specific erosion is related to local water depth, sediment properties, vegetation, and exposure time per tidal cycle. Six zones of the intertidal mudflat are divided on the basis of above-mentioned factors. They are the mature and pioneer marshes \( M_1 + M_2 \) vs. \( M_3 \), the upper and lower sections of the bare middle mudflat \( B_1 \) vs. \( B_2 \), and the upper and lower sections of the lower mudflat \( B_3 \) vs. \( B_4 \). These zones have different magnitude and phase of erosion and accretion in each bed-level measurement. The calculated net change \( \sum D \), Activity \( A \) and preservation coefficient \( K \) are quick different among six zones over the three-month monitoring period. \( K \) is positive and increases as the monitoring intervals increase at the higher mudflat (above the MSL) with accretion dominated. \( K \) is negative at the lower mudflat (below the MSL) where erosion is dominant during the stormy season. Statistics over two or more zones or over a longer-term scale will blunt the mudflats’ sensitivities to intermittent wave processes.

Wave processes are greatly modulated by tides. Wave heights and the intensity of wave processes at the intertidal mudflats are related to the local water depth regardless of incident wave heights. The magnitude of erosion is greater for a weak storm during spring tides than a strong storm during neap tides. The redistribution of resuspended fine sediments out of the wave-breaking zone is mainly controlled by tidal currents. Entrainment capacity of onshore currents differs significantly from neap to spring tides, accounting for different erosion and accretion models at the intertidal mudflat. Weak neap tidal currents tend to form the middle accretion zone by rapidly settling of suspended sediment from high turbidity water near the wave-breaking zone, and the inner erosion zone by reforming waves. Strong spring tidal currents transport more sediment farther out of the erosion zone, resulting in higher erosion rate at the wave-breaking zone and higher accretion rate in the marshes.

Typhoon season coincides with river flood season and the growing season of pioneer plants. The lost materials can be replenished by huge riverine sediment input, and the mudflat recovers to its ‘quasi-equilibrium’ profile to normal wave conditions in several tides after the typhoons. The maximum accretion site is located just ahead of the pioneer marsh over the monitoring period. The elevated bare mudflat favors seaward colonization of pioneer plants. A high and convex profile is maintained even in the stormy season.

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