Transport and flux of suspended particulate matter (SPMs) are important but hotly debated topics in the Bohai Sea (BS), Yellow Sea (YS) and East China Sea (ECS). In this study, we calculated the sediment flux and its seasonal variation combining observed suspended sediment concentration (SSC) with numerically simulated currents. Field observations were conducted in the BS, YS and ECS at 43 stations in summer and 46 stations in winter along five transects. HYCOM/NCODA reanalysis data were used to calculate climatologically monthly averaged currents in January and July from 1998 to 2007. The results indicated that a high concentration of SPM moved out of the BS and moved southward into the YS and ECS in winter, with a net sediment flux of 0.12 t/s at the Bohai Strait and 4.37 t/s south of the Yangtze River. In summer, SSC increased from the surface to the bottom layer due to stratification. A southerly wind and stronger warm currents in summer transported SPM from the ECS to the YS and the BS, with a net northward sediment flux of 4.79 t/s at the boundary of the ECS and the YS, and a net sediment flux of 0.08 t/s input into the BS. This study can help to distinguish the contribution of the Yellow River- and Yangtze River-derived sediments to the mud-areas’ generation on the continental shelves area of the Yellow Sea and East China Sea. Copyright © 2016 John Wiley & Sons, Ltd.

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KEY WORDS suspended particulate matter; flux; seasonal variation; vertical distribution; numerical model; Yellow Sea; East China Sea

1. INTRODUCTION

Transport and flux of suspended particulate matter (SPMs) are important for marine ecology and material recycling (Lee et al., 1981; Su, 2005; Dong et al., 2011). In the Bohai Sea (BS), Yellow Sea (YS) and East China Sea (ECS), suspended sediments are mainly delivered by the two largest rivers in East Asia, the Yellow River and the Yangtze River, with annual sediment inputs of $1.1 \times 10^9$ and $4.8 \times 10^8$ t, respectively (Milliman and Meade, 1983; Saito and Yang, 1995). In addition, SPM resuspended from the seabed, especially at the old Yellow River mouth ($0.5 \times 10^9$ t/a) in winter, is another important sediment source (Wang and Jiang, 2007).

A large amount of work has been conducted on the SPM distribution, transport and flux in the BS, YS and ECS. Unfortunately, sediment flux calculation is particularly difficult for in situ and synchronous observations on suspended sediment concentration (SSC) and currents at each station along a transect. Thus, scientists try to use numerical models to simulate sediment transport and calculate its flux. Zeng et al. (2015) used a wave–current–sediment coupled model to study the transport of the Yellow River- and Yangtze River-derived sediments in the BS, YS and ECS over the past several decades. They concluded that about 3% (13.75 Mt/year) of the sediments delivered by the Yellow River entered the Yellow Sea, 1.17 Mt/year of it subsequently passed the Taiwan Strait into the South China Sea. Of the mean Yangtze River-derived sediment of 267.72 Mt/year, 8% (21.85 Mt/year) entered the YS, and 32% (87.00 Mt/year) passed through the Taiwan Strait. Wang and Li (2009) reported that about 4% of the Yellow River-derived sediment was transported to the YS through the Bohai Strait. Based on a three-dimensional sediment transport model, Zhou et al. (2015) pointed out that approximately 16% (133.00 Mt/year) of Yellow River-derived sediment was transported out of the Bohai Strait, of which around 44% (57.2 Mt/year) was finally transported to the South Yellow Sea. Based on observed SSC and simulated
currents, Li et al. (2015a) concluded that the net sediment flux dispersed into the YS was about 2.51 Mt/year. Pang et al. (2011) used an improved method to calculate the three-dimensional (3D) suspended sediment flux from ocean colour remote sensing and in situ observations. They concluded that the long-term transport of suspended sediment was controlled mainly by local circulation pattern, especially the currents in winter. However, in a sediment numerical model, only a few classes of sediment, sometimes just one class, were considered, and some sediment processes (e.g. flocculation) are not included. Furthermore, an abundance of sediment on the seabed can be eroded without consolidation, which can result in an overestimated sediment flux.

Muddy patches, located at the northern BS, southern YS, Yangtze estuary and Zhe-Min coast (Fig. 1), are recognized as sediment sinks on the continental shelves of the ECS.

Figure 1. Map of the Bohai Sea, Yellow Sea and East China Sea, showing currents and location of observation stations along transects T1, T3, T4, T7 and T10. Open squares for stations in winter and filled triangles for stations in summer. Currents in winter—black lines with arrows denote cold coastal currents, while red lines with arrows denote warm intrusion currents and mud areas shown in grey shading. Star A indicates the location of ADCP observation. ZMCC: the Zhe-Min Coastal Current, which flows southward in winter carrying cold, low-salinity water and northward in summer. TWC: the Taiwan Warm Current, which flows northeastward along the isobaths of 50–100 m (Su and Pan, 1987) with high-temperature, high-salinity water all year round. The Kuroshio Current carries high-temperature, high-salinity water, a branch of which enters the YS named as the Yellow Sea Warm Current (YSWC; Su, 2001; Yuan and Hsueh, 2010). YSCC: the Yellow Sea Coastal Current, which flows southward in winter and northwestward in summer. M1 shows the western Bohai Mud Area; M2, the northern Yellow Sea Mud Area; M3, the southern Yellow Sea Mud Area; M4, the southwest Cheju Island Mud Area, and M5, the Zhe-Min Coast Mud Area.
Sediment sources and contributions of the Yellow River and Yangtze River to the mud area generation are hot topics. Sediment magnetic analysis, X-ray diffraction mineralogical analysis, cores and dating methods are widely used to trace sediment transport (Liu et al., 2007a, b; Xu et al., 2009). However, not much has been done on SPM transport flux, especially based on observed data.

To better estimate the sediment transport in the ECS, we calculate the sediment flux and its seasonal variation, combining the observed SSC with numerically simulated current in this study. The field data used were measured in July 2006 and January 2007, which is described in Section 2. Vertical distributions of fluxes, together with fluxes at five transects in winter and summer, are described in Section 3. Sediment flux and its contribution to the mud area generation are discussed in Section 4.

2. MATERIAL AND METHODS

2.1. Data sources

Field observations were collected in the BS, YS and ECS at 43 stations in summer and at 46 stations in winter along five transects (Fig. 1). Section T1 is at the interface between the BS and YS, which is the only pathway for the sediment from the Yellow River into the YS. Section T3 is located in the southern YS, which crosses one of the largest and most important mud areas on the continental shelves of the ECS. Section T4 is at the interface between the YS and ECS, which is the only pathway for sediment from the Yellow River to the mud area generation are hot topics. Section T7 and T10 are perpendicular to the coastline and can be used to study the southward transport of Yangtze River-derived sediment in winter and the northward transport of Taiwan River-derived sediment in summer. All the surveys were finished within 38 days, from 28 June to 31 July in 2006 and from 6 January to 13 February in 2007 (Table 1). Considering the absence of strong wind (thus no high waves) and heavy rain (thus small sediment discharge) in the study area during the surveys (Yang and Zhou, 2007), the observed results can be shown in one contour plot, as done in other studies (Lim et al., 2007; Qiao et al., 2010; Dong et al., 2011; Li et al., 2013).

Water temperature, salinity and SSC were measured at each station during each cruise. Vertical distributions of temperature and salinity were measured by SBE-911 plus CTD (Sea-Bird Electronics Inc., USA). At each station, the instrument was released at a uniform speed using a winch. The vertical resolution of the data was higher than 0.1 m. Water samples were taken by CTD at each station at depths of 1, 10, 20, 30, 50, 75, 100, 150, 200, 300 and 500 m and in the bottom layer. Then, the mass concentration of suspended particles for each sample was collected by membrane filtering and by drying and weighing in the laboratory.

HYCOM/NCODA reanalysis data are composed of the 1/12° global HYbrid Coordinate Ocean Model (HYCOM) and the Navy Coupled Ocean Data Assimilation (NCODA) system (http://hycom.org/dataserver/glb-reanalysis). Surface forcing of the numerical model is from 1-hourly National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) with a horizontal resolution of 0.3125°, which includes wind stress, wind speed, heat fluxes and precipitation. NCODA uses the model forecast as the first guess in a 3D variation scheme and assimilates available satellite altimeter observations and in situ sea surface temperature (SST) as well as available in situ temperature and salinity (vertical) profiles by Argo floats and moored buoys (Fox et al., 2002; Cummings and Smedstad, 2013). HYCOM/NCODA reanalysis data supply daily 3D ocean temperature, salinity, currents, surface mixed layer and mesoscale features, such as eddies, meandering currents and fronts (Metzger et al., 2010). Because of the isopycnal-sigma-pressure coordinate used, this model has high vertical resolution in coastal regions (Large et al., 1997; Chassignet et al., 2007). Climatologically, monthly averaged currents in January and July from 1998 to 2007 were used to calculated sediment fluxes in winter and summer, respectively.

Table 1. Observation time periods

<table>
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<th>Transect</th>
<th>Winter cruises</th>
<th>Summer cruises</th>
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<tr>
<td>Transect</td>
<td>Start time</td>
<td>End time</td>
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2.2. Model validation

HYCOM/NCODA-reanalyzed currents compared well with those based on satellite altimeter data and observation data in the ECS (Yin, 2014). To further validate the model result, we collected the observed currents from 17 to 31 August and 17 to 31 December, 2012, respectively, in summer and winter, at Station A (Fig. 1) in the southern YS. Currents at Station A were observed by an Acoustic Doppler Current Profiler (ADCP), and detailed observation settings can be found in Li et al. (2015c). Comparison of daily averaged vertically integrated currents between the model and observations show a good agreement (Fig. 2), which indicates that the HYCOM/NCODA-reanalyzed currents can be reasonably used to calculate the sediment flux.

2.3. Flux calculation

To verify the sediment transport pattern, we calculated depth-integrated sediment flux at each station in July 2006 and January 2007, respectively, using the following equation (Harris et al., 2008):

$$F_s = \int C Udz$$

(1)

where $F_s$ is the depth-integrated sediment flux per unit width at each station; $C$ is observed SSC; $U$ is the monthly mean current velocity, whose direction is transformed to be normal to the transect, and $H$ is water depth. Since the observation of SSC were almost finished within 1 month in each season, the monthly averaged current in January and July representing winter and summer, respectively, was used to calculate the sediment flux.

Integrated net sediment flux along the whole transect is calculated by

$$F_T = \int \int C Udz ds$$

(2)

Figure 2. Comparison of HYCOM-simulated daily averaged currents with observations.
Figure 3. HYCOM-simulated currents: (a) at surface and (b) in the bottom layer in winter; (c) at surface and (d) in the bottom layer in summer.
Figure 4. Vertical distributions of water temperature (°C; left panels) and salinity (psu; right panels) in winter for the five transects T1, T3, T4, T7 and T10.
Figure 5. Vertical distributions of water temperature (°C; left panels) and salinity (psu; right panels) in summer for the five transects T1, T3, T4, T7 and T10.
where $F_T$ is depth-transect-integrated net sediment flux and $S$ is the distance between the first station and the last station along a transect.

3. RESULTS

3.1. Hydrologic environment and its seasonal variation

In winter, one of the most important characteristics of the hydrologic environment in the ECS is that cold coastal waters flowing southward coexist with warm water intrusion flowing northward (Fig. 3a). The Kuroshio Current can be found in the upper layers along transect T10 with a central water temperature of 25 °C (Fig. 4a and e'). A branch of the Kuroshio Current became the Taiwan Warm Current (TWC), which flowed northward through the central and eastern transects T10 and T7, respectively (Fig. 4a and d), and even reached the eastern part of transect T4 (Fig. 4c). The Zhe-Min (Zhejiang-Fujian) coast water was controlled by the cold and hypohaline Zhe-Min Coastal Current (ZMCC) flowing southward (Fig. 4d-e'). In the YS, the warm current could even intrude into the YS in the bottom layer via the Yellow Sea Warm Current (YSWC) with a central water temperature of 10.8 °C and salinity of 33.2 psu (Practical salinity units) (Fig. 4b and b'). This warm current could reach the Bohai Strait but was blended with the surrounding waters (Fig. 4a and a'). Due to the strong northerly winter wind, the cold BS water flowed out of the BS through the southern Bohai Strait (Fig. 4a), moving southward passing through transect T3 (Fig. 4b and b') and then moving southeastward towards transect T4 (Fig. 4c and c'). Cold and hypohaline water could be found at Station w0404 of transect T4 (Fig. 4c and c'). Thus, thermohaline fronts could be found between the nearshore cold water and offshore warm water.

In summer, stratification can be found in the ECS due to strong surface heating. The northward TWC was strengthened because of the summer monsoon (Figs. 3b and 5e and d). The YSWC became weaker and was replaced by cold water masses in the bottom water along transects T4 (Fig. 5c), T3 (Fig. 5b) and T1 (Fig. 5a), which were reported as the Cold Eddy in southwest Cheju Island, the South Yellow Sea Cold Water Mass and the North Yellow Sea Cold Water Mass, respectively. These cold water masses were below the thermocline at a water depth of 15 to 20 m; they were also characterized by high salinity (Fig. 5a', b' and c').

During our observation in summer, Typhoon Ewiniar moved on a generally northward track passing through the ECS (Fig. 6) during 9–10 July, which was the third named storm in the 2006 Pacific typhoon season. Observations along transects T7 and T10 were just 1 day and 8 days ahead of Ewiniar, and observations along T4 and T3 were 1 day and 4 days after the typhoon, respectively. The salinity in summer in the surface layer had obviously low values of 1.2–8.9 psu at transect T7 and 1.9–16.8 psu at transect T10, which indicates a heavy precipitation induced by Ewiniar.

3.2. Vertical distribution of SSC and its seasonal variation

High concentrations of SPM can be found in the shallow waters of the southern Bohai Strait (Fig. 7a), which could be caused by strong waves and currents in winter. Together with the eastward current off the northern Shandong Peninsula at this area, as shown in Figure 2a, the southern strait is recognized as an important path for the Yellow River-derived sediments transported to the YS. In the central strait, SSC was lower than 4 mg/l. Comparing with high vertical mixing in winter, SSC increased from surface to bottom layer in summer (Fig. 7a'), but was much smaller than that in winter.

Coastal currents flowed southeastward, taking high concentration of SPM to the South YS in winter (Fig. 7b and 7c). SSC at Station w404 could reach 30 mg/l. In summer, high concentration SPM along transects T3 and T4 can be...
Figure 7. Vertical distributions of SSC (mg/l) in winter (left panels) and in summer (right panels).
found in the front area between the cold water mass and coastal current (Fig. 7b’ and c’). Furthermore, SSC was more than three times higher than the value in winter, which may have been induced by Typhoon Ewiniar.

In the ECS, most of the SPM was trapped by the front at 122.5°E between the coastal current and the TWC in winter (Fig. 7d). On the seaward side of the front, SSC was lower than 2 mg/l. A similar situation can also be found along transect T10. The high concentration in the bottom layer of Station w1005 may have been caused by the Taiwan River-derived sediments (Fig. 7e). Due to the strong wind of Typhoon Ewiniar (Fig. 6), the SSC in the bottom layer of T7 increased (Fig. 7d’).

3.3. SPM flux and its seasonal variation

SPM fluxes in winter and summer were calculated using the method described in Section 2.2, respectively (Fig. 8). In winter (January), SPMs were transported out of the BS, with a net sediment flux of 0.12 t/s; most sediments moved eastward from the BS to the YS through the southern part of the Bohai Strait, while some sediments moved from the YS to the BS through the northern strait (Fig. 8a). This ‘north-in-south-out’ pattern of sediment flux resulted from the circulation in winter (Fig. 3a and b). Sediments from the BS, combined with the old Yellow River sediments, moved southward along the western YS to the ECS with a sediment flux of 1.25 t/s (Table 2). The northward sediment flux along the offshore stations of transects T4 and T3 (Fig. 8a) might be induced by the YSWC (Fig. 3b). Most of the Yangtze River-derived sediments moved southwestward in winter because of strong coastal currents induced by the northerly winter wind (Fig. 3a). Along transect T7, the net sediment was 4.37 t/s. Large northward sediment flux can be found in the TWC and Kuroshio Current along transect T10 (Fig. 8a), with a net flux of 7.12 t/s. However, the northward sediment transport was weak along transect T7, which supports the weaker TWC in winter (Bao et al., 2015).

The sediment transport patterns varied obviously from summer to winter (Fig. 8b). In summer (July), only some sediment moved from the BS to the YS via the southern Bohai Strait, most of the sediment was transported into the BS through the northern Bohai Strait. The net sediment flux was 0.08 t/s. Due to the southerly summer wind, sediments were transported northward across the transects in the ECS (Table 2), with net sediment fluxes of 2.23 and 13.35 t/s across transects T7 and T10, respectively. Large sediment fluxes of 64.5 and 68.9 g/s/m can be found at stations in the TWC and Kuroshio Current (Fig. 8b).

4. DISCUSSION

We can estimate the yearly sediment flux using 6-month winter flux plus 6-month summer flux. There were in total 0.30 and 0.01 t/s (Table 2) sediments in winter and summer, respectively, transported from the BS to the YS through the Bohai Strait. Thus, the total sediment transported to the YS was about 4.72 Mt/a, which was 2.67% of 177 Mt/a (the annual averaged Yellow River-derived sediment during 1998–2007). This proportion is close to the result of Zeng et al. (2015), which is 3%. However, the amount of sediment is smaller than that of Zeng et al. (2015), 13.75 Mt/a, because the Yellow River-derived sediments used in his model is temporally averaged from 1966 to 2005, with the annual value of 447 Mt/year. Our result is also smaller than the value of 133 Mt/a simulated by Zhou et al. (2015), the reason should be an overestimated sediment flux caused by an abundance of sediment on the seabed in the numerical model. Yearly sediment passing through transect T4 to the ECS was about 1.95 × 10^7 t/a. Considering the old Yellow River mouth could supply sediments of 0.5 × 10^9 t/a, the sediments travelled to the ECS account for 2.89% of the modern and old Yellow River-derived sediments.

An elongated distal subaqueous mud wedge extending from the Yangtze River mouth southward off the Zhejiang and Fujian coasts into the Taiwan Strait (Fig. 1), which is referred to as the Zhe-Min Mud Area. The total mass of this distal mud wedge was about 5.4 × 10^{11} t (Liu et al., 2007a,b). Due to the northerly wind in winter, Yangtze River-derived

<table>
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<th>Transect</th>
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<th>Summer (t/s)</th>
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<tr>
<td></td>
<td>Net flux</td>
<td>Total positive flux</td>
</tr>
<tr>
<td>T1</td>
<td>0.12</td>
<td>0.34</td>
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<tr>
<td>T3</td>
<td>0.32</td>
<td>0.39</td>
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<tr>
<td>T4</td>
<td>1.60</td>
<td>2.57</td>
</tr>
<tr>
<td>T7</td>
<td>−4.37</td>
<td>1.65</td>
</tr>
<tr>
<td>T10</td>
<td>7.12</td>
<td>8.24</td>
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Table 2. Sediment flux at each transect (total positive value indicates eastward or northward sediment flux normal to the transect, while total negative value indicates westward or southward sediment flux normal to the transect)
Figure 8. Depth-integrated SPM flux at each station in (a) winter and (b) summer (units: g/s/m). The bars in blue indicate northward or eastward SPM transport, while the bars in red indicate southward or westward SPM transport.
Sediment was transported southward at transect T7 via a flux of 6.02 t/s, thus a annual flux of 93.6 Mt/a, which accounts for about 24% of the yearly Yangtze River-derived sediment, 390Mt/a. Taking the southward transport sediment of 1.12 t/s, thus 17.4 Mt/a at transect T10 into account, the net sediment transported to the Zhe-min mud area is about 76.2 t/a in winter. Via a flux of 4.75 t/s, which is equivalent to an annual flux of 7.38 × 107 t/a. Assuming all of these sediments were deposited in the mud area for 7000 years, the Yangtze River-derived sediments thus contributed to 98.8% of the mud area generation in the southern YS and northern ECS, which indicated the overestimation of the contribution of the Yangtze River-derived sediments.

Note that, although the daily wind effect was taken into account in the HYCOM/NCODA currents, the relatively mild conditions in the observation of SSC may have resulted in an underestimate of sediment flux, especially during winter storms and typhoons (Xu et al., 2016). Furthermore, no tidal currents were included in the HYCOM/NCODA product. Thus, the effect of tidal residual currents on the sediment transport flux was not discussed in this study, although a good agreement between model and observation results (Fig. 2) indicates a negligible effect of tidal residual current in this area.

5. CONCLUSIONS

In this paper, we described the vertical distribution of SPM at five transects in the BS, YS and ECS. We calculated the sediment flux and its seasonal variation by combining the observed SSC with numerically simulated currents.

In winter, one of the most important characteristics of the hydrology environment in the ECS is that nearshore cold coastal waters coexist with offshore warm water intrusion. Coastal waters carrying high concentration of SPM moved out of the BS and flowed southward in the YS and ECS, with net sediment fluxes of 0.12 t/s at Bohai Strait and 4.37 t/s south of the Yangtze River.

In summer, the water column is well stratified, and SSC increases from the surface to the bottom layer. Furthermore, high concentration of SPM in the southern YS can be found in the front area between the west boundary of the cold water mass and the coastal current. During the observation, SSC in the southern YS and northern ECS were influenced by Typhoon Ewiniar, with three times higher SSC in the bottom layer than the value in winter. However, because of strong stratification, it was hard for the high concentration SPM to spread to the surface layer. Due to the southerly derived summer wind, SPMs were transported ‘backward’ from the ECS to the YS and BS, with a net northward sediment flux of 4.79 t/s at the boundary of ECS and YS and a net sediment flux of 0.08 t/s into the BS.

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REFERENCES


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