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Seasonal Transfer and Net Accumulation of Suspended Sediment in the Yellow and East China Seas

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ABSTRACT: The monthly mean suspended sediment flux, then net deposition or erosion driven by shelf circulation in the YECSs are attained via retrieval of remote sensing data, statistical analysis of historical data, and numerical simulation of circulation velocity. Furthermore, five representative subareas are selected to quantify the annual mean circulation-driven accumulation rates. The results on deposition or erosion manifest that during the summer half-year, significant deposition only occurs along the coast, while during the winter half-year, significant deposition occurs not only along the coast, but also offshore areas with water depth of deeper than 100 m, such as the SWCIM, which is acknowledged as the only mid-shelf modern depocenter in the YECSs. The seasonal variability in net deposition or erosion of suspended sediment implies that riverine suspended sediment is stored inshore in summer and transported to offshore in winter in the YECSs, which is consistent with the widely accepted viewpoint. The estimated accumulation rates only driven by the shelf circulation at five subareas are 0.51 mm/yr in the SWCIM, 0.45 mm/yr at the cross-shelf pathway, 0.04 mm/yr in the CYSM, 3.62 mm/yr in the Changjiang Estuary, and 3.83 mm/yr off the Zhejiang Coast, respectively, which agree with measured ones reasonably well.

Keywords: Seasonal transfer, Net accumulation, Suspended sediment, in the Yellow and East China Seas

1 INTRODUCTION

The Yellow and East China Seas (YECSs) are semi-enclosed wide shelf seas with seasonally variable hydrodynamic features, and relatively high suspended sediment concentration (SSC). On an annual basis, these seas receive approximately 10^9 tons of terrigenous material from neighboring rivers but mostly from the Changjiang and Huanghe rivers, and about 0.5×10^9 tons from coastal erosion at the Jiangsu coast of the Old Hunghe delta (Milliman and Meade, 1983). The transportation of fine-grained sediments derived from these rivers is controlled by estuarine processes, tidal currents, shelf circulation, and episodic storm/typhoon events. Because of the large discharge (up to about 10% of the world's river sediment load) and complex sedimentation processes, the Yellow and East China Sea shelf has attracted many geological research projects, yielding a better understanding of sedimentary processes in this ancient epicontinental setting (Hu, 1984; Milliman et al., 1985a,b; Yang et al., 1992; Saito et al., 1995; Shi et al., 2003; Lim et al., 2007; Liu et al., 2007; Yuan et al., 2008; Pang et al., 2011; Bian et al., 2013).

Surface sediments in shelf areas of the YECSs are dominated by fine-grained mud except for relict sands on the middle and outer shelf zone (Lim et al., 2007). The most characteristic feature of the continental shelf is the existence of two isolated mud patches (>6-7 phi in mean grain size) associated with coastal mud belts and open shelf mud patches, which are the Central Yellow Sea Mud (CYSM) and the Southwestern Cheju Island Mud (SWCIM), located in deeper continental shelf areas of the YECSs. They are formed by specific sedimentation mechanisms (i.e., a cyclonic gyre upwelling/downwelling processes) and consist mainly of clay-sized material finer than other deposits of the region (Hu, 1984; Shi et al., 2003). Their sediments are considered to be derived primarily from the Huanghe or Changjiang Rivers, or both, based on the circulation pattern in the central Yellow Sea and spatial distributions of various sedimentological, clay mineralogical, and geochemical attributes (Milliman et al., 1985a,b; Lim et al., 2006; Liu et al., 2007). In comparison with the CYSM whose maximum accumulation rate is less than 2 mm/yr and mean rate is about 1 mm/yr, the SWCIM is the only modern depocenter far from the coast or sediment source, due to its high accumulation rate of up to 5 mm/yr (Lim et al., 2007).

In this paper, the seasonal transfer and net accumulation of suspended sediment in the YECSs are explored by calculating the suspended sediment flux, which might provide the explanation on the formation of distinctive modern depocenter SWCIM.

2 METHODS

2.1 *The flux of total suspended sediment in the YECSs*

Generally, the shelf circulation dominates the advection and long-term fate of suspended sediment in shelf seas, whereas the wave action and tidal currents govern re-suspension and vertical diffusion. This study would highlight the long-term transport and fate of suspended sediment in the YECSs, and pay attention to circulation-induced transport. The transport of suspended sediment could be expressed quantitatively as the suspended sediment flux (SSF).

The flux of total suspended sediment is calculated using the method established by Pang et al. (2011). Firstly, the 3D suspended sediment concentration (SSC) is estimated by surface suspended sediment concentration inverted from SeaWiFS (Sea-Viewing Wide Field-of-View Sensor) ocean color remote sensing data, and vertical distribution of suspended sediment concentration determined by statistical analysis of historical observation data. Secondly, the 3D shelf circulation is numerically simulated. The 3D suspended sediment flux is eventually attained by the product of 3D SSC and circulation velocity. The seasonal variability for both SSC and circulation in the YECSs is significant and one order of magnitude larger than the inter-annual change, so all time series data have been processed into multi-year monthly mean dataset, and the simulated circulation is climatological monthly mean.

The evaluation of SSF largely depends on the accuracy of simulated shelf circulation. Hence, in this paper, the climatological monthly-mean circulation data in the YECSs simulated with ROMS (Regional Ocean Modeling System), are provided by Yang (Yang et al., 2011), which are considered as the best simulation results to be consistent with observations. In comparison with Pang et al. (2011)'s result, the SSF in this study might be upgraded by enhancing the accuracy of simulated circulation with the substitution ROMS for the POM (Princeton Ocean Model).

The multi-year monthly mean SSF driven by the shelf circulation in the YECSs, excluding the wave motions and tidal currents with short time scales (from seconds to hours), are attained via retrieval of SeaWiFS remote sensing data, statistical analysis of historical SSC data, and 3D ROMS numerical simulation of circulation velocity. The horizontal resolution of the SSF is 5' × 5'and the same as the ROMS numerical simulation for circulation.

2.2 *The deposition or erosion of suspended sediment in the YECSs*

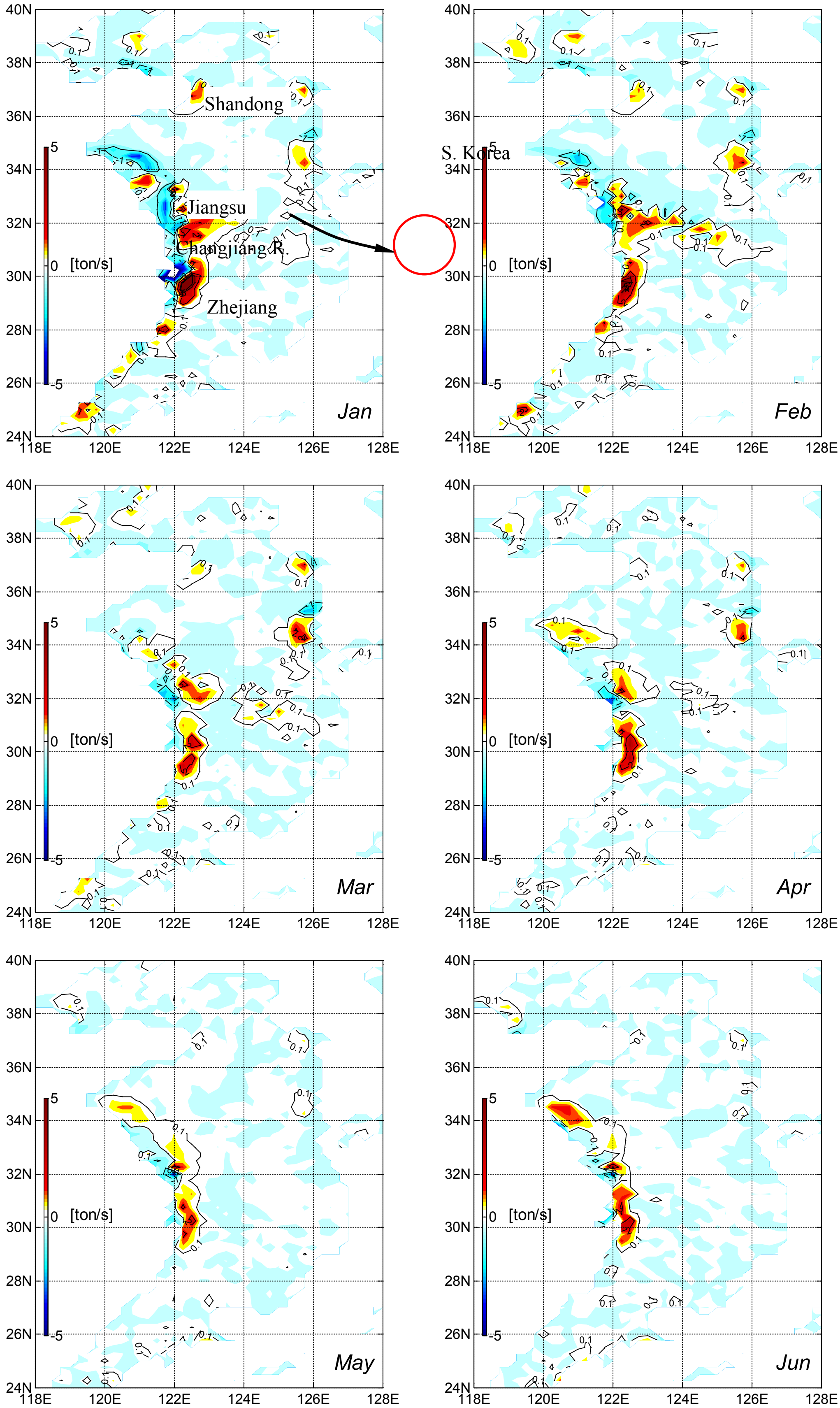
Based on the SSF, monthly mean net deposition or erosion could be computed. The monthly mean net deposition (positive) or erosion (negative) at each model grid is defined as the sum of the differences of SSF between two adjacent sections in the X (east-west) and Y (south-north) directions. For simplicity, the horizontal resolution for net deposition or erosion is assumed as 1/4 degree, 15'× 15', while the net deposition or erosion of suspended sediment are resolution-dependent, and more schemes on horizontal resolution should be tested.

Furthermore, five representative sedimentation areas with distinct hydrodynamic conditions and sediment characteristics, especially including the Central Yellow Sea Mud (CYSM) and the Southwestern Cheju Island Mud (SWCIM), are selected to testify the validity of this paper's approaches, and quantify the annual mean accumulation rates by comparing with the measured ones derived from the previous studies.

3 RESULTS

3.1 *Monthly mean net deposition or erosion in the YECSs*

The calculated results on deposition or erosion in the YECSs manifest that during the summer half-year (from May to Oct.), significant deposition (> 0.1 ton/s) only occurs along the coast, especially the Jiangsu coast and Changjiang Estuary, while during the winter half-year (from Nov. to next Apr.), significant deposition occurs not only along the coast, but also offshore areas with water depth of deeper than 100 m, such as the Southwestern Cheju Island Mud (SWCIM), which is acknowledged as the only mid-shelf modern depocenter in the YECSs.



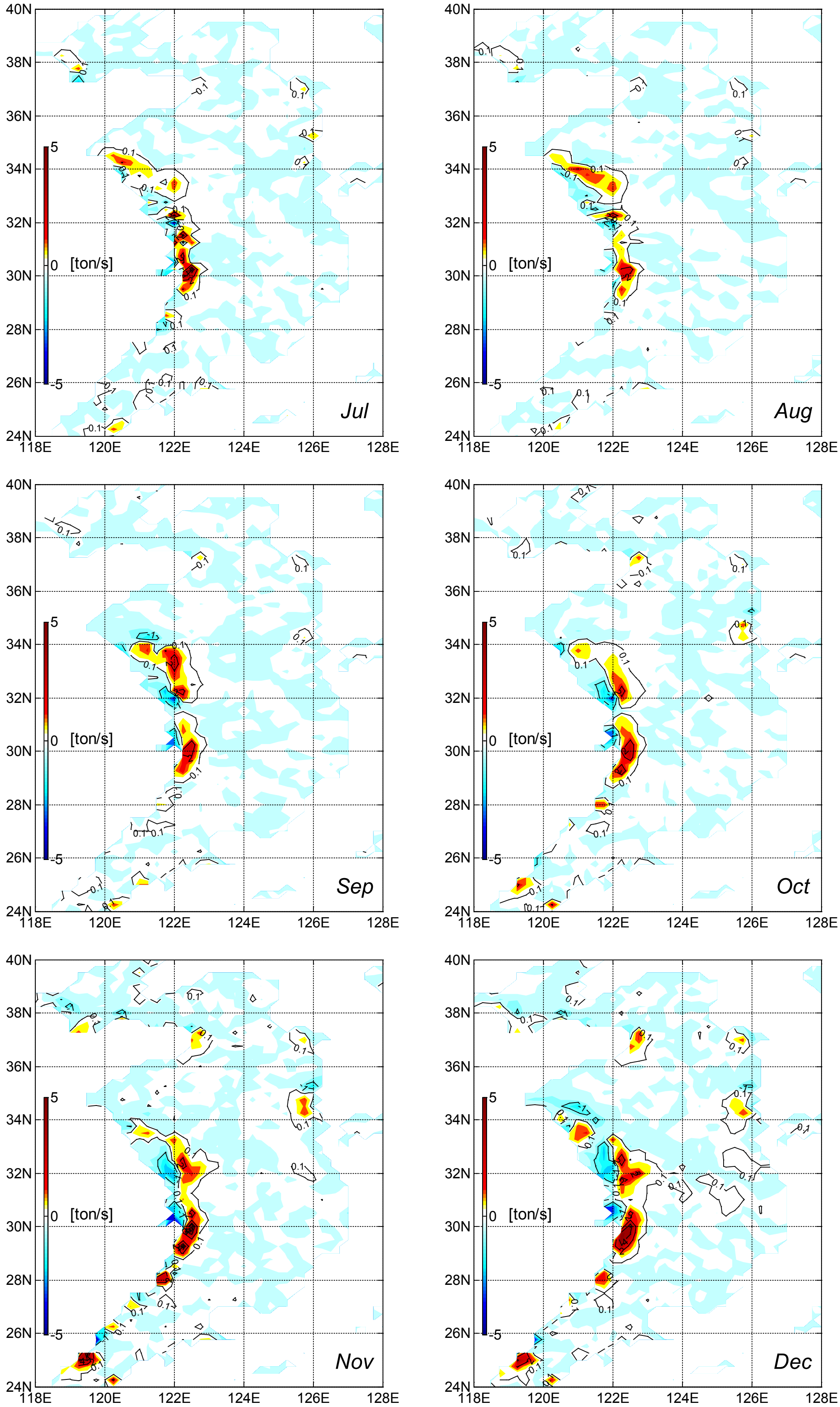


Figure 1. Monthly mean net deposition or erosion at each model grid in the YECSs, which is the sum of the differences of SSF between two adjacent sections in X and Y directions. Red: deposition; blue: erosion (unit: ton/s; resolution: 15'× 15').

The annual cycle in net deposition or erosion of suspended sediment in the YECSs is significant (shown in Figure 1), from the minimum in May, then a slow increase only along the Jiangsu Coast and Changjiang Estuary throughout the whole summer (June, July and August) and till September, in October deposition occurring in other nearshore areas except the Jiangsu Coast and Changjiang Estuary, in November a little deposition appearing in the offshore area, such as the SWCIM (shown as the circle in Figure 1), then to the maximum in net deposition or erosion during the entire winter (December, next January and February), in March and April a slow decline in the whole YECSs.

The January and July will be taken as representative months, respectively for winter and summer. In January, net deposition or erosion of suspended sediment is the maximum due to the highest SSC and strongest circulation driven by winter monsoon in the entire YECSs. The evident erosion, even larger than 1 ton/s occurs in the shallow water of less than 20m along the Jiangsu coast, Changjiang Estuary, and Hangzhou bay. Then the net heavy deposition appears adjacent to these erosion areas with the maximum deposition near the Zhoushan Islands (around the 30°N). The Yellow Sea (or Subei) Coastal Current with high SSC flows southeastward along the Changjiang Bank, causing significant deposition extend eastward from the Jiangsu coast and Changjiang Estuary (shown as black arrow in January of Figure 1). The isolated significant deposition (>0.1 ton/s) exists at the end of the Changjiang Bank, which almost coincides with the location of the SWCIM (shown as the circle in January of Figure 1). Furthermore, the broad deposition areas along the coast are generally consistent with notable modern depocenters in the YECSs, including the mud wedge off the southeast of Shandong Peninsula, the Southeastern Yellow Sea Mud located off the southwestern coast of the South Korea, and the Zhejiang Coast Mud.

In July, net deposition or erosion of suspended sediment is small due to the low SSC and weak circulation in the entire YECSs, but not the minimum because of heavy sediment load discharged from the Changjiang River in flood season. Hence, the heavy deposition only occurs at the Changjiang Estuary with water depth of less than 20 m, and the light deposition also appears at the old Huanghe Estuary. The annual cycle and seasonal variability in net deposition or erosion of suspended sediment imply that riverine suspended sediment is stored inshore in summer and transported to offshore in winter in the YECSs, which is consistent with the widely accepted viewpoint by many researchers (Yang et al., 1992; Liu et al., 2007; Yuan et al., 2008; Pang et al., 2011; Bian et al., 2013).

3.2 *Five representative deposition areas*

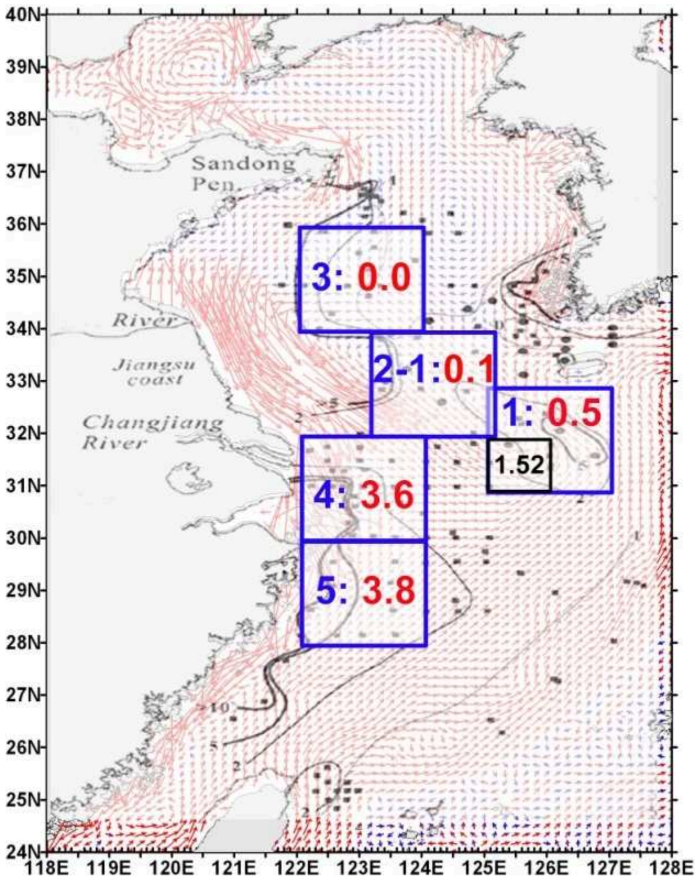


Figure 2. The location of five subareas and their annual accumulation rates (in red numbers) in the YECSs. The arrows show the SSF vectors in January. The contour is the annual accumulation rate (mm/yr) described by Lim et al., 2007.

Five representative locations (2°×2°) are chosen as Figure 2, depending on their hydrodynamic conditions and sediment characteristics. No.1: the SWCIM area, also known as East China Sea Cold Eddy Mud area (31°-33°N, 125°-127°E), No.2: cross-shelf sediment transport pathway (32°-34°N, 123°-125°E), No.3:

the center of the southern Yellow Sea, almost the same location as the Central Yellow Sea Mud (34°-36°N, 122°-124°E), No.4: the Changjiang Estuary (30°-32°N, 122°-124°E), No.5: off the Zhejiang Coast (28°-30°N, 122°-124°E).

The monthly mean net deposition of suspended sediment (See Table 1.) generated just by the circulation at five subareas implies the distinctive seasonal variation with high deposition in winter and low in summer except for the Changjiang Estuary, which testify the above-mentioned viewpoint of riverine suspended sediment storing inshore in summer and transporting to offshore in winter in the YECSs, once again.

The annual accumulation rates (Table 1 and red numbers in Figure 2) at five representative locations, which is the sum of all seasons (unit: mm/yr), display that the high rates exist at the Changjiang Estuary (No. 4 subarea, 3.62 mm/yr) and off the Zhejiang Coast (No. 5 subarea, 3.83 mm/yr) due to the abundant sediment supply from the Changjiang River, the lowest rate being at the center of the southern Yellow Sea (No. 3 subarea, 0.04 mm/yr) due to the far distance from the coast and almost no availability of sediment. Just a little sediment accumulates annually at the cross-shelf pathway (No. 2 subarea, 0.45 mm/yr), which was defined firstly by Yuan et al. (2008). Additionally, the location of west boundary of No. 2 subarea which is near the suspended sediment sources, is crucial to calculating the net deposition, thereby the accumulation rate at named as No. 2-1 subarea will be 0.11 mm/yr if the west boundary moves 10 minutes (about 10 nautical miles) eastward, whereas the rate at No. 2-2 subarea will greatly increase to 0.76 mm/yr if it moves 10 minutes westward. Although the East China Sea Cold Eddy Mud area (SWCIM, No. 1 subarea) is farther away from the coast, and deeper than 100 m, its accumulation rate of 0.51 mm/yr is not the lowest. Furthermore the rate in the southwestern part of No. 1 subarea that is indicated as No. 1-1 subarea, even could reach to 1.52 mm/yr. During the winter half-year (from Nov. to next Apr.), under the action of winter monsoon the re-suspended sediment derived from the old Huanghe Estuary is delivered by the Yellow Sea Coastal Current across the shelf, and subsequent routes to the No. 1 subarea, where the re-suspended sediment is caught and convergent by the East China Sea Cold eddy, eventually deposited, causing relatively high accumulation rate in comparison with the Central Yellow Sea Mud area (No. 3 subarea).

As shown in Figure 2, the estimated accumulation rates only driven by the shelf circulation in the YECSs agree with the measured ones (presented in Lim et al., 2007) reasonably well. Nevertheless, the discrepancy might be yielded by the inaccuracy in simulated circulation, and the other excluded dynamic controlling factors, for example wave motion and tidal currents. The tidal current is generally regarded as the dominant hydrodynamic factor, which controls sediment transport, especially in shallow waters, or inshore area.

Table 1. Monthly mean net deposition (ton/s) and annual accumulation rate (mm/yr) of suspended sediment at five representative locations in the YECSs.

No.	1	2	3	4	5	2-1	2-2	1-1
Jan.	**2.55**	**6.90**	**-0.74**	**-0.62**	**24.47**	**2.59**	**8.52**	**1.84**
Feb.	**5.51**	**3.27**	**-0.33**	**15.29**	**28.16**	**0.33**	**4.97**	**4.60**
Mar.	**6.04**	**2.36**	**0.31**	**9.72**	**12.32**	**-0.28**	**4.59**	**4.53**
Apr.	**1.42**	**1.28**	**0.54**	**17.12**	**9.65**	**1.38**	**2.41**	**0.89**
May	0.33	0.78	0.23	13.79	5.67	0.68	0.87	0.30
Jun.	-0.18	0.39	0.28	21.86	3.41	0.33	0.40	0.17
Jul.	-0.27	0.42	0.35	25.27	4.04	0.40	0.51	0.14
Aug.	-0.28	0.25	0.60	12.77	3.14	0.19	0.34	0.06
Sep.	0.02	0.61	0.58	5.31	10.45	0.38	0.81	0.09
Oct.	0.32	0.40	0.33	9.22	13.20	0.23	0.93	0.37
Nov.	**1.60**	**0.78**	**0.01**	**4.87**	**17.62**	**-0.33**	**2.79**	**0.44**
Dec.	**3.56**	**1.12**	**-0.35**	**13.12**	**24.05**	**-1.46**	**3.90**	**2.02**
Net deposit	20.6	18.6	1.8	147.7	156.2	4.4	31.0	15.5
Accumu-rate	**0.51**	**0.45**	**0.04**	**3.62**	**3.83**	**0.11**	**0.76**	**1.52**

Note: The monthly mean net deposition during the winter half-year (from Nov. to next Apr.) in bold font.

4 CONCLUSIONS

The seasonal transfer and net accumulation of suspended sediment in the YECSs are explored by calculating the multi-year monthly mean SSF, then net deposition or erosion at each model grid. Furthermore, five representative deposition areas with distinct hydrodynamic conditions and sediment characteristics, especially including the CYSM and the SWCIM, are selected to quantify the annual mean circulation-driven accumulation rates.

The calculated results on deposition or erosion in the YECSs manifest that during the summer half-year (from May to Oct.), significant deposition only occurs along the coast, especially the Jiangsu coast and Changjiang Estuary, while during the winter half-year (from Nov. to next Apr.), significant deposition occurs not only along the coast, but also offshore areas with water depth of deeper than 100 m, such as the SWCIM, which is acknowledged as the only mid-shelf modern depocenter in the YECSs. The annual cycle and seasonal variability in net deposition or erosion of suspended sediment imply that riverine suspended sediment is stored inshore in summer and transported to offshore in winter in the YECSs, which is consistent with the widely accepted viewpoint.

In January, net deposition or erosion of suspended sediment is the maximum due to the highest SSC and strongest circulation driven by winter monsoon in the entire YECSs. The Yellow Sea Coastal Current with high SSC flows southeastward along the Changjiang Bank, causing significant deposition to extend eastward from the Jiangsu coast and Changjiang Estuary. The isolated significant deposition formed by the convergency of the East China Sea Cold eddy exists at the end of the Changjiang Bank, which almost coincides with the location of the SWCIM. Furthermore, the broad deposition areas along the coast are generally consistent with other notable modern depocenters in the YECSs.

The estimated accumulation rates only driven by the shelf circulation at five representative deposition areas in the YECSs are 0.51 mm/yr in the SWCIM area, 0.45 mm/yr at the cross-shelf pathway, 0.04 mm/yr in the CYSM area, 3.62 mm/yr in the Changjiang Estuary, and 3.83 mm/yr off the Zhejiang Coast, respectively, which agree with the measured ones reasonably well.

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