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Net accumulation of suspended sediment and its seasonal variability dominated by shelf circulation in the Yellow and East China Seas

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ABSTRACT

The seasonal transfer and net accumulation of suspended sediment, especially the forming mechanism of the Southwestern Cheju Island Mud (SWCIM) are investigated using multi-year monthly mean suspended sediment flux to establish the linkages between sediment transport and hydrodynamic conditions and to determine the dominant long-term sediment transport process in the Yellow and East China Seas (YECSs). The more accurate suspended sediment flux, and net deposition or erosion driven by shelf circulation in the YECSs are attained using 10-year time series data on surface suspended sediment concentration and more reliable numerically simulated circulation velocity.

The calculated net deposition or erosion of suspended sediment with distinct seasonal variability in the YECSs demonstrates that during the wintertime significant deposition occurs not only along the coast, but also offshore areas with water depth of about 100 m, such as the SWCIM, which is acknowledged as the only mid-shelf Holocene depocenter in the YECSs. The annual cycle of net deposition or erosion verifies the widely accepted viewpoint, that riverine suspended sediment is stored in the inner shelf, especially adjacent to the estuary in summer and transported to middle or outer shelf in winter in the YECSs. Active sediment-transport process and the forming of the SWCIM mainly influenced by shelf circulation have been reproduced using the vector field analysis on suspended sediment flux. In winter, the Yellow Sea Coastal Current with high suspended sediment concentration flows southeastward along the Changjiang Bank, and interface with the Yellow Sea Warm Current to drive the East China Sea Cold Eddy at the end of the Changjiang Bank, which contributes to the convergency of suspended sediment, eventually generating the SWCIM. The circulation-driven accumulation rates in the YECSs are 0.51 mm a^{-1} in the SWCIM area, 0.45 mm a^{-1} at the cross-shelf pathway, 0.04 mm a^{-1} in the Central Yellow Sea Mud area, 3.62 mm a^{-1} in the Changjiang Estuary, and 3.83 mm a^{-1} off the Zhejiang Coast, respectively, which agree with the measured ones reasonably well, and further reveal that shelf circulation dominates long term sediment transport. Some uncertainties on the accuracy of suspended sediment flux and influence of tidal residual currents should be resolved in the future study to achieve a more quantitative picture about sediment transport in the YECSs.

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). The YECSs receive 0.2×10^{10} t a^{-1} sediments before 1990s, supplied mainly by the Changjiang River (0.48×10^{9} t a^{-1}; Milliman and Meade, 1983), the Huanghe River (0.11×10^{10} t a^{-1}; Milliman and Meade, 1983) and the erosion of the Old Huanghe Delta (0.5×10^{9} t a^{-1}; Saito and Yang, 1995). Although the amount of terrigenous sediment has dramatically declined over the past two decades due to anthropogenic activities especially the Huanghe River (Wang et al., 2010), the huge sediment load and complex sedimentation process have still attracted many research projects, achieving a better understanding of sedimentary processes in this continental shelf setting (Lim et al., 2007; Yuan et al., 2008; Dong et al., 2011; Pang et al., 2011; Bian et al., 2013a, 2013b).

The transport of fine-grained suspended sediment in the YECSs is controlled by estuarine processes, wave action, tidal currents, shelf circulation, and episodic events (storm, typhoon, etc.). Therefore part of difficulties in understanding the suspended sediment transport in the YECSs is the complexity of the hydrodynamics and its strong seasonal variability. Generally speaking, the tides and waves have an important effect on the nearshore sediment suspension. Strong

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tidal currents can readily suspend or resuspend nearshore sediments (Larsen et al., 1985; Yuan et al., 2008). Wind-generated waves in winter can induce strong bottom shear stresses which tend to resuspend the loosely consolidated sediment; this is also an important factor for resuspending sediment in the YECSs near coastal area (Bian et al., 2010; Li et al., 2010; Wang and Jiang, 2008). However, the subtidal currents (shelf circulation) play a significant role in transporting the terrigenous sediment to the outer seas, which are crucial to long-term sediment transport. In the present study, we pay attention to the shelf circulation controlling long-term sediment transport in the YECSs.

The sediment transport process in the YECSs has been widely researched by geological sampling, hydrodynamic measurement, remote sensing and numerical modeling since 1980s. The regional geological sampling and hydrodynamic measurement always hardly cover the entire YECSs due to the huge domain except for some special national observing programs, such as Bian et al. (2013b). Although the remote sensing has a broad coverage of the YECSs, the retrieved data from satellite sensors can only describe the characteristics in the surface layer, while near bottom process is dominant for sediment transport besides winter strong mixing (Yuan et al., 2008). Numerical modeling is usually taken advantage of exploring the mechanism of sediment transport (Bian et al., 2013a), and its accuracy is questionable and depends on the understanding of the complicated sediment settling and sediment mobility. After summing up the capacity of various methods, an improved method is introduced in Pang et al. (2011) to obtain the sediment flux field in the YECSs via retrieval of ocean color remote sensing data, statistical analysis of historical suspended sediment concentration data, and numerical simulation of three-dimensional flow velocity. In this study, based on the method established by Pang et al. (2011), more accurate sediment flux field in the YECSs is attained using the improved numerically simulated shelf circulation.

Fine-grained terrigenous sediments are transferred across-isobath from the inner shelf deposits to mid-shelf deposits, even to the deep sea, such as the Okinawa Trough, forming Holocene mud patches found in the Yellow Sea Trough, southwest of Cheju Island and in the Okinawa Trough. The source and transport mechanism of these three mud patches have been widely studied since 1980s and various plausible mechanisms on sediment transport have been proposed (Bian et al., 2010; Bian et al., 2013a; Li et al., 2014; Wang et al., 2014; Zhou et al., 2015). Some researchers (Milliman et al., 1985a; Hu and Pang, 2001; Pang et al., 2001; Yuan et al., 2008; Bian et al., 2013b; Zhou et al., 2014; Dou et al., 2015) argue that in winter, the Yellow Sea Coastal Current carries resuspended sediments eroded from the Old Huanghe Delta to the shelf edge south of Cheju Island, forming the Southwestern Cheju Island Mud (SWCIM), while part of the sediment continues to be delivered to the north by the Yellow Sea Warm Current to form the Central Yellow Sea Mud (CYSM) in the Yellow Sea Trough. However, the above-mentioned widely accepted hypothesis deduced from the remote sensing data or in-situ observation on suspended sediment concentration, has not been supported by direct velocity measurement (the southeastward branch of the Yellow Sea Coastal Current, named as the East China Sea Current by Yuan and Hsueh, 2010 has never been directly measured by current meter). Moreover, not any numerical model on sediment transport in the YECSs has the capacity of reproducing the seasonal variability and deposition mechanism governing the SWCIM, even the recent study conducted by Bian et al. (2013a). In comparison with the CYSM also located in the middle shelf, whose maximum accumulation rate is less than 2 mm a^{-1} and mean rate is about 1 mm a^{-1}, the SWCIM is the only Holocene depocenter far from the coast or sediment source, due to its high accumulation rate of up to 5 mm a^{-1} (Lim et al., 2007). The forming mechanism of the distinctive Holocene depocenter (SWCIM) should be clearly elucidated, and the above hypothesis could be verified by means of vector field analysis, including current velocity and sediment flux.

In this study, the seasonal transfer and net accumulation of suspended sediment in the YECSs are explored based on the accurate suspended sediment flux originally established by Pang et al. (2011) and further improved by this paper, which might establish the linkages between sediment supply, transport, accumulation, and hydro-dynamic conditions, determine the dominant sediment transport process, and finally provide insight into the genesis of Holocene mud deposits, particularly the SWCIM.

1.1. Regional setting

The Yellow and East China Seas (YECSs) are comprised of a semi-enclosed basin with a mean depth of 44 m in the north (the Yellow Sea) and a broad continental shelf with a mean depth of 72 m in the south (the East China Sea). The artificial boundary between the Yellow Sea and the East China Sea is a straight line connecting the Changjiang Estuary and the Cheju Island (Fig. 1).

1.2. Waves and currents

In the YECSs, strong northeasterly monsoon dominates the winter time with a mean wind speed of 5–10 m s^{-1}, while weak southwesterly monsoon prevails in summer with a mean wind speed of 4–7 m s^{-1}. Wind-induced waves are around 1–3 m high in this region, occasionally exceeding 4 m during winter storms and typhoons.

The tide in the YECSs is predominantly semi-diurnal with the tidal range of about 2–4 m. There are strong tidal currents along the coast, for example, the largest tidal current speed being more than 150 cm s^{-1} near the Changjiang Estuary.

The shelf circulation in the YECSs shows evident seasonal variation. The circulation in the Yellow Sea in winter is characterized by the

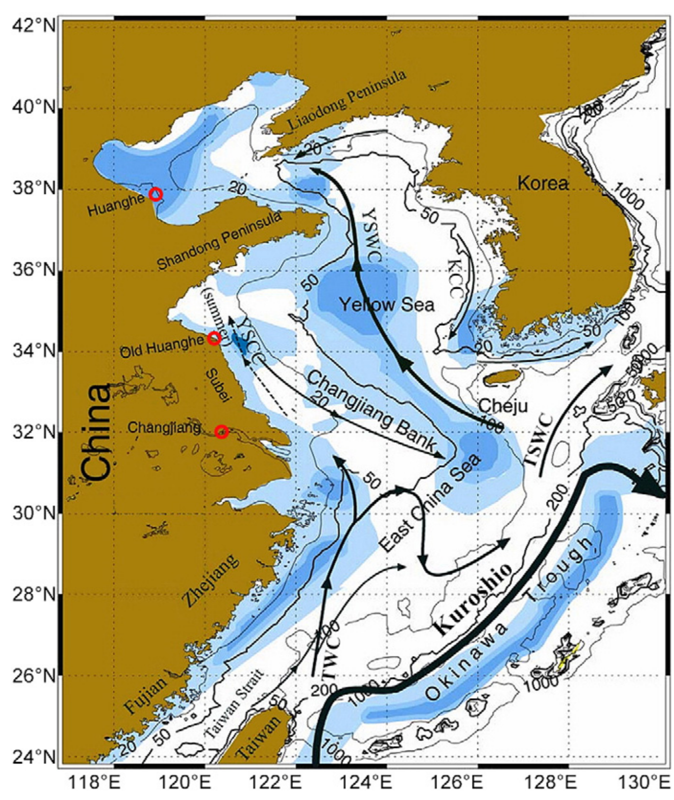

Fig. 1. Map of the Yellow and East China Seas (after Yuan et al., 2008). The arrows indicate the Yellow Sea Warm Current (YSWC), the Yellow Sea Coastal Current (YSCC), the Korea Coastal Current (KCC), the Tsushima Warm Current (TSWC), the Taiwan Warm Current (TWC), and the Kuroshio. Regional map and topography of the YECS area are based on ETOPO5 dataset. Contour unit is meter. Shaded areas show distribution of mud patches at the sea bottom, with darker colors indicating fine-grained sediments.