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Seasonal and intra-seasonal variations of suspended-sediment distribution in the Yellow Sea

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A B S T R A C T

Seasonal and intra-seasonal variability of hydrodynamics and suspended sediment concentration (SSC) in the Yellow Sea were investigated using combined ship measurements and physical fields extracted from the global Hybrid Coordinate Ocean Model (HyCOM). Model-data comparison indicates that the HyCOM solutions fairly agree with the observed temperature fields, both showing strong horizontal and vertical seasonality. High SSC was observed in waters near the Chengshantou Cape and above the old Yellow River subaqueous delta in November 2012, and was coincident with enhanced velocity shear. Thermal fronts were identified in waters less than 60 m deep with their prominent appearances in November 2012, inhibiting the offshore sediment transport. The previously reported depo-center of distal Yellow River mud-patch off the Chengshantou Cape was confined between the positions of the strong velocity shear in a shoreward direction and the thermal fronts in an offshore direction. We concluded that the nearshore mixing front and the offshore thermal front play critical roles in both capture of the fine-grained suspended sediment and formation of the Omega-shaped mud patch.

1. Introduction

Large rivers play an important role in delivering particles and dissolved materials from land to marginal seas. Global rivers deliver as much as 20 billion tons of sediments to the oceans annually, more than 70% of which are contributed by Asian rivers (Milliman and Meade, 1983; Milliman and Syvitski, 1992; Milliman and Farnsworth, 2011). Upon their arrival at river mouths, the majority of riverine sediments will be either trapped near estuaries or deposit in the adjacent marginal seas - only ~ 5–10% can reach the deep sea (e.g. Alexander et al., 1991; Meade, 1996; Yang and Liu, 2007; Wang et al., 2007a; Liu et al., 2009; Wang et al., 2014). Transport and deposition of sediments in marginal seas is controlled jointly by various factors including ocean dynamics and characteristics of the sediment itself. Comprehensive understandings of sediment transport and deposition processes are still needed because: 1) river-derived sediments from long-term records are indicative to the changes of terrestrial upland (basin) and marine environments; and 2) the associated transport of nutrients and organic matters are important components of biogeochemical cycling in the marine ecosystem (Chen et al., 2003; Cai and Dai, 2004; Hu et al., 2011, 2013; Xue et al., 2013).

The Yellow River is one of the largest rivers along the Western Pacific Ocean and it is the major source of terrestrial sediments to the Bohai Sea and Yellow Sea (e.g. Guo et al., 2003; Bianchi and Allison, 2009; Xu et al., 2009a, 2009b; Bi et al., 2011; Wang et al., 2011; Hu et al., 2014). The two marginal seas used to receive ~ 1100 million tons of sediments from the Yellow River per year (Milliman and Meade, 1983; Saito and Yang, 1994). However, this flux decreased sharply over the past 50 years, mainly because a large amount of sediments have been intercepted by the flourishing dams in the river basin (Yang et al., 2005, 2006; Xu and Milliman, 2009; Wang et al., 2010).

The Yellow Sea is a semi-closed marginal sea surrounded by the

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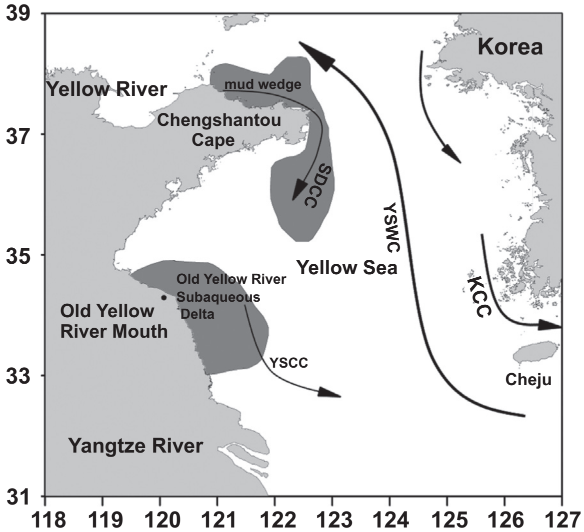

Fig. 1. Circulation pattern (winter) and the locations of mud patches (dark grey) in the Yellow Sea. YSWC, Yellow Sea Warm Current; YSCC, Yellow Sea Coastal Current; KCC, Korean Coastal Current; SDCC, Shan-Dong Coastal Current.

China mainland and Korean Peninsula with a mean depth of 38 m. It connects to the Bohai Sea through the narrow Bohai Strait in the north and the East China Sea in the south. Previous observations of sediment distribution on the seabed revealed paleo-sandy sediments on the broad continental shelf of the Yellow Sea that were accumulated during the last glacial maximum when the sea level was low (Emery, 1968). Mud patches are appearantly distributed in the northeast of Shandong Peninsula, Yellow Sea Trough, old Yellow River subaqueous delta, southeast of the Yangtze River Estuary and southwest of Cheju Island (Saito and Yang, 1994; Liu et al., 2007). For instance, Yang and Liu (2007) reported a large Omega-shaped ("Ω") mud patch along the Shandong Peninsula and specified this feature as the distal depo-center of Yellow River-derived sediment formed during the early Holocene.

Circulation in the Yellow Sea is dominated by the Yellow Sea Warm Current, Yellow Sea Coastal Current, Shan-Dong Coastal Current, and Korea Coastal Current (Fig. 1). The Yellow Sea Warm Current carries warm and salty water into the Yellow Sea along the Yellow Sea Trough (Fig. 2a) and presents strong seasonal variability: it is much stronger in wintertime than that in summer, as it extends to the northern Yellow Sea as a compensative flow to the southward coastal current (Hsueh, 1988; Tang et al., 2000; Teague and Jacobs, 2000; Bao et al., 2002; Fig. 1). The tidal regime in the Yellow Sea is remarkable for its high tidal ranges along the eastern coast of Korea (~ 3.5 m) and the western coast (~ 3.0 m) (Choi et al., 2003). Tidal currents on the Yellow Sea shelf are mainly semi-diurnal (M_2 and S_2) throughout the postglacial stages, with intensities of spring-neap modulation and diurnal inequity remaining similar as present (Uehara and Saito, 2003). The speed of semi-diurnal currents is high on the western coast of Korea and at the estuary of the Yangtze River, and is in the order of 100 cm/s (Bao et al., 2001). Due to the strong tidal currents, large radial sand ridges formed along the Chinese coast in the south Yellow Sea, where a large amount of sediments from the Yangtze and Yellow Rivers has deposited since the early Cenozoic times (Wang et al., 2012).

Several thermal fronts have been identified in the Yellow Sea. Thermal fronts usually appear across major oceanic currents and upwelling zones (Feliks et al., 2004). They are generally referred to as water bodies with a high gradient of sea surface temperature (SST) ranging from 4 to 10 °C/km (Sweet et al., 1981). They are permanent features of the mid-latitude ocean circulation and their position and strength change on time scales of weeks to years (e.g. the Gulf Stream and Kuroshio; Stommel, 1965; Feliks et al., 2004). In our study region, the Yellow Sea Coastal Current Front was detected along the edge of Chinese coast from the central South Yellow Sea to the northern East China Sea (Ning et al., 1998). Another thermal front with a relative narrow width was found along the southern edge of the Yangtze River bank (He et al., 1995; Hickox et al., 2000). To the east and in the west of Cheju Island, satellite remote sensing detected another regional thermal front (He et al., 1995; Hickox et al., 2000; Tang et al., 2001). A N-shaped thermal front was also identified between the cold coastal water and warm water south of the Shandong Peninsula (Wang and Liu, 2009).

Existing sedimentary studies in the study area have been mainly focused on the deposition pattern of sediments on the seabed (e.g. Liu et al., 2004; Yang and Liu, 2007; Dong et al., 2011; Huang et al., 2014). Recent works on the regional sediment dynamics relied largely on numerical models. For example, using a coupled wave-ocean-sediment transport model, Bian et al. (2013a) concluded that Yellow River sediments could be transported to the Yellow Sea by coastal currents in wintertime, and the sediments resuspended from the old Yellow River delta can be delivered to the Yellow Sea Trough by the Yellow Sea Warm Current. Zeng et al. (2015) proposed that the resuspension and transport of fine-grained sediment along the Shandong Peninsula were mainly controlled by the distribution of wave-induced bottom stress. And the distal mud patches presented by Yang and Liu (2007) were ascribed to weak bottom stress and regional circulation patterns. Nevertheless, a lack of multi-seasonal in-situ SSC observation has presented a big challenge to the validation and evaluation of these modeling efforts. In this study, we present the results of in-situ measured SSC and temperature from four cruises conducted in the spring and autumn of 2010 and 2012. Together with the hydrographic data (temperature, velocity, and wave height) retrieved from two global models (HyCOM and WAVEWATCH III), we aim to: 1) present the seasonal and intra-seasonal SSC patterns in the Yellow Sea in associated with hydrodynamics; and 2) assess the impacts from different physical processes on the regional sediment dynamics.

2. Data and method

2.1. In-situ hydrographic observations and SSC sampling

Temperature and SSC data were collected from four cruises in April 2010, September 2010, May 2012 and November 2012 by *R/V* DONGFANGHONG 2 (for sampling stations see Fig. 2). At each station, temperature and water depth were measured using Seabird CTD (model: 911 Plus). Water samples were collected using Niskin bottles at 3–6 depths to assure the coverage of surface, intermediate, and bottom water in the vertical dimension. Water samples were filtered onboard using a GAST model pump (Gast Manufacturing, Inc., Benton Harbor, MI, USA) with double filter membrane (pore diameter: 0.45 µm) to obtain the weight of suspended particles, which were then dried at 60 °C and weighed at room temperature with an electronic scale (resolution: 1/100,000 g).

2.2. Hydrographic data from global models

To fill the spatial and temporal gaps of in-situ observations, we retrieved temperature and velocity fields from the Hybrid Coordinate Ocean Model (HyCOM, experiment GLBu0.08/expt_19.1; Chassignet et al., 2006) covering the same period of the four cruises. The HyCOM solution has a horizontal resolution of 0.08° and 40 standard vertical z-levels ranging from 0 to 5000 m depths. This experiment employed a multivariate optimal interpolation scheme to assimilate altimetry, sea surface temperature (SST), vertical profiles of water temperature and salinity from moored buoys and Argo floats (Tanajura et al., 2013). To evaluate HyCOM's robustness in the Yellow Sea, we interpolated the SST field acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) to the grid of HyCOM and compared the two datasets (Fig. 3). The correlation coefficients between the HyCOM and