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Remote sensing observations and numerical studies of a super typhoon-induced suspended sediment concentration variation in the East China Sea

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ABSTRACT

By integrating remote sensing observations and a numerical modeling technique, we studied the influences of super Typhoon Saomai on the suspended sediment concentration (SSC) in the Yangtze River estuary and its adjacent coastal areas in the East China Sea. First, three consecutive Moderate Resolution Imaging Spectroradiometer (MODIS) images acquired during the post-typhoon stage were used to estimate the SSC. Then, we implemented a hydrodynamic model, including a sediment transport module, based on Delft3D to simulate the sediment erosion, re-suspension, transport and deposition processes in the study area during the passage of Typhoon Saomai. The model-simulated water level was validated against the in situ station data to show the feasibility of the model. The simulated SSC results agree reasonably well with the satellite observations. Time series of the simulation results showed that the model revealed the whole SSC variations during this extreme weather event and made up for the scarcity of in-situ and satellite observations. SSC significantly increased during the passage of the typhoon and decreased gradually during the post-typhoon stage. Modeled results also reveal that the spring-neap tidal effect significantly controlled the distribution and variation of SSC in the shallower coastal water (<20–30 m in depth) and the typhoon-induced re-suspension is evident in most of the study area, especially in the coastal waters near the Yangtze River estuary and Hangzhou Bay during the passage of the typhoon. Finally, based on the simulation results, we discuss the dynamic mechanisms including turbulent energy, bed shear stress and vertical mixing that caused the SSC variation.

1. Introduction

As one of the important water quality parameters susceptible to hydrodynamics in the coastal and estuarine areas, suspended sediment concentration (SSC) has been the focus of study by scientists in the coastal engineering, ecological and environmental fields among others (Ouillon et al., 2004; Smith et al., 2009; Ellis and Cappietti, 2013). Among other processes, SSC can vary with winds, tidal currents, submarine topography, saltwater intrusion and seasonal variations of river runoff (Shen and Zhang, 1992; Chen et al., 1999; Chen et al., 2003; Pang et al., 2010; Wu et al., 2010; Hennings and Herbers, 2014). Numerous studies have been carried out to understand its spatial distribution and temporal evolution (Chen et al., 2003; Umezawa et al., 2009; Bian et al., 2013a). To understand the long-term changes and large spatial distribution of SSC, Chen et al. (2003) used the surface SSC data from 8 stations at the Yangtze River estuary and its adjacent coastal waters to do a detailed analysis of SSC variations over a one year period. Using observed turbidity data and simulation results, Bian et al. (2013a) studied the distribution of SSC in the Bohai Sea, Yellow Sea and East China Sea and analyzed the sediment transport processes with modeled bottom stress, mixed layer depth and turbulent kinetic energy. The formation of underwater sand ridge associated with tidal current and sediment transport are also studied usind satellite data (Li et al., 2009; Shi et al., 2011). To better understand the topography-dependent characteristics of SSC in a tropical shallow estuary during dry seasons, Umezawa et al. (2009) investigated the physical factors causing the increase of SSC and the source of SSC using regression analyses.

Accurate measurement of SSC is of great importance in SSC-related studies. In general, it can be done using in situ and remote sensing measurements and each have their advantages and disadvantages. For in situ measurements, SSC is measured by analyzing water samples collected by ships or at fixed stations

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or by automated samplers (Shen and Zhang, 1992; Chen et al., 2003; Li et al., 2011). Recently, advanced instruments are able to provide faster and more convenient measurements of proxies for SSC. Two examples of such instruments are the LISST (Laser In Situ Scattering and Transmissometery) instrument (Agrawal and Pottsmith, 2000) and Seapoint Turbidity Meter (Bian et al., 2010; Bian et al., 2013b). This in situ measuring method is accurate but is time-consuming and costly, and cannot provide large-scale synoptic measurements of SSC (Puls et al., 1994). Remote sensing enables SSC to be measured overlarge scales. With the launch of advanced large-swath ocean color satellites, i.e., The National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS), SSC retrieval algorithms have been developed and are now sufficiently mature to retrieve SSC accurately over large areas in cloud free conditions (Pan et al., 2001; Miller and McKee, 2004; Ouillon et al., 2004; Bian et al., 2013b). Nevertheless, remote-sensing sensors can only detect SSC in limited surface waters and measurements are not always available due to cloud conditions and satellite orbital characteristics.

To understand the SSC temporal and spatial variations in a specific area, numerical simulation is also widely used to compensate the observations (Pang et al., 2010; Bian et al., 2013b). In the literature, numerical simulation studies have reproduced the distribution and variation of SSC, the hydrodynamic deposition/erosion and the re-suspension/transport processes of sediments (Chen and Wang, 2008; Hu et al., 2009; Li et al., 2010a, 2010b; Bian et al., 2013b; Song and Wang, 2013). Some researchers have also attempted to integrate remote sensing observations and numerical simulation techniques for SSC studies. For example, Ouillon et al. (2004) used satellite-derived SSC to validate a model simulation. Utilizing satellite-derived SSC as an initial condition in the MIKE-21 Mud Transport model, Ramakrishnan and Rajawat (2012) simulated the suspended sediment transport in the Gulf of Kachchh. Lu et al. (2014) established a SSC retrieval model using numerical simulated SSC and remote sensing reflectance, and further studied the SSC distribution pattern in the Bohai Sea, China.

In an estuary or coastal sea region, extreme weather events-tropical storms such as hurricanes or typhoons, can cause floods, which can carry large amounts of terrestrial sediment (Cheng et al., 2013), and storm-surges, which can cause significant change to the hydrodynamic conditions (Miner et al., 2009; Goff et al., 2010; Bian et al., 2010; Cheng et al., 2013), intensify the erosion of shorefaces, beaches and barrier islands and intensify the re-suspension of sediments on the seafloor (Bian et al., 2010). Consequently, remarkable impacts can be imposed on ecosystems (Smith et al., 2009), coastal engineering facilities, for instance, harbor and navigational channels (Hu et al., 2009; Ellis and Cappietti, 2013), local morphology (Miner et al., 2009; Goff et al., 2010), Li et al., 2008, and a change in geological characteristics (Feagin and Williams, 2008; Horowitz et al., 2014), etc. Numerous studies have focused on the influences of tropical storm events on sediments via in-situ observations and sampling and numerical modeling (Yang et al., 2007; Hale et al., 2012; Huang and Montgomery, 2013; Miles et al., 2013). For example, based on in-situ temperature, salinity and turbidity measurements and the calculations of swell-induced orbital velocity and bed shear stress, Bian et al. (2010) studied the impacts of Typhoon Ewiniar on the thermocline depth and the SSC of the East China Sea. They found that typhoon-induced wave and swell could push the thermocline depth down and increase the SSC. Moreover, other scientists have studied the impacts of typhoons on sediment transport and depositional processes (Hale et al., 2012) and regional sediment plumes and sediment discharges (Huang and Montgomery, 2013). Additionally, combining field observations with model simulation results, Palinkas et al. (2014) studied the sediment deposition at Chesapeake Bay during Hurricane Irene and Tropical Storm Lee.

As an important estuary in China, the dynamic characteristics of sediments in the Yangtze River estuary and its adjacent coastal waters (Fig 1) has received increasingly attentions from governments and scientists due to its impacts on navigation, ecosystem, geomorphological changes, and artificial structures (Liu et al., 2006; Zuo et al., 2009; Kuang et al., 2013; Song and Wang, 2013; Shi et al., 2014; Wang et al., 2014). Song and Wang (2013), Ma et al. (2013), Xie et al. (2010) and Kuang et al. (2014) studied the sediment transport dynamics due to the construction of the Deepwater Navigation Channel in the Yangtze River estuary. Those results can be aided to design and evaluate the dredging and dumping schemas of the navigation channel and to guide the construction of diversion dikes and jetty-spur structures. Based on daily surveys of bed-level changes and measurements of sedimentological properties, Shi et al. (2014) examined the erosion and deposition on a mudflat–saltmarsh transition on eastern Chongming Island, an intertidal wetland in the Yangtze River estuary. Some other researchers focused on the impact of an extreme flood and the construction of Three-Gorges Dam on SSC and sediment flux and environmental changes (Chen et al., 2001; Watanabe, 2007; Wang et al., 2008; Hsu and Lin, 2010; Kuang et al., 2013).

In comparison to SSC studies combining in situ observations and numerical modeling, there are relatively few studies taking advantage of the synergy between remote sensing observations and numerical models to study the phenomenon. By integrating remote sensing and numerical simulation techniques, this paper aims to study the impacts of a typhoon on SSC distribution and variation and to analyze its hydrodynamic mechanism at the Yangtze River estuary and adjacent coastal areas. The remainder of the paper is organized in the following parts. In Section 2, we present the study area and meteorological and tidal station data used in this study. Typhoon Saomai is also introduced. Section 3 details the SSC observations from remote sensing data. The configuration of a numerical model for the typhoon-induced SSC variations and the model validation are given in Section 3. Then, Section 4 analyzes the influences of the typhoon on the SSC. Finally, we present conclusions in Section 5.

2. Study area and processing data

2.1. Study area

The rectangle inset in Fig 1 shows the study area. It covers the Yangtze River estuary and adjacent coastal areas in the East China Sea. The Yangtze River is the largest river in China with a length of 6300 km and a drainage area of 1,808,500 km^2. It originates from the plateau of Tibet and flows into the East China Sea through four outlets, i.e., North Branch, North Channel, North Passage and South Passage. According to observations at station Datong (see Fig 1 for its location) from 1950 to 1985, the annual maximum, minimum and average discharge of the Yangtze River reached 4.31×10^4, 2.14×10^4 and 2.84×10^4 m^3/s, respectively. The discharge varies with the seasons. The maximum monthly average discharge appears in July (4.86×10^4 m^3/s), and the minimum appears in January (1.04×10^4 m^3/s). The river discharge in the flood season (May–October) accounts for 71.1% of the yearly discharge while the remaining 28.9% is discharged in the dry season (November to the following April). Due to the river flow expansion, its velocity decreases rapidly away from the estuary which diminishes the ability of sediment transport. As a result, most sediment is deposited at the Yangtze River estuary and the nearby coastal waters, resulting in the formation of deltaic lobes and side lobes, which can further form subaqueous sandbars and shoals. Only very few fine-grained sediments are transported to the offshore waters and eventually settle on the seafloor (Chen et al., 1999). The tides in the Yangtze River estuary are semi-diurnal and moderate with a mean tidal