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Variability of Yellow River turbid plume detected with satellite remote sensing during water-sediment regulation

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ABSTRACT

Water Sediment Regulations (WSRs) of the Yellow River (YR) have fundamentally altered the dynamics of freshwater and sediment transport in YR estuary and might profoundly affect water quality and ecosystem of the adjacent Bohai Sea. In this study, empirical algorithms were established to infer sea surface salinity and turbidity of YR plume using on surface reflectance products of MODIS and GOCI satellites in combination with observations from hydrographic surveys during the 2014 WSR event. Inter- and intraday variability of salinity and turbidity were quantitatively assessed and correlated with external forces including river discharge, tides, Coriolis force, and wind-driven circulation. The results revealed the enhanced offshore extension of turbid plume as WSR drastically increased freshwater and sediment discharge to river mouth. During WSR event, the area of low salinity plume (< 25 psu) increased to 267 km^2, while sediment plume (SR_{645} > 0.12sr^{-1}) occupied a maximum area of 162 km^2. Intraday variation observed from geostationary GOCI data clearly illustrated the dominance of tidal current on short term dispersal pattern of freshwater and sediment plume. In comparison, wind field dominated the seasonal variation in flume transport but had insignificant impact on short term river plume dynamic during WSR. Overall, this study demonstrated that the spatial and temporal dynamic of YR plume was successfully captured by satellite remote sensing, which provided an effective tool for evaluating the environmental and ecological impact of WSRs.

1. Introduction

With a total of 40% global fresh water being transported from continent to ocean by the world's ten largest rivers, these rivers constitute the primary interface between terrestrial and ocean environments (Dagg et al., 2004). Coastal river plume is the major transport mechanism for fresh water, suspended sediment, dissolved carbon, nutrients, and pollutants in the estuarine and coastal waters. This river-sea interaction promotes a tandem effect on biological processes such as facilitating local fish larvae retention and fish recruitment (Grimes and Kingsford, 1996). The spatial and temporal variability of river plumes are tightly associated with environmental factors including Coriolis force, wind, river discharge, coastal currents, tidal cycles, shelf slope and submarine channel direction.

Satellite data products provide synoptic and frequent overviews of coastal water and might be the only viable approach to monitoring the dispersal of river plumes over synoptic scales (Hopkins and Lucas, 2013). The optical properties of coastal surface waters can be used to distinguish turbid plume water from ambient water masses (Lahet and Stramski, 2010). Supervised classification of ocean color data has been successfully employed to develop link between light absorption of Chromophoric Dissolved Organic Matter (CDOM) and surface salinity in Columbia River plume (Palacios et al., 2009). Four types of remote sensing data (temperature, salinity, chlorophyll, and sea level) coupled with EOF analysis has been used to identify the dispersal and movement of Congo plume (Hopkins et al., 2013). In the case of the Amazon River Basin, patterns of surface sediment distribution has been modeled based on Moderate Resolution Imaging Spectroradiometer (MODIS) data to detect the variability in main channel and observe the tributary influence on main system (Park and Latrubesse, 2014). Total suspended matter concentrations within the Adour River turbid plume has been obtained from MODIS 250 m imagery to describe the seasonal spatio-temporal of this plume (Petus and Marieu, 2014). It is established that the responses within ocean surface visible spectrum as a function of plume characteristic parameters (e.g. suspended sediments, salinity, CDOM, turbidity and chlorophyll-a) could enable quantitatively depict river plume variability (Long and Pavelsky, 2013; Aurin et al., 2013). Studies (Bowers et al., 2004; Kutser et al., 2005;

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Ahn et al., 2008) have confirmed the existence of a tight relationship between the ratio of reflection coefficients and CDOM absorption, particularly in the ultraviolet (UV) and blue portion of the visible spectrum. In addition, strong linear and inverse correlation between salinity and CDOM in surface water has been observed in estuaries and coastal waters around the globe. Therefore, surface reflectance properties observed from satellite remote sensing has been established as a reliable property to assess the variation of plume area and shape (Hu et al., 2004; Ahn et al., 2008; Palacios et al., 2009). However, majority of the remote sensing studies on river plumes were conducted at interannual or seasonal time scale, whereas few studies have investigated short term (inter-day or intraday) variation of plumes, which is critical for understanding the drastic change associated short-term events. The Geostationary Ocean Color Imager (GOCI) satellite launched in June 2010 provided opportunity to measure dynamic variation in semi-diurnal environments for its better temporal coverage (Choi et al., 2012).

The Yellow River (YR), the most sediment-filled and the sixth longest river on earth, carries tremendous amounts of freshwater and sediment through its plume to the semi-enclosed Bohai Sea. Field measurements and numerical simulation have been conducted to study the dynamics of YR plume. Based on the cruise observation data from 2000 to 2005, it was reported that salinity level in nearby Laizhou Bay was primarily controlled by YR plume (Zhao et al., 2010). The survey in summer 2007 demonstrated that suspended sediments concentrated in the river mouth and extended southerly driven by tidal current (Qiao et al., 2010). A 3-D baroclinic hydrodynamic model was set to simulate YR plumes and the result showed that the seasonal behavior of the plume corresponded to seasonal variation in wind field. The prominent plume extended northeastward in summer time and propagated to the southeastern corner of the Laizhou Bay in response to the strong northerly wind in winter (Wang et al., 2008). Monthly averaged surface reflectance data retrieved from MODIS demonstrated that the YR turbid plume extended seaward but had little impact on the SSC distributions in the southern Bohai Strait during the flood season (Bi et al., 2011). Suspended sediment fluxes and dispersion patterns off the past and present YR plume were studied based on the hydrographic data by Wang et al. (2007) and Bi et al. (2010a) respectively, and they reached an agreement that tidal shear fronts and alongshore tidal currents were the major dynamic factors controlling the sediment dispersion.

During the past decades, the annual water discharges of YR have dramatically reduced 70% compared with 1950s due to dam construction, water consumption, and climate change (Wang et al., 2006). The unbalanced relationship between water and sediments results in an elevated riverbed over 10 m above the surrounding floodplain (Yu et al., 2013). Therefore in year 2002, the YR Conservancy Committee (YRCC) initialized the Water–Sediment Regulation (WSR) for improving the river ecological environment. Through the joint operation of three large reservoirs in the middle reaches of the YR, large quantities of fresh water were released on a period of two weeks when about 50% of annual sediment discharge (Bi et al., 2014) and over 20% of annual water discharge (Wang et al., 2011) took place. These flash flood scours river channel covered with huge deposits of sediment and transported them into sea. Consequently, this intensive freshwater and sediment injection in short time also caused YR plume pathway shift (Wang et al., 2005), variation of horizontal and vertical salinity distribution (Mao et al., 2008; Wang et al., 2011), and change of suspended sediment transport (Yu et al., 2013). Despite those research efforts, substantial knowledge gap on the variability and controlling mechanisms of YR plume still exists due to limited measurements and becomes an obstacle for scientific planning of the WSR scheme.

The objectives of this study are: 1) establishing empirical algorithms to infer salinity and turbidity of YR plume using surface reflectance products of MODIS and GOCI satellites in combination with in-situ data measured during the 2014 WSR cruises; 2) evaluating the inter-day and intra-day variation of YR plume using retrieved sea surface salinity (SSS) and surface turbidity; and 3) elucidating the evolution mechanisms of YR turbid plume as impacted by external forces such as river discharge, tidal current, Coriolis effect, and wind-driven circulation.

2. Material and methods

2.1. Study area

The Yellow River is one of the world's most turbid rivers and contributes 71% of total runoff freshwater inputs to Bohai Sea. Since 1960s, the annual averaged flow discharge of YR has dropped dramatically from 1900 m^3/s to 320 m^3/s in the 1990s (Mao et al., 2008). Similar conditions appears on the annual sediment load, which declined sharply from 1.33 Gt in 1960s to 0.15Gt after 2000 (Bi et al., 2014). The river mouth also altered position from abandoned Qingshuigou river mouth in 1996 to the present northeastward to Bohai Sea (Fig. 1). The tide of YR estuary is irregular semi-diurnal with an average tidal range of 0.6–0.8 m at river mouth and rising to 1.5–2.0 m at Laizhou Bay and Bohai Bay (Zhang et al., 1990). The tidal currents have an average speed of 0.5–1.0 m/s, and move in paralleling to the coast in the form of reciprocating flows (Bi et al., 2010a). In the northeast and middle transects off the present YR delta, the currents flow southward during the flood tide and northward during the ebb tide (Bi et al., 2014). The shear fronts between YR plume and coastal water with different flow directions and velocities have been observed in YR estuary (Li et al., 2001). Time-series data and water samples simultaneously observed in 1995 demonstrated the hindrance effect of tidal shear fronts on the suspended sediment dispersion of around YR estuary (Wang et al., 2007). The northern winds in winter season and prevailing southern wind during summer could drive the sea surface residual current moving northward and southward respectively at an average speed of 0.2 m/s (Bi et al., 2014), which has been demonstrated as the dominant force controlling the seasonal variation of YR plume (Wang et al., 2008). The strong wind could also generate surface waves in this area. The wave impact on YR plume during summer was considered to be negligible since the wind mainly blew from land to sea (Wang et al., 2014).

2.2. Field measurements

Three hydrographic surveys were conducted during June 10-July 20, which covered the period of WSR in year 2014. The sampling sites were shown in Fig. 1. Salinity, temperature, depth, and turbidity were measured on site with RBR concerto CTD system at sampling frequency of 6 Hz. The CTD instrument was calibrated using the standard protocols and was attached to a rosette. The database of CTD profiles was subjected to quality controls, which included the removal of spurious data by visual inspection and low-pass filtering with a moving-median filter. The salinity and turbidity obtained for sea surface layer were calculated as the average of readings between 0.5 m and 1 m below water, because the measurements of 0–0.5 m below surface were frequently interfered by the sea surface shaking.

Daily river runoff and suspended sediment concentration (SSC) in Fig. 2 were recorded at the Lijin Station, which is the nearest hydrological station located ~100 km upstream river mouth. Release of water from the Xiaolagndi Reservoir started from June 30 and lasted until July 6. The daily total water discharge started from 380 m^3/s before WSR and rise to peak flow of 3320 m^3/s on July 7. The suspended particulate matter (SPM) in Fig. 2 also exhibited variability with minimum and maximum values of 750 mg/L and 8360 mg/L. The peak suspended sediment concentration was 6 days lag behind the peak flow.