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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 ($SR_{645} > 0.12 \text{ sr}^{-1}$) 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 plume 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

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al., 2013). Studies (Bowers et al., 2004; Kutser et al., 2005; 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 intra-day) 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 m³/s to 320 m³/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 m³/s before WSR and rise to peak flow of 3320 m³/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.

Fig. 1. Bathymetric map of the study area. Black circles represent sampling stations in June and July 2014. The numbers indicate water depth (m). The channel of Yellow River are depicted as solid curves.

Fig. 2. Yellow River daily (a) runoff and (b) concentrations of suspended particulate matter (SPM) recorded at Lijin Station over the period Jun 21 to Jul 15, 2014.

2.3. Satellite data

2.3.1. MODIS reflectance

The MODIS L2G products were used in this study to detect YR flume, which had been radiometrically corrected for the variations in atmospheric gases and aerosols to yield surface spectral reflectance (SR) (Petus et al., 2014; Park and Latrubesse, 2014). These daily products provide surface reflectance at 250-m resolution for band 1 (620–670 nm) and 500-m resolution for band 4 (545–565 nm). We used band 1 as a qualitative proxy for amounts of turbidity (sediment dominated) levels, because earlier studies has found that reflectance centered on 645 nm had high and constant sensitivity to suspended particles and was often integrated into empirical bio-optical algorithms to quantify the total suspended sediment (mg/L) or turbidity levels (NTU) (Lahet and Stramski, 2010; Aurin et al., 2013; Park and

Latrubesse, 2014; Petus et al., 2014; Fernández-Nóvoa et al., 2015). Band 4 was used for depicting sea surface salinity patterns, because SR at the green-blue range is a better indicator of surface salinity than other visible spectrum wavelengths (Hu et al., 2004; Ahn et al., 2008; Palacios et al., 2009). For this study, a total of 42 scenes covering YR estuary were downloaded with each image acquisition date corresponding to the date of field survey. The satellite data were processed in three steps: (1) selecting the clear satellite images with non-cloud pixels in the region of interest; (2) geometric reprojection of study area subset scenes using SEADAS software; (3) filtering the scenes severely contaminated by clouds/extreme atmospheric conditions and nearshore resuspension.

2.3.2. GOCI reflectance

The GOCI is the world's first ocean color observation satellite placed in a geostationary orbit, which provides 8 images each day with a 500-m spatial resolution at hourly interval since it was launched in June 2010 (Choi et al., 2012; He et al., 2013). GOCI is considered to be exclusive and specific in identifying spatiotemporal dynamics of river plume on hourly time scale. Because the red or NIR band is more sensitive to coastal waters containing high turbidity, the surface reflectance of band 5 centered at 660 nm can provide the hourly observation of turbid plume (Choi et al., 2012). This band has a low penetration in the water and hence avoids bottom influence in shallow water (Lahet and Stramski, 2010). The L1B data was downloaded and then processed to L2 data using the GOCI data processing software (GDPS) with default parameters and standard atmospheric and geometric correction, generating the spectral remote sensing reflectance products for analysis of the hourly dynamics of YR turbid plume.

2.3.3. ASCAT wind field

The Advanced Scatterometer (ASCAT) neutral stability winds 10 m above sea level were provided by NOAA/NESDIS utilizing measurements from ASCAT aboard the EUMETSAT METOP satellite since launch time 2007. Based on standard products ASCAT L2B 12.5 km, the averaged gridded L3 fields having spatial resolutions of 0.25° at global scale are used in this study. The calculation of daily estimates

uses ascending as well as descending valid retrievals and the L3 format data were recorded for locations near YR delta.

2.4. Salinity retrieval

Match-up of field collected salinity data and digital reflectance derived from satellite imagery is based on the rules established by previous studies (Cui et al., 2010; Qing et al., 2013). A 3×3 window centered on each sampling site is used with time lag between the satellite overpass and field measurement less than 3 h. The average value from 9 satellite pixels of MODIS was calculated as the reflectance on each sampling sites. Totally 33 groups of matched data were selected for model construction. The multi-regression model for surface water salinity prediction is expressed below:

$$\lg(\text{Salinity}) = -0.131 \times \frac{SR_{645}}{SR_{555}} + 1.499 \quad (1)$$

The salinity in Eq. (1) is in psu, and SR_{645} and SR_{555} are the reflectance values derived from band 1 and band 4. Band 1 (SR_{645}) is used here for normalizing purposes because CDOM influence on Band 1 is quite low (Kutser et al., 2005; Choi et al., 2012), and previous studies have demonstrated the benefit of including this red-green band to monitor water quality (e.g. CDOM) in estuarine and coastal waters (Bowers et al., 2004; Kutser et al., 2005; Lahet and Stramski, 2010). The model reveals a strong empirical relationship between the salinity and the reflectance with high correlation coefficient ($R^2=0.84$) and low residual in fitting the model (RMSE = 0.82 psu) (Fig. 3a).

2.5. Turbidity retrieval

The relationship between field measurements of turbidity and reflectance data from MODIS imagery was established using protocols same as SSS retrieval. Surface turbidity was estimated as a function of atmospherically corrected reflectance values at 645 nm:

$$\lg(\text{Turbidity}) = 9.96 \times SR_{645} + 0.61 \quad (2)$$

In Eq. (2), turbidity is denoted in NTU and unit of SR centered on 645 nm is sr^{-1} . The upper limit in Eq. (2) is 112 NTU (Fig. 3b), which

is lower than the maximum turbidity (429 NTU) recorded in-situ. Therefore in following discussion we would use SR_{645} as a proxy for turbidity levels. This approach of turbidity represented by SR has been used for the remote-sensing of turbid waters in various studies (Lahet and Stramski, 2010; Aurin et al., 2013).

3. Results and discussion

3.1. Characterization of YR plume during WSR

The regression models of Eq. (1) and Eq. (2) were used to estimate the spatial-temporal variability of sea surface salinity and turbidity in the YR estuary. The spatial distribution of sea surface salinity synthesized from MODIS reflectance data is illustrated on Fig. 4 from June 27 to July 14, 2014. Before WSR (June 27 to June 30), the main axis of salinity plume was predominantly concentrated in front of the river mouth. The salinity distribution was consistent with numerical simulation results of YR salinity plume in summertime (Wang et al., 2008), especially the 26–27 psu isohaline profile. During WSR (July 6 and 7), the remote sensing results demonstrated a drastic northward extension of the low salinity plume. The decrease of salinity in the estuary corresponded with freshwater release from upstream reservoirs, which started from July 1 to July 14 with a peak discharge of 3320 m^3/s (see Fig. 2a). This dynamic responds of salinity plume were in accordance with field measurement during 2007 WSR (Bi et al., 2010b). On July 14 the river discharge decreased to 900 m^3/s at the end of 2014 WSR. The post WSR salinity pattern in YR estuary was illustrated on the image of July 14, which shows a shrink of plume area.

Image sequence of MODIS SR_{645} as a proxy for turbidity levels showed an increasing trend in turbid area during WSR (Fig. 5). The high turbidity region under pre-WSR condition (June 27 to June 30) could be identified as bulges near the river mouth. The images of July 6 to July 7 illustrated that plume area sharply extended to the north, which was close to the observation during 2009 and 2012 WSR (Yu et al., 2013). As depicted on Fig. 2b, the maximum suspended sediment concentration ($1.2 \times 10^4 \text{ mg/L}$) was observed on July 13 at Lijin Station, 6 days behind peak freshwater discharge. Similar asynchronous arrival of sediment and freshwater discharge had been observed during the

Fig. 3. (a) Sea surface salinity as a function of MODIS remote sensing measurements. (b) Surface turbidity as a function of MODIS surface reflectance. The red circles represent field observations from the WSR surveys conducted in June and July 2014. The blue lines depict predictions from optimized regression models. SR_{645} and SR_{555} are surface reflectance at 645 nm and 555 nm, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Spatial distribution of sea surface salinity (SSS) synthesized from MODIS surface reflectance at 645 nm (SR_{645}) and 555 nm (SR_{555}) from June 27 to July 14, 2014. The dates of image acquisition are indicated on upper right corner of each plot. White pixels are areas with invalid data due to cloud mask or nearshore resuspension. Land is shown in grey.

previous WSR and was attributed to the fact that majority of suspended sediment was coarse particles transported as bed load during the artificial flooding (Bi et al., 2010b). This significant difference in transport of freshwater and sediment explained the disparities between the estimated extent of salinity and turbidity plume.

During the WSR, YR flood delivered tremendous amounts of sediments and CDOM from upstream reservoirs and stream channels to the estuary. These two substances are the major factors to alter optical reflectance in water surface. The suspended particles scatters the reflectance of solar radiation in the red and near-infrared portions of the spectrum, while the CDOM absorbs light in the lower wavelengths (Palacios et al., 2009; Lahet and Stramski, 2010; Petus and Marieu, 2014; Park and Latrubesse, 2014). The results from 2014 WSR proved that band 1 (620–670 nm) and band 4 (545–565 nm) of MODIS could capture the dynamics of salinity and sediment in YR plume in response to the abrupt change of freshwater and sediment load due to artificial flooding. The satellite remote sensing products provided a valuable dataset to analyze the physical factors influencing the short term variation of river plume.

To quantify the variability of plume area and direction, threshold values of salinity and turbidity for delineating plume boundary were determined based on the linear regression analysis between calculated plume areas and freshwater discharges (Lahet and Stramski, 2010; Fernández et al., 2015). The correlation coefficients R^2 were plotted as a function of threshold values in Fig. 6. A threshold surface salinity at 25 psu was determined with maximum R^2 in Fig. 6a. In the case of turbidity, the maximum R^2 occurred on the SR_{645} of $0.12sr^{-1}$, which corresponds to turbidity of 64 NTU in Eq. (2).

Using above threshold values, the plume area (PA) and the plume shape (PS) were calculated. The plume areas measured in the number

of pixels within the river plume boundary were converted to unit of km^2 by multiplying with grid resolution. The plume shapes were calculated as main angle of plume direction by application of Linear Direction Mean function on the polygons delineating the plume occupied region (Moller et al., 2010). The calculated PA and PS are plotted as a function of image dates in Fig. 7.

3.2. Responses to freshwater and sediment discharges

As illustrated in Fig. 7, the low salinity plume area (<25 psu) increased to $267 km^2$ on July 7, corresponding to the peak of river inflow, then decreased to about $150 km^2$ on July 14 as the flood from WSR receded. The significant correlation between plume area and river discharge ($R^2=0.96$) indicated that inter-day variability of YR plume is largely controlled by upstream release of freshwater. Freshwater mainly accumulated in front of the river mouth (Fig. 4) and reduced the average salinity of YR estuary by ~ 2.5 psu (Fig. 7). The plume shape exhibited no significant correlation with discharge, which suggested that variation of plume shape is not controlled by river flow. The turbid plume area ($SR_{645} > 0.12sr^{-1}$) extended from $82 km^2$ before WSR to a maximum of $162 km^2$ on July 7, 2014. However, the average turbidity of the YR estuary further increased until July 14. The results indicated that majority of sediment carried by YR deposited in a rather small area in front of the delta, which was consistent with the observation that large fraction of the YR sediment consisted of coarse particles. Nevertheless, the increasing surface turbidity throughout WSR event indicated that a considerable amount of fine sediment was carried into the estuary, which might change the biochemical and ecological function of the coastal water.

Fig. 5. Spatial distribution of MODIS surface reflectance at 645 nm (SR_{645}) from June 27 to July 14, 2014. Here SR_{645} is a surrogate of sea surface turbidity. The dates of image acquisition are indicated on upper right corner of each plot. White pixels are areas with invalid data due to cloud mask or nearshore resuspension. Land is shown in grey.

Fig. 6. Correlation coefficient between calculated plume area and Yellow River discharge as a function of threshold values: (a) sea surface salinity, and (b) surface reflectance at 645 nm (SR_{645}) as a surrogate of sea surface turbidity.

3.3. Effect of Coriolis force and wind-driven circulation

Modelling and observational studies of surface plumes showed buoyant outflow spreading radially offshore from its source, rotating anticyclonically, and then subsequently being deflected to the right in the northern hemisphere by Coriolis force (Hopkins et al., 2013). The results in Figs. 4 and 5 illustrated that the YR buoyant plume was strongly driven by the Coriolis force, which promoted the anticyclonic turning around the YR delta and the downstream current along the western coasts of Laizhou Bay. These patterns had been identified in early numerical studies on YR plume dynamics in the presence of buoyancy forcing only (Wang, 2008). As result, the anticyclonic bulge and the downstream coastal current carried plume waters towards the western or even south shelf of Laizhou Bay.

The dependence of YR plume on summertime wind force can be described with wind-driven currents (Hopkins et al., 2013). The Ekman surface currents (V , m/s) were calculated from the ASCAT wind fields using the formula:

$$V = \frac{E}{\rho \sqrt{N_z} |f|} \quad (3)$$

where E is the wind stress magnitude in Pa, ρ is the water density in kg/m^3 , and the eddy viscosity N_z near the YR estuary is taken as $0.0023 \text{ m}^2/\text{s}$ (Wang et al., 2011), f is the Coriolis frequency in s^{-1} . The calculated daily wind-induced surface Ekman current fields around YR delta in Fig. 8 did not show significant correlation with plume area or shape. This suggested that influence of wind field on the YR plume variability is relatively small, which is inconsistent with previous nu-

Fig. 7. Variations of parameters during 2014 WSR event for (left) low salinity plume and (right) turbid plume. The parameters are: Q_w , Yellow River daily freshwater discharge; PA, plume area (km^2); PS, plume direction ($^\circ$); SSS, sea surface salinity; and SR_{645} , surface reflectance at 645 nm as a surrogate of sea surface turbidity.

Fig. 8. Ekman surface velocity (m/s) vectors derived from ASCAT wind fields from June 27 to July 14, 2014. The dates of image acquisition are indicated on each plot. Land is shown in grey.

merical experiments (Wang et al., 2008). In their modeling study, Wang et al. (2008) applied southeasterly wind at constant magnitudes from June 1 to September 30 and found a strong dependence of the YR plume on magnitude of summertime wind stress. However, the wind field observed from ASCAT showed the summertime wind in the estuary was short-lived and of low magnitude. The weak winds blowing from delta to sea were further calmed down by terrestrial friction before inducing seaward movement of YR plume.

3.4. Intraday responses to tidal currents

In order to monitor the impact of tidal cycle, the hourly variability of YR turbid plume were estimated from GOCI L2C products. The surface reflectance at 660 nm (SR_{660}) of band 5 were used as indicator of turbidity and displayed on Figs. 9 and 10. On July 6, the turbid plume flowed westward at 0:16 (GMT), then gradually moved eastward until 3:16, followed by shifting back westerly and extending offshore (Fig. 9). Turbid plume on July 7 demonstrated a similar swing feature, with the shift occurring one hour later on 4:16 (Fig. 10). The tidal regime

Fig. 9. Hourly spatial distribution of surface reflectance at 660 nm (SR_{660}) retrieved from GOCI satellite on July 6, 2014. Here SR_{660} is a surrogate of sea surface turbidity. The time (GMT) of image acquisition are indicated on each plot. White pixels are areas with invalid data due to cloud mask or nearshore resuspension. Land is shown in grey.

Fig. 10. Same as Fig. 10, but for July 7, 2014.

Fig. 11. Hourly variation of calculated Yellow River turbid plume area (PA) and plume direction (PS) on July 6 and July 7, 2014. The metrics are calculated from surface reflectance at 660 nm (SR_{660}) retrieved from GOCI satellite (Figs. 9 and 10) using 0.12 as the threshold value.

near YR plume was dominated by an irregular semidiurnal tide with a tidal cycle of about 6 h (Bi et al., 2010a). This variance of plume pattern corresponded to the tidal flow progressing from flood to ebb. Our analysis showed that intraday YR plume dynamics could be clearly captured by GOCI reflectance images. Meanwhile, the shape of turbid plume co-varied with tidal flow, suggesting that tide was a major factor controlling spatial distribution of river discharge in estuary.

Threshold of $0.12sr^{-1}$ was used to calculate turbid plume area and shape on GOCI band 5. The results are displayed as a function of time on Fig. 11. The mean turbid plume areas were $129.6 m^2$ and $143.5 m^2$ on July 6 and 7, respectively, which were smaller than plume area estimated by the salinity indicator and close to the result from MODIS band 1 (Fig. 7). The most dramatic change of plume shape on July 6 occurred on 2:16 to 3:16 corresponding to shift of tidal flow. The observed variation of plume shape on July 7 was consistent with July 6 but with 1 h delay. Our analysis validates that quantitative estimation of tidal currents in estuaries is feasible based on dispersal pattern of turbid plume (Choi et al., 2012).

3.5. Inter-annual variations

To further investigate the inter-annual variation of YR turbid plume, MODIS data during WSR in year 2004 and 2009 were also processed. Spatial distributions of synthesized surface salinity and SR_{645} at different dates are displayed on Figs. 12 and 13. Substantial variation of plume area was observed between three years, which well corresponded to the scale of WSR in selected years. On June 29, 2004, both the low salinity and turbid plume extended further north, covering a maximum area of $367 km^2$, while the maximum plume area in 2009 was merely $179 km^2$. The WSR in 2004 started from June 19 and ended on July 13 with a total freshwater discharge of $4.8 \times 10^9 m^3$ and sediment load of $7.0 \times 10^7 Mg$. In comparison, WSR in 2009 was between June 19 and July 7 with a total freshwater discharge of $3.5 \times 10^9 m^3$ and sediment load of $4.5 \times 10^7 Mg$. The remote sensing results illustrated the transport of freshwater and sediment in the YR estuary and established a rich dataset for calibrating the numerical models. Overall,

the satellite remote sensing data were capable of capturing the short term (intraday) as well as long term (inter-annual) variation of YR plume and provided a low-cost and efficient tool for the planning and design of WSR scheme.

4. Conclusions

Accurate depictions of water and sediment dynamics in river plumes are crucial for understanding fluvial morphodynamics and environmental characteristics of the river mouth and coastal water. In this study, MODIS and GOCI satellite products were processed to provide a detailed examination of the dynamic of freshwater and sediment in YR estuary during WSR. Surface salinity and turbidity retrieved from the regression analysis well correlated with in-situ measurements, and established reliable indicators of the plume. Threshold values for delineating freshwater and sediment plumes were established for synthesized sea surface salinity ($< 25 psu$) and surface turbidity ($SR_{645} > 0.12sr^{-1}$) based on correlation analysis. The results showed that area of low salinity plume increased from $105 km^2$ before WSR to $267 km^2$ as freshwater released from upstream reservoirs reached river mouth. The maximum concentration of suspended sediments was observed 6 days behind the peak flow, which suggested a different transporting mechanism of sediment load. The area of turbid plume ($SR_{645} > 0.12sr^{-1}$) extended from $82 km^2$ before WSR to a maximum of $162 km^2$ on July 7, 2014. The cross-correlation analysis confirmed that river discharge is the main factor controlling the plume area.

Hourly GOCI surface reflectance images well depicted the rapid shift of turbid plume in response to reciprocating tidal current. Our analysis established tide as the primary force regulating the intra-day variation of plume direction and shape. The remote sensing data also clearly illustrated anticyclonic turning of buoyant plume around the YR delta and downstream transport toward the west coast of Laizhou Bay, which was explained with Coriolis force and longshore transport. Although the wind driven Ekman transport dominates seasonal variation of plume dispersion, it had little effect on the short term movement of river plume during WSR in summer time.

Overall, remote sensing based on MODIS and GOCI satellite data provided a substantially more detailed quantification of YR plume dynamics, especially the inter- and intraday variation of salinity and turbidity during WSR events. The approach provides a powerful tool for monitoring plume dynamic and its potential impacts on the ecological health of coastal waters over the short-term events caused by climate events or anthropogenic activities.

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Fig. 12. Spatial distribution of (a) sea surface salinity (SSS) synthesized from MODIS surface reflectance at 645 nm (SR_{645}) and 555 nm (SR_{555}), and (b) MODIS SR_{645} from June 22 to July 15, 2004. Here SR_{645} is a surrogate of sea surface turbidity. The dates of image acquisition are indicated on upper right corner of each plot. White pixels are areas with invalid data due to cloud mask or nearshore resuspension. Land is shown in grey.

Fig. 13. Spatial distribution of (a) sea surface salinity (SSS) synthesized from MODIS surface reflectance at 645 nm (SR₆₄₅) and 555 nm (SR₅₅₅), and (b) MODIS SR₆₄₅ from June 20 to July 12, 2009. Here SR₆₄₅ is a surrogate of sea surface turbidity. The dates of image acquisition are indicated on upper right corner of each plot. White pixels are areas with invalid data due to cloud mask or nearshore resuspension. Land is shown in grey.

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