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Sediment Transport and Dispersal Pattern from the Bohai Sea to the Yellow Sea

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ABSTRACT

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Suspended sediment flux, dispersal patterns and its possible mechanisms in the Bohai Sea were investigated based on the observational data in May and November, 2012, data retrieved from MODIS imageries and the ocean current data from HYCOM. The sediment dispersal pattern and the annual net sediment flux presented evident seasonal variability. During wintertime, the prevailing strong northerly winds and the related high wave heights resuspended the sediment along the coast of the Huanghe Delta that was transported into the Laizhou Bay along its western coast and exported to the Bohai Strait through the eastern Laizhou Bay as enhanced by the coastal current. The wintertime contributed approximately 4. 84 Mt of suspended sediment flux to the Yellow Sea, as higher than the flux in summertime by one order. In summertime, the less energetic environment together with the stratified water column was unfavorable to the sediment export to the Yellow Sea. As a result, the sediment delivered by the Huanghe to the sea in summertime mostly accumulated within the subaqueous delta, which acted as a primary source of sediment export to the Yellow Sea in wintertime.

ADDITIONAL INDEX WORDS: *Bohai Sea, Bohai Strait, suspended sediment transport, seasonal variability, dispersal patterns.*

INTRODUCTION

Over the last several thousand years, the Huanghe (Yellow River) had been well-known for its high sediment load with annual discharge of ~1. 08 billion tons per year, ranking the second after the Ganges (Milliman and Meade, 1983). The river thus acted as a major contributor of terrestrial sediment to the global ocean, presenting significant influence on global material cycling and marine ecosystem (Martin *et al.*, 1993). Yang and Liu (2007) suggested that over the past 7 000 years, almost 30% of the terrestrial materials from the Huanghe had been transported to the Yellow Sea from the Bohai Sea. Previous studies also suggested that the sediment derived from the modern Huanghe was a primary source to the mud deposits in North Yellow Sea (Milliman *et al.*, 1985; Milliman *et al.*, 1986; Park and Khim, 1990; Qin and Li, 1983; Wang *et al.*, 2010b; Yang and Liu, 2007; Yang *et al.*, 2002), and even to the south of Cheju Island (Milliman *et al.*, 1985). Therefore, the processes of sediment transport from the Bohai Sea to the Yellow Sea are of broad interests to the community of both marine geology and marine ecosystem (Jiang *et al.*, 2004; Wang *et al.*, 2014).

In early times the suspended sediment flux (SSF) from the Bohai Sea to the Yellow Sea was roughly estimated based on limited field observations without considering the seasonal variation (*e. g.*, Qin and Li, 1983; Maritin *et al.*, 1993). They suggested that the flux was about (5 ~ 10) Mt yr^{-1} and 11. 9 Mt yr^{-1}, respectively, less than 1% of the Huanghe sediment discharge. Nevertheless, Alexander *et al.* (1991) proposed that about 160 Mt yr^{-1} (about 9 ~ 15% of the Huanghe sediment discharge) of sediments from the Bohai Sea was accumulated in the Yellow Sea, according to the ^{210}Pb and ^{14}C sediment accumulation rates in the Yellow Sea. Recent estimates from the numerical modeling suggested that about 100 Mt yr^{-1} (Jiang *et al.*, 2000), 42 Mt yr^{-1} (Li *et al.*, 2010b) (4% of the suspended sediment from the Huanghe deposits) of sediment exported to the Yellow Sea from the Bohai Sea through the Bohai Strait. Considering the seasonal variation of the cross-strait SSF, Bi *et al.* (2011) estimated the annual sediment flux to be approximately 40 Mt yr^{-1} based on the field investigations combined with the remote sensing, and 80% sediment was transported through the Bohai Strait in the winter season. Therefore, the quantity of sediment that is transported from the Bohai Sea to the Yellow Sea through the south Bohai Strait is still under debate. In addition, under the influence of human activities (*e. g.*, urbanization, deforestation, agricultural practices, mining and the retention of sediment by the reservoirs), the global modern sediment flux has decreased to 12. 6 GT yr^{-1} (Syvitski *et*

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al., 2005). In particular, the sediment discharge from the Huanghe to the Bohai Sea has decreased drastically to only 0.15 Gt yr^{-1} since 2000 (Wang *et al.*, 2007b), which eventually impacts the regional marine environment and the sediment exchange. Besides, most of previous studies have only focused on the sediment transport flux through the Bohai Strait and its dispersal patterns, and less attention has been paid to the sediment dispersal patterns in Laizhou Bay before the sediment escaping to the Yellow Sea. An overall picture of river sediment dispersal patterns over the whole Bohai has not yet been achieved and it is critical for understanding the pathway of sediment transport and seasonal flux off the Bohai Sea.

This study discussed the seasonal variation of suspended sediment transport and its seasonal dispersal patterns from the Bohai Sea to the Yellow Sea, as well as in Laizhou Bay, based on the datasets measured in two cruises in summer and in winter of 2012, monthly averaged MODIS data and numerical modelling product of ocean current (HYCOM) which has already been established.

REGIONAL SETTINGS

The Bohai Sea is located in the northeast China (37°N–41°N, 117°E–121°E) with three shallow bays (*e. g.*, Laizhou Bay, Bohai Bay and Liaodong Bay) and the central Bohai Basin (Figure 1). It is the shallowest semi-enclosed inner sea of China with an average depth of 18m (Qin and Li, 1983) and only connected to the Yellow Sea through the Bohai Strait. The Bohai Strait is about 104.3 km in width and is believed to be the interface for suspended sediment exporting to the open ocean (MGLIO, 1985).

Fine-grained sediment (*e. g.*, soft clay mud, fine silt mud, coarse silt and fine sand) with a grain size of less than 0.01mm (MGLIO, 1985) covers most of the Bohai Sea as almost 90% of the Huanghe sediment was derived from Loess Plateau featuring fine-grained sediment (Ren and Shi, 1986). In the northern Bohai Strait and its adjacent area, the surface sediment became coarser with sand and gravel (grain size more than 0.1 mm in average) (Wang *et al.*, 2014).

The largest part of the Bohai Sea exhibits a mixed semidiurnal tide with two counter-clockwise semi-diurnal amphidromic systems (M_2 and S_2) formed (Sun and Xi, 1988). Transport directions of sediments are mostly controlled by residual circulation (Delhez, 1996; Wei *et al.*, 2004; Zhao *et al.*, 1995). In the Bohai Sea, the residual circulation showed a seasonal variation. In wintertime, there were an anticlockwise gyre along the west coast of the Bohai Sea and a clockwise gyre within the Liaodong Bay, whereas there was a clockwise circulation along the shelf of the Bohai Sea, and an anticlockwise gyre in the Liaodong Bay in summertime (Fang *et al.*, 2000; Guan, 1994; Li *et al.*, 2005). The currents are generally weak with a maximum surface current velocity no more than 1.5 m/s, except for the Bohai Strait where the maximum current velocity can reach 2.5 m/s with north-side inflow and the south-side outflow (Jiang *et al.*, 2000). Winds contribute to the residual currents both in winter and summer, and baroclinic circulation is essential during summertime due to the high discharge of river freshwater and strong stratification, while it is negligible during the wintertime because of strong mixing induced by winds and waves (Wang *et al.*, 2010a).

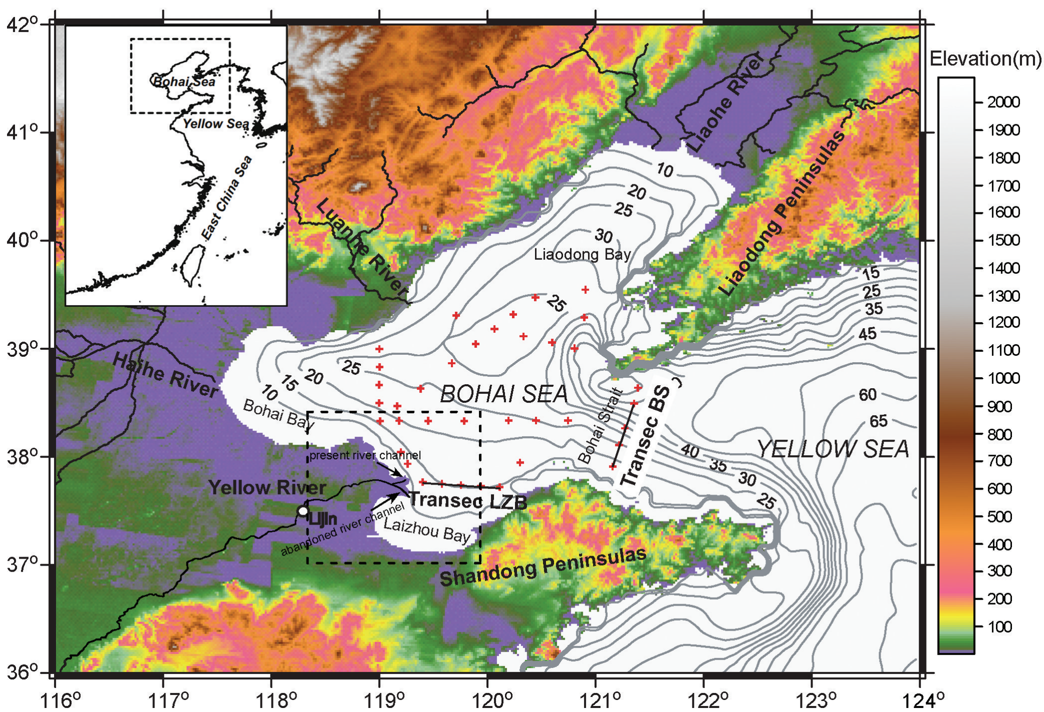


Figure 1. Topography of the Bohai Sea (depth in meter) and stations for cruises in 2012

Wind waves are critical to the sediment transport, especially to the sediment resuspension. The wave heights are smallest in summer when the prevailing southeastern winds occur from July to August, while are largest in winter with the prevailing northwesterly winds from October to March (Wang *et al.*, 2014; Wang *et al.*, 2012; Yang *et al.*, 2011). The mean annual maximum wave heights are usually identified near the Bohai Strait about 1.1 m (MGLIO, 1985).

The dynamics of the Bohai Sea are significantly affected by the seasonal variation of the strength of the East Asia Monsoon, with strong hydrodynamics in winter and weak hydrodynamics in summer. In summer, more than 60% of water and sediment discharged to the sea from the Huanghe (Wang *et al.*, 2007b). However, ~90% of the river-derived sediments were directly deposited near the river mouth given the weak hydrodynamics in summertime and the barrier effects of shear front off the Huanghe River Mouth (Bi *et al.*, 2010; Bi, 2009; Li *et al.*, 2001; Wang *et al.*, 2007a). In wintertime, the energetic wave actions induced significant resuspension of the previously deposited sediment in the shallow area and resulted in high amount of sediment exporting to the open ocean (Bi *et al.*, 2011; Yang *et al.*, 2011). The suspended sediment was transported through the Bohai Strait and dispersed into the Yellow sea along the coast of Shandong Peninsula (Alexander *et al.*, 1991; Bi *et al.*, 2011; Cheng *et al.*, 2004; Li *et al.*, 2010a; Martin *et al.*, 1993; Qin and Li, 1983; Yang *et al.*, 1989).

DATA AND METHODS

Cruise and sampling

Based on the multidiscipline oceanographic observations in different seasons in the Bohai Sea and the Yellow Sea supported by the National Science Foundation of China (NSFC), two transects were selected in the Laizhou Bay and Bohai Strait to illustrate the suspended sediment transport and its dispersal patterns. The cruises were conducted by R/V Dong Fang Hong 2 from May 15 to May 20, 2012 and Nov. 16 to Nov. 19, 2012. Water samples and the parameters of temperature, salinity were collected by the CTD (Model: SeaBird 911 Plus) cast packaged with Niskin bottles at each grid station. At the grid station, samples at 3 or 4 specific layers (at the surface, in the middle of the water column and in the bottom layer at 2-3m above the sea bed) depending on the local water depth were taken. It took about 10 to 20 minutes to complete the CTD operation and approximately 10 hours to finish the water samples collecting of one transect. The water samples of 1000 mL were filtered onboard by pumping (using the instrument of GAST model pump) through pre-weighted and double-layer membrane of 47 mm diameter and pore diameter of 0.45 um. The suspended sediment concentration (SSC, mg L^{-1}) was calculated from the ratio of sediment mass (with remove of the mass of membrane) to the volume of water after the filter. The filtered sediment was washed three times with distilled water to remove sea salt, then dried at 60℃ for 24 hours and weighted using electronic balance (1/100 000) in laboratory.

Retrieve of satellite remote sensing data

The Aqua spacecraft which has an on-board Aqua MODIS (Moderate Resolution Imaging Spectroradiometer) views the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands within a range of 405-14 385 nm with spatial resolution of 250 m for bands 1-2 500 m for bands 3-7 and 1000 m for bands 8-36. Band 1 (spectral range of 640-670 nm) itself or coupled with band 4 (spectral range of 545-565 nm) is widely used to retrieve suspended sediment concentration in coast water (Bi *et al.*, 2011; Han *et al.*, 2006; Miller and McKee, 2004; Petus *et al.*, 2010; Warrick *et al.*, 2004). MODIS L1B imageries are accessed from the MODIS L1 and Atmospheres Archive and Distribution System (LAADS) of NASA (http://ladsweb.nascom.nasa.gov/data).

The MODIS imageries data were re-projected for geometric calibration to removal of the bow-tie effect and then corrected for the atmospheric effect in the interesting area (see Bi *et al.*, 2011) using ENVI 4.6.1. Then imageries were selected to establish the relationship (Figure 2) between water-leaving reflectance ratio of band 1 to band 4 and the measured SSC in surface layer, if the ranges of time between the acquisition of MODIS imagery and field sampling were less than 30 min in coastal areas shallower than 15 m and 3 h in offshore area deeper than 15 m.

$$SSC = \exp(6.16 \times R645/R555) \times 0.058$$

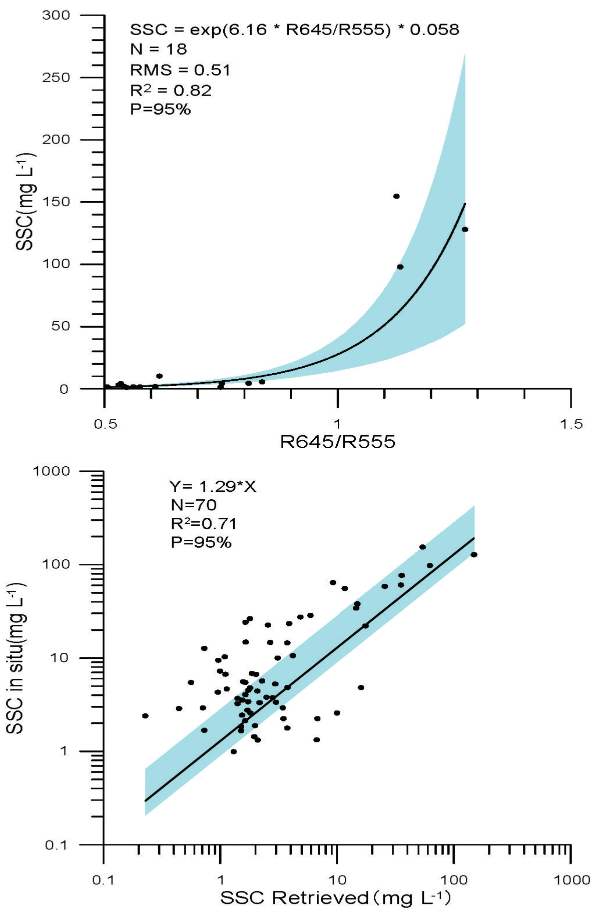


Figure 2. The SSC as an exponential function of the ratio of the reflectance values of band 1 (R645) with band 4 (R655) (A) and the evaluation curve of retrieval quality (B)

where SSC represents the suspended sediment concentration ($mg\ L^{-1}$), R645 and R555 are the water-leaving reflectance values of Band 1 and Band 4, respectively. Such a statistical relationship with a determination coefficient of $R^2 = 0.82$ allows a conversion of MODIS data to surface suspended sediment concentration at regional scale.

Subsequently the monthly averaged suspended sediment concentration can be calculated based on the 3 to 12 daily cloud-free MODIS imageries and the model of SSC retrieval.

Ocean current data were accessed from the production of Hybrid Coordinate Ocean Model (HYCOM) (http://hycom.org). As a primitive equation ocean general circulation model, it was improved from the Miami Isopycnic-Coordinate Ocean Model (MICOM). Among various HYCOM production, HYCOM+NCODA Global 1/12° Analysis (GLBa 0.08) data were selected to calculate the transport flux, that were carried out on the HYCOM 2.2 dynamical model and native Mercator-curvilinear horizontal grid. There were 32 vertical layers which were interpolated on isopycnic in the open, stratified ocean, Z coordinates in the weakly-stratified upper-ocean mixed layer, to terrain-following sigma coordinate in shallow water regions and back to level coordinates in very shallow water. In the Bohai Sea, there were only 5 vertical layers, with surface, 10 m, 20 m, 30 m and 50 m, respectively. Surface forcing was from Navy Operational Global Atmospheric Prediction System (NOGAPS) and includes wind stress, wind speed, heat flux (using bulk formula) and precipitation, so that the calculated results were greatly improved.

RESULTS

Seasonal variation of the sediment transport flux based on observations

Two transects were selected to present the vertical dispersal patterns and their seasonal variability: (1) transect LZB located at the mouth of Laizhou Bay and (2) transect BS across the Bohai Strait. The sediment transport efficiency and sediment transport flux were calculated as follows:

$$SSE = SSC_i \times u_i + SSC_i \times v_i \tag{1}$$

$$SSF = \int_0^t \int_0^L \int_0^H SSE\,\mathrm{d}h\,\mathrm{d}l\,\mathrm{d}t \tag{2}$$

Where H represents the thickness of the layer, which depends on the local water depth, L is the length of transect, i is the layer number, u and v are the components of eastward and northward current velocity which are perpendicular to the transects, and t is the time in seconds.

Sediment transport at transect LZB

Transect LZB is located near the present mouth of the Huanghe River with water depth less than 18 m (Figure 1), where the coarse silt covers most of the surface (Wang *et al.*, 2014).

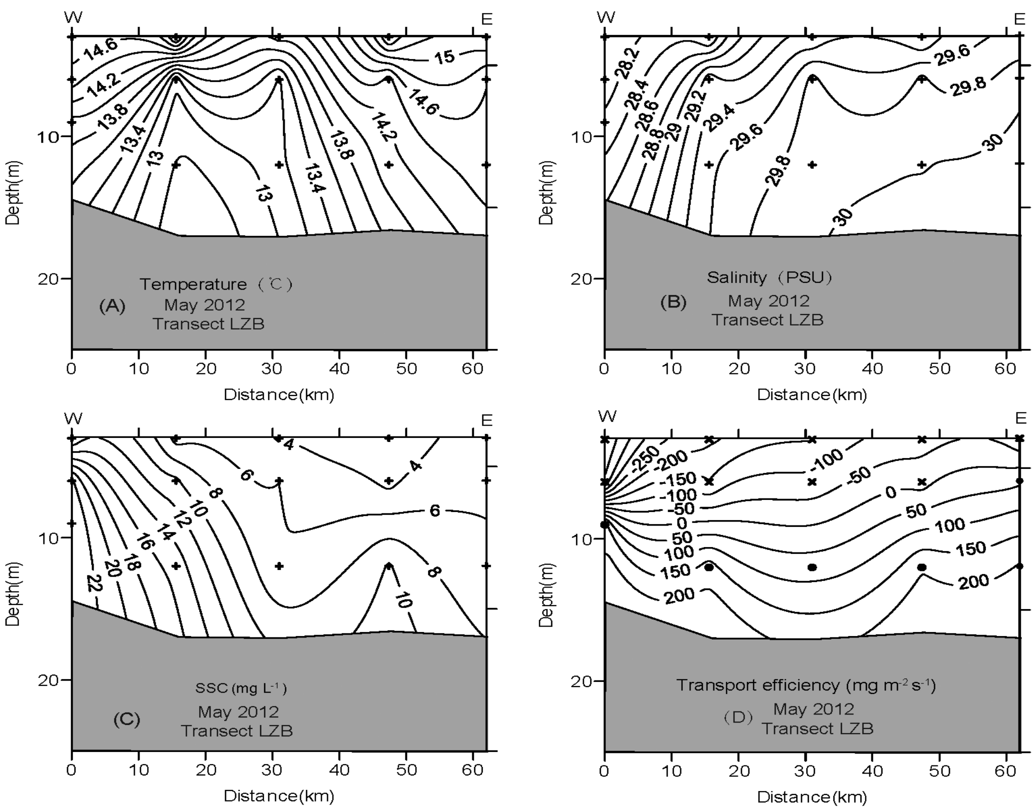


Figure 3. Vertical variation of temperature (℃) (A), Salinity (PSU) (B), Suspended sediment concentration ($mg\ L^{-1}$) (C), Suspended sediment transport efficiency ($mg\ m^{-2}\ s^{-1}$) (+represent the samples collected layer, ×represent the northward flow and · represent the southward flow) (D) at transect LZB in May 2012

In May 2012, high temperature was identified in the near-shore area in both the western and the eastern coast of the Laizhou Bay, and the lower temperature (< 13℃) was found in the middle of transect with a thermocline at 5 m below surface (Figure 3A). The salinity increased eastwards with a halocline in the eastern side, which indicated the influence of freshwater discharge from the Huanghe. The profiles of SSC presented the impacts of river plume as indicated by the high SSC in the western side of transect, whereas the SSC in the eastern side was relatively higher than that in the middle of transect (Figure 3C). The results indicated that the sediment in the surface layer was transported to the central Bohai Sea while those in the bottom layer was transported to the Laizhou Bay but with low transport efficiency (< 250 mg m^{-2} s^{-1}) (Figure 3D). In November 2012, the average temperature decreased to 10℃ and the vertical mixing was enhanced (Figure 4 A and B). However, the SSC became much higher, approximately 10 times of that in May, although the sediment discharge from the Huanghe (~2.6 million tons) was comparable to that in May (~3.0 million tons). The primarily high SSC was found in the western side of transect near the present river mouth with vertically uniform distribution, while the secondly high SSC was found in the eastern side of transect in the bottom layer (Figure 4C). The pattern of SSC distribution in wintertime might be resulted from the significant resuspension due to strong wave actions in shallow water (Jiang *et al.*, 2004; Jiang *et al.*, 2000; Wang *et al.*, 2014). The high SSC resulting from wave actions in combination with the enhanced coastal currents led to the transport efficiency much higher than that in May with maximum of more than 2000 mg m^{-2} s^{-1} (Figure 4D). The anti-clockwise transport indicated that the sediment entered into Laizhou Bay along its western coast and exported to southern Bohai Strait from the eastern coast mostly within the bottom layer.

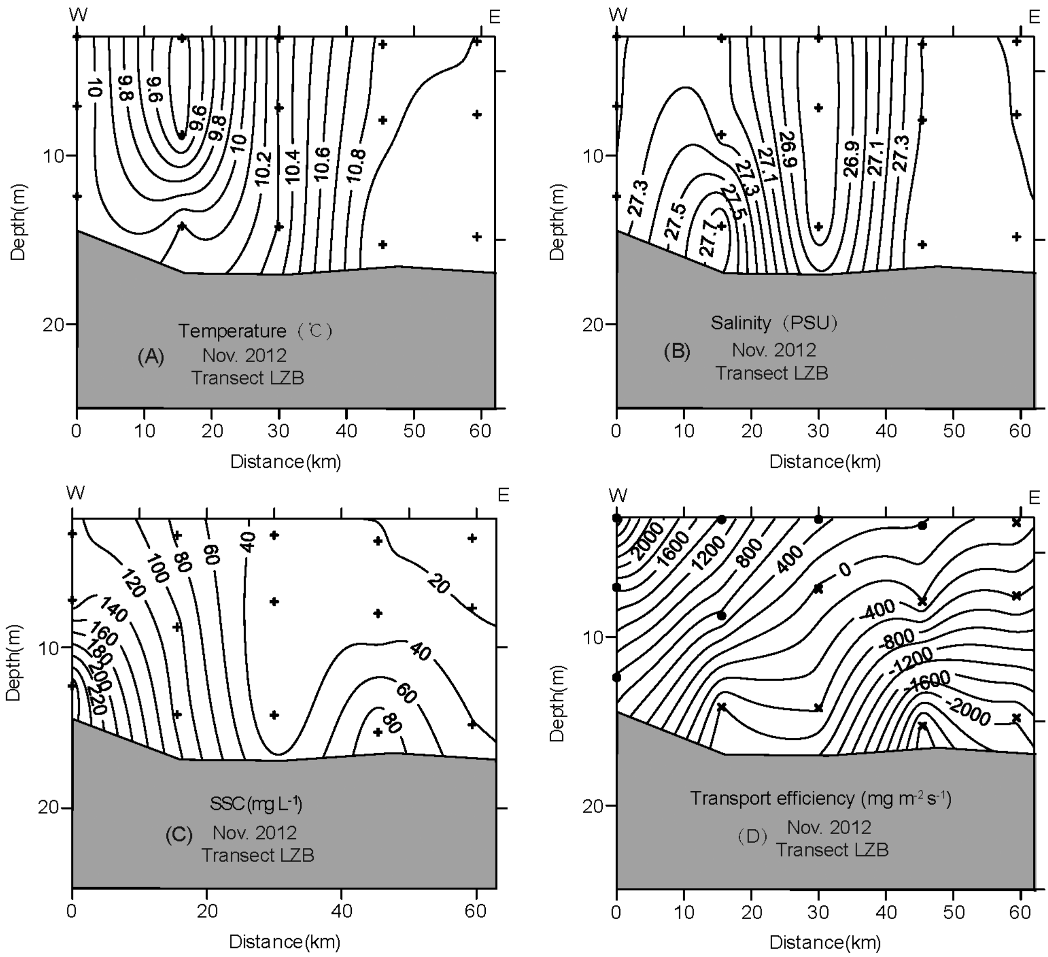


Figure 4. Vertical variation of temperature (℃) (A), Salinity (PSU) (B), Suspended sediment concentration (mg L^{-1}) (C), Suspended sediment transport efficiency (mg m^{-2} s^{-1}) (+represent the samples collected layer, ×represent the northward flow and · represent the southward flow) (D) at transect LZB in November 2012

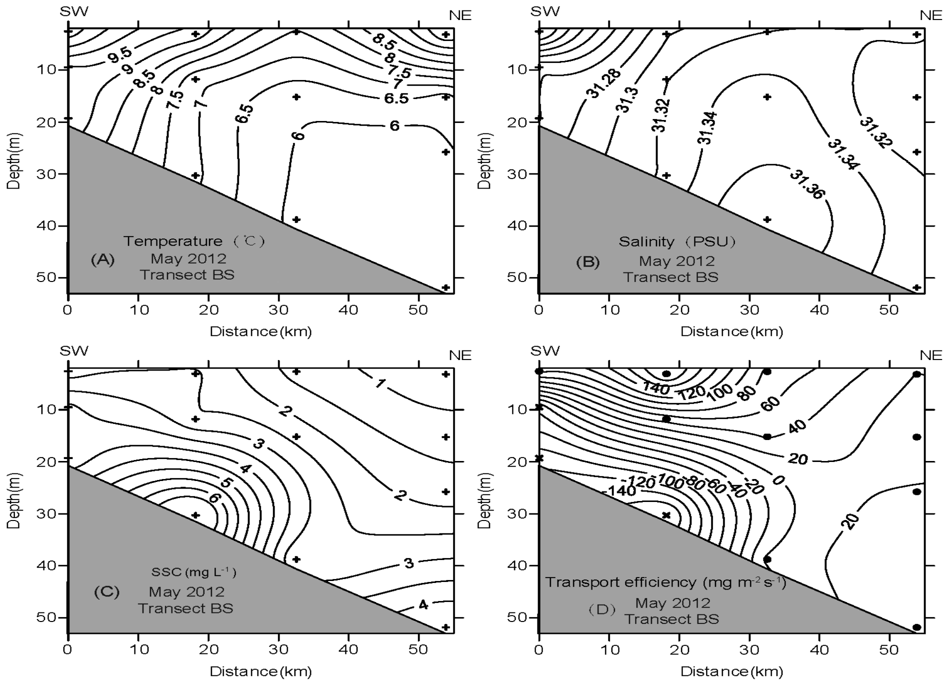


Figure 5. Vertical variation of temperature (℃) (A), Salinity (PSU) (B), Suspended sediment concentration (mg L^{-1}) (C), Suspended sediment transport efficiency (mg m^{-2} s^{-1}) (+represent the samples collected layer, ×represent the northwestward flow and · represent the southeastward flow) (D) at transect BS in May 2012

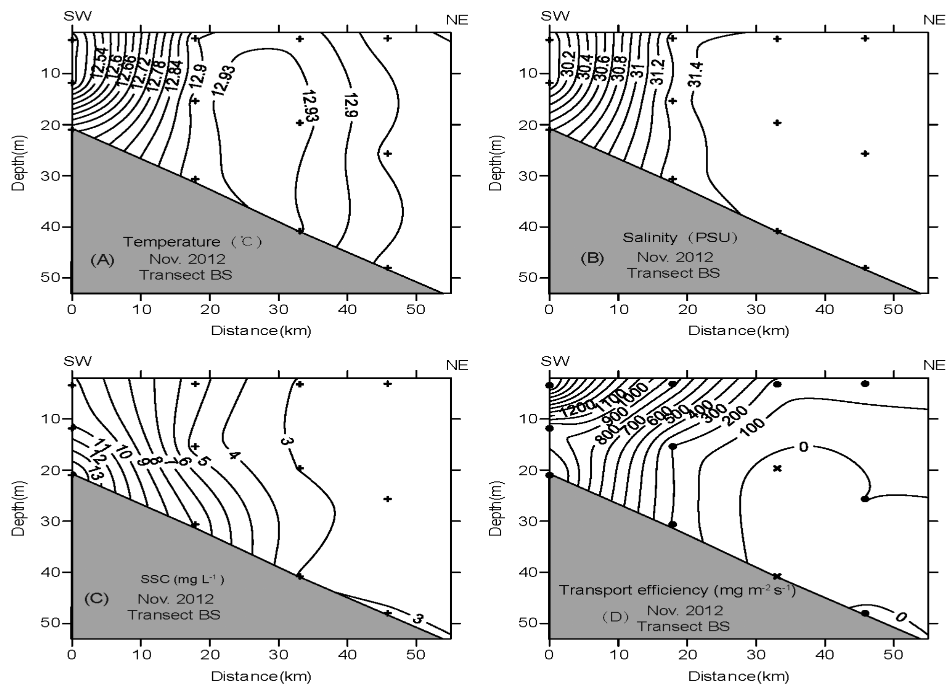


Figure 6. Vertical variation of temperature (℃) (A), Salinity (PSU) (B), Suspended sediment concentration (mg L^{-1}) (C), Suspended sediment transport efficiency (mg m^{-2} s^{-1}) (+ represents the samples collected layer, × represents the northwestward flow and · represents the southeastward flow), (D) at transect BS in November 2012

Sediment transport at transect BS

In May 2012, the water column presented significant stratification as the cool and saline water was mostly concentrated in the bottom layer in the northern Bohai Strait (Figure 5A and B). The SSC increased slightly downward with the maximum of 7.6 mg/L in the near-shore bottom water. The transport efficiency was fairly low as well, about 100 mg m^{-2} s^{-1}. The sediment export generally directed to the Yellow Sea except for that in the bottom water of southern Bohai Strait (Figure 5 C and D). In November 2012, the vertical mixing was evidently enhanced (Figure 6). The profiles of temperature and salinity showed that the horizontal gradients were more significant than the vertical gradients. Compared with the profile in May 2012, the SSC was much higher in the southern Bohai Strait, while the SSC in the northern strait was almost unchanged. The sediment was transported to the Yellow Sea through the south Bohai Strait with high sediment transported efficiency (Figure 6D). The datasets at transect BS in wintertime indicated that suspended sediment exported to the Yellow Sea was concentrated in the southern Bohai Strait and driven by the enhanced coastal current, whereas the sediment transport to the Bohai Sea from the Yellow Sea was found in the northern strait but with very low flux (Jiang *et al.*, 2004; Ren and Shi, 1986).

Seasonal variation of the suspended sediment flux and its dispersal patterns based on MODIS data

Although the MODIS imagery can retrieve only the surface SSC (Bi *et al.*, 2011), we can still use the limited datasets to quantitatively analyze the seasonal variation of sediment dispersal patterns in quantitative. The transport efficiency was calculated based on the MODIS-derived surface SSC and monthly depth-averaged current derived from HYCOM.

The sediment transport efficiency in the Bohai Sea showed evident seasonal variability (Figure 7). In summertime, the sediment discharged from Huanghe was transported northeastward to the central Bohai Sea along the offshore current but with low transport efficiency, which was partly exported to the Yellow Sea through the middle Bohai Strait. In wintertime, the sediments discharged by the Huanghe and those resuspended from the shallow water were transported to the Laizhou Bay along the coast, forming an anti-clockwise dispersal pattern (see Figure 4D). Driven by the enhanced coastal current in wintertime, the sediment was transported to the southern Bohai Strait from the Laizhou Bay, and exported to the Yellow Sea (Figure 7 k and l). As a result, a longshore belt with high transport efficiency was extended clearly along the coast of Shandong Peninsula.

DISCUSSION

Mechanism of seasonal variation of suspended sediment flux and patterns of sediment transport

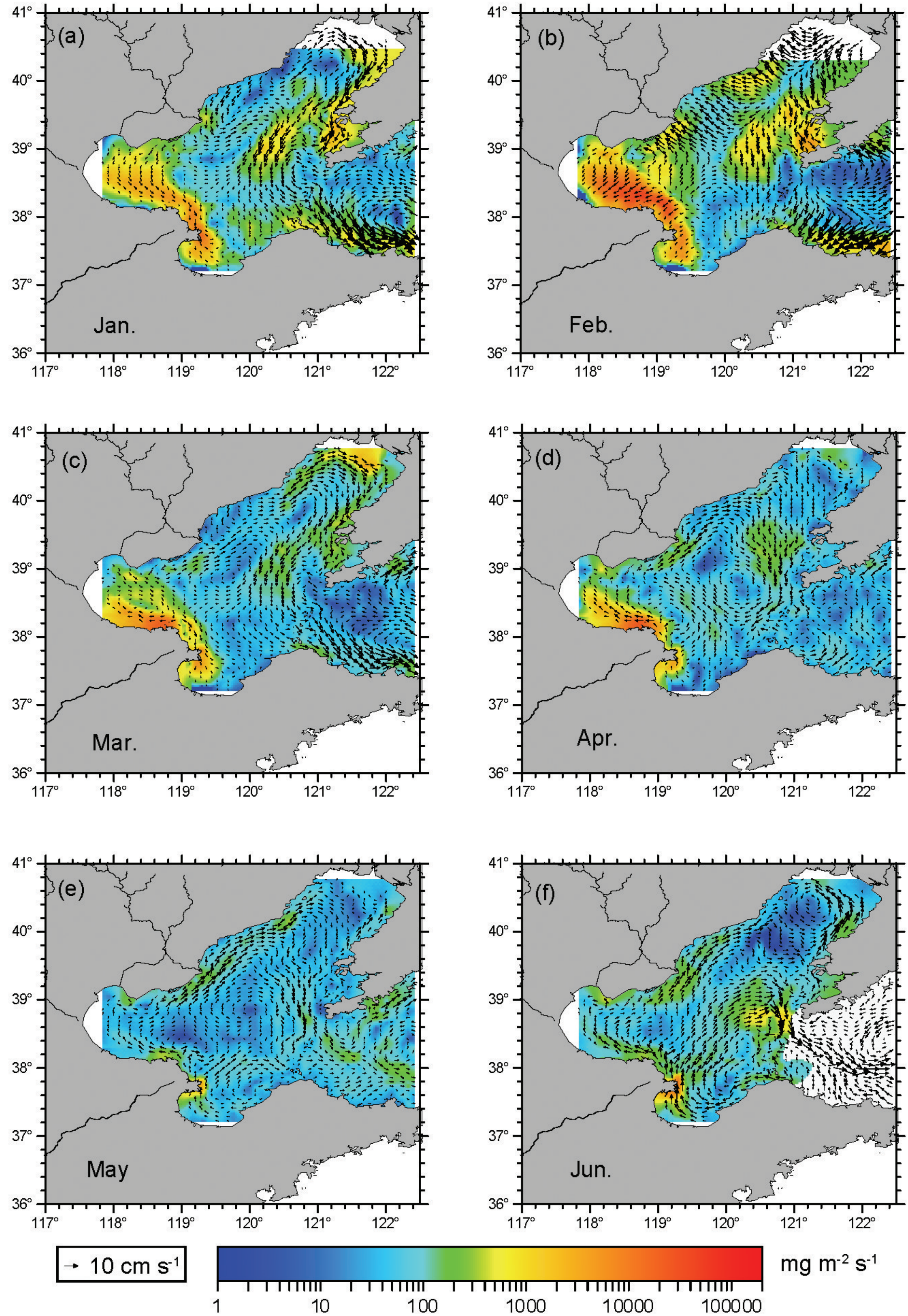
The Huanghe River sediment discharge and the hydrodynamic condition play an important role on the seasonal distributions of suspended sediment (Bi *et al.*, 2011; Jiang *et al.*, 2000; Wang *et al.*, 2014). As shown in Figure 8 A, the freshwater and sediment were discharged to the sea from the Huanghe mostly during the summertime, which presented strong seasonal variability. In contrast, the MODIS-derived monthly surface SSC averaged in the Huanghe Delta (see the dashed line area in Figure 1) illustrated a pattern in reverse to the river discharge (Figure 8C) with high SSC in wintertime. The retrieved data of daily significant wave height from WAVEWATCH III model and daily current velocity from HYCOM confirmed that the high SSC (approximately 10 times of the concentration in summer time) along the Huanghe Delta was mostly derived from wave-induced resuspension in wintertime, since in the wintertime the strong northerly wind could produce considerable waves to resuspend the previously deposited sediment, whereas the prevailing southerly wind had marginally impact on that (Figure 8B, C). Meanwhile, the enhanced coastal currents became a primary forcing to the sediment transport along the coast and sediment export to the Yellow Sea. Although more than 80% of the Huanghe sediment was discharged into the Bohai Sea during June to August, due to the Water and Sediment Regulation Project, the SSC was fairly lower together with less energetic condition in summertime (Figure 8C). In addition, the tidal shear front off the Huanghe mouth was an effective barrier for the offshore transport of river discharge and ~90% of the river-deliver sediment was deposited rapidly inside the shear frontal zone (Bi *et al.*, 2010; Bi, 2009; Wang *et al.*, 2007a). Recent study using the tracing particles in the Bohai Sea also indicated that the total particle number accumulated the maximum at the end of the first year, but decreased sharply in the winter and spring (Liu *et al.*, 2012).

Suspended sediment flux across the Laizhou Bay and through the Bohai Strait

Our data from cruise observations provided detailed profiles of SSC, but were limited in term of time period. Although the MODIS data could cover a large temporal scale, the derived data were limited to surface layer and could not provide vertical profiles of SSC. Here we used the Kriging Interpolation (linear model) to infer the vertical section of the suspended sediment concentration based on the surface SSC retrieved from MODIS. According to previous studies, there were two major vertical distribution models in the Bohai Sea: slash distribution with uniform gradient and quasi-straight line distribution with slightly changing from the surface to the bottom layer (Gu and Hu, 1989).

The weight factor used in this model was calculated from the in-situ data in May and November, 2012 based upon the assumption that there were two seasons in a year, summer (April to September) and winter (October to March) and each season only had one vertical structure of the water column. This assumption was reasonable because of the seasonal variation of the monsoon activity with southerly and southeasterly winds prevailing in summer and northerly and northwesterly winds dominating in winter (Wang *et al.*, 2014).

The interpolated results reproduced the general features of SSC distribution through water column at transect LZB (Figure 9). For example, the SSC was much higher in winter season with well-mixed water column (Figure 9A) than that in summer season (Figure 9C). Two zones with high SSC were identified at the western side of transect near the Huanghe River mouth and at the bottom of the eastern side of transect in both summer and winter seasons, which indicated the pathway of sediment transport within the Laizhou Bay. These primary features were coinciding with the observations discussed in the section of sediment transport at transect LZB. Thus, it can be concluded that the model was capable to retrieve the seasonal distributions of SSC though the water column.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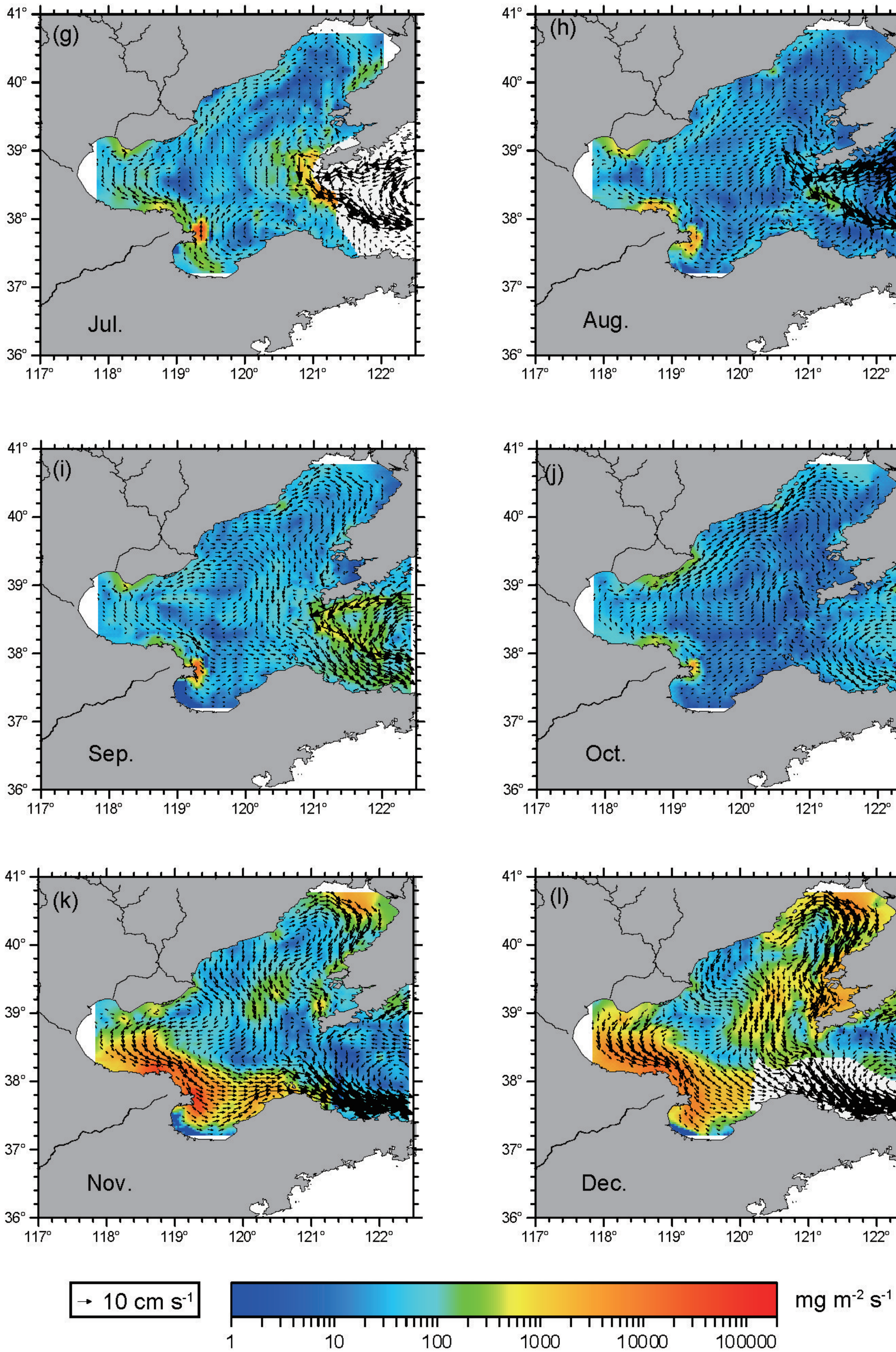

Figure 7. Seasonal variations of suspended sediment transport efficiency (mg m^{-2} s^{-1}) and its dispersal patterns based on the model of SSC and ocean current from HYCOM (http://hycom.org)

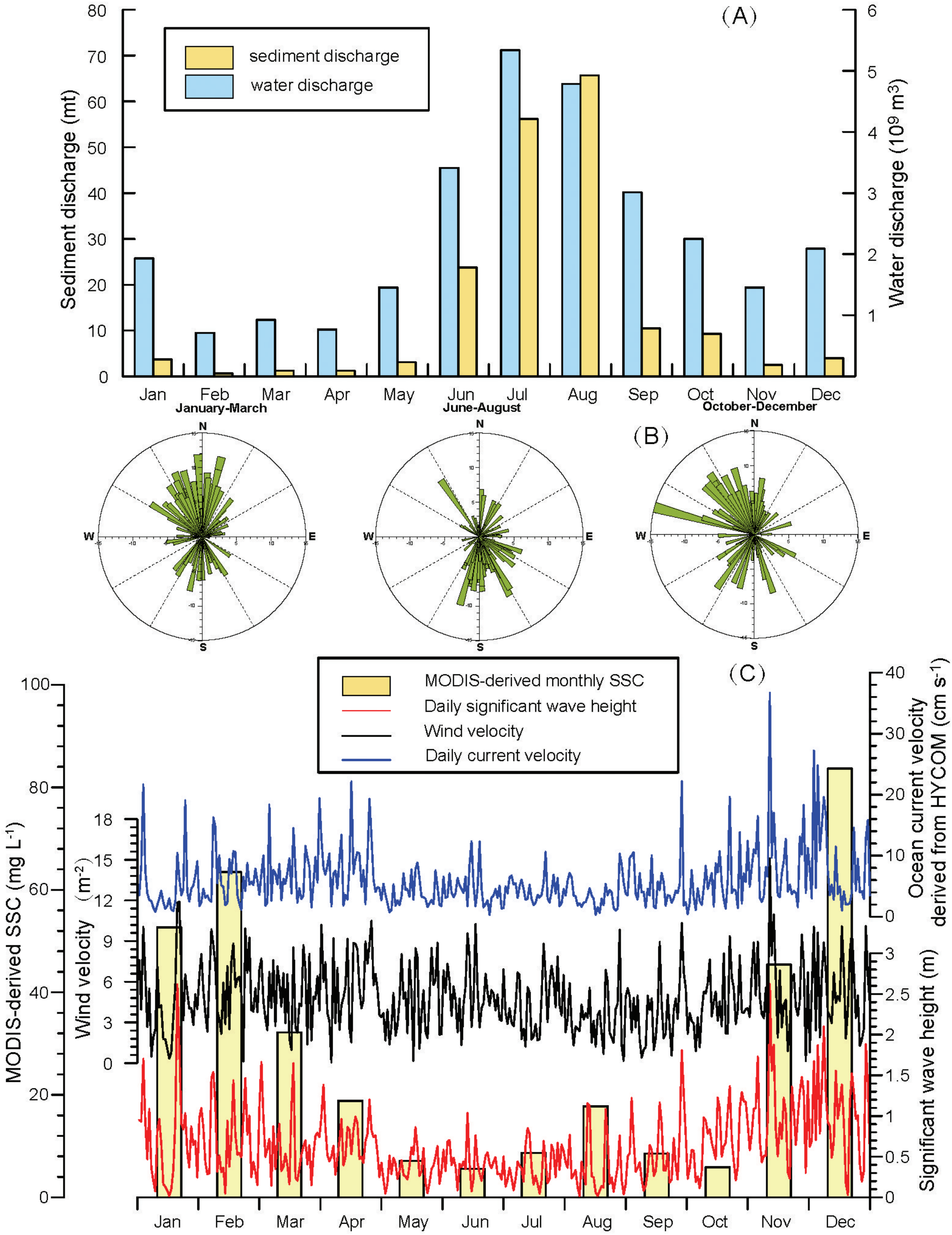

Figure 8. Monthly discharge of water and sediment at gauging station Lijin (Location show in Figure 1) in 2012 (Data are from Yellow River Sediment Bulletin, available at http://www.yellow river.gov.cn/nishagonggao/) (A); Seasonal wind rose diagrams at 120°E, 37.5°N (B); Daily wind velocity, spatially averaged daily significant wave height, ocean current velocity and monthly surface suspended sediment concentration (SSC) derived from MODIS data in the southern Bohai Sea in 2012. The data of daily wave heights are derived from the WAVEWATCHIII Global Model with a spatial resolution of 0.5°. The daily wind data are retrieved from NCEP-DOE Reanalysis Ⅱ data with a spatial resolution of 2.5°×2.5° which are available at Earth System Research Laboratory (http://www.esrl.noaa.gov/). The domain for spatial average is shown in Figure 1 as the dashed line (C)

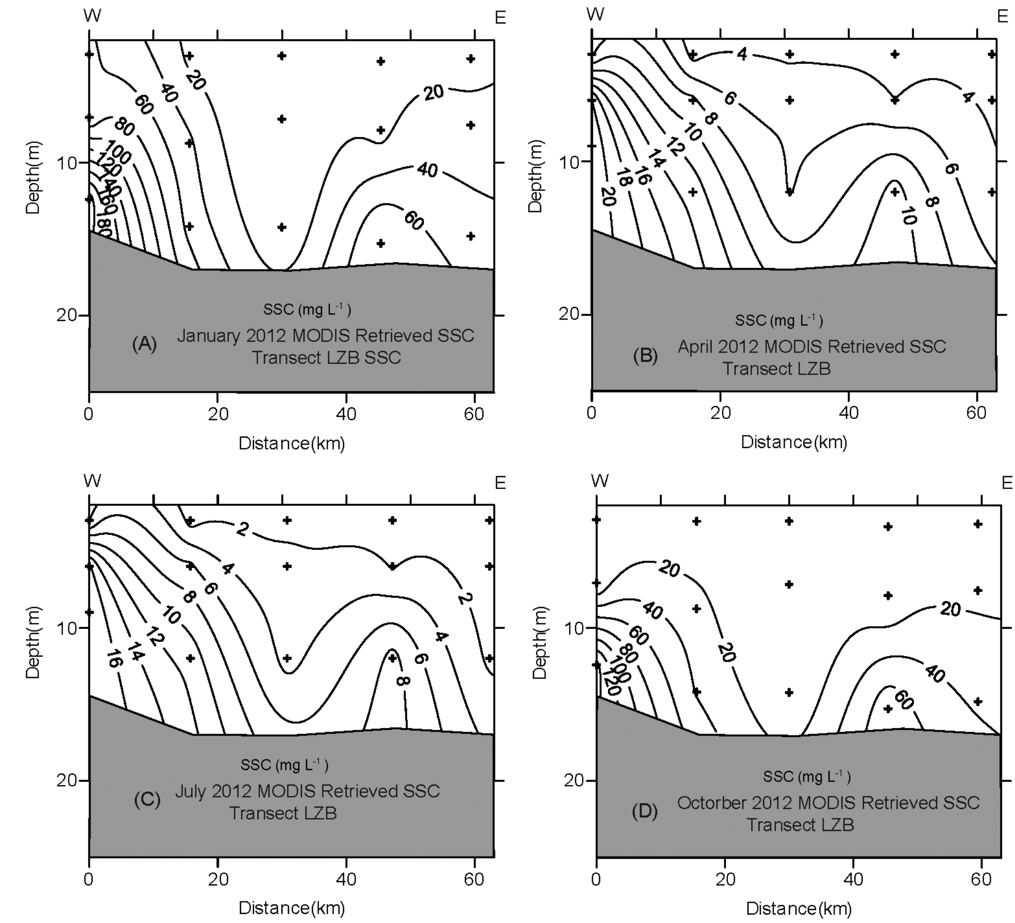

Figure 9. Vertical distribution of suspended sediment concentration (mg L^{-1}) at transect LZB based on the model of SSC retrieval and Kriging Interpolation (Linear Model)

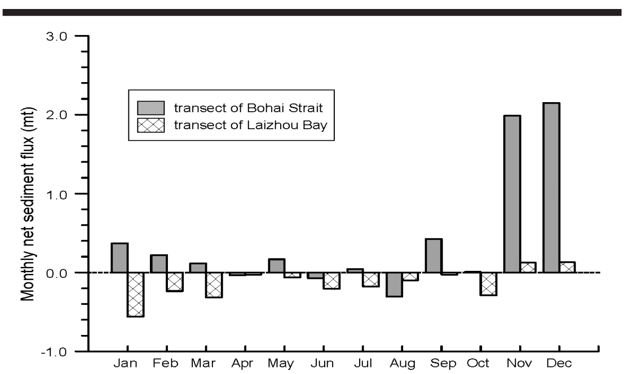

Figure 10. Seasonal variation of net suspended sediment flux (Mt) across Laizhou Bay and in Bohai Strait

The estimate of annual net sediment flux (Figure 10) indicated that the annual net sediment flux was negative at transect LZB, about 1.75 Mt, which meant that most of the suspended sediment was escaping from the Laihzou Bay rather than accumulating within the bay area. The annual net sediment flux through the Bohai Strait was about 5.07 Mt; however, the estimate seemed to be much less than the results proposed by Bi *et al.* (2011) (about 40 Mt) and Li *et al.* (2010b) (about 42 Mt). The underestimation was probably ascribed to the limited transects scope (See Figure 1) and simplified vertical structure of the water column. Since the Kriging Interpolation (linear model) was simply based on the weight factor calculated from the in-situ data in May and in November, 2012 with a limited range and the assumption of two seasons in a year, the coastal region, the significant pathway for sediment transportation and complicated seasonal changes were out of consideration, otherwise the sediment flux would be more than 10 Mt. In addition, Bi *et al.* (2011) estimated the sediment flux only based on two point data in winter and summer without considering the SSC spatial variation and the sediment flux was all the material from the Bohai Sea to the Yellow Sea rather than the net exchange between those two seas that would be overestimation. Furthermore, sea ice was perhaps the other significant factor for underestimation. In 2012, the area of sea ice coverage in the Bohai Sea was estimated to be 34 000 km^2 in the wintertime (data from the Chinese Marine Disaster Bulletin released by the Ministry of Land and Resources of People's Republic of China). The coverage of sea ice in the coastal region effectively restrained the coastal resuspension and decreased the coastal current, which eventually decreased the sediment flux through the Bohai Strait. Bi *et al.* (2011) estimated the sediment flux through the Bohai Strait based on the observational data in wintertime of 2006 when the coverage of sea ice had been the lowest during the past 25 years (see the Chinese Marine Disaster Bulletin). Therefore based on the in-situ data only in one year, the estimates showed contingency and particularity. It was not enough to illustrate the universal law of the sediment dispersal pattern and to estimate the annual net sediment flux. Therefore, more data collected in different seasons or months with a wide scope across the Bohai Strait are needed to improve estimating accuracy.

Although the limited transects scope, simplified vertical structure of the water column and the sea ice had significant impacts on the seasonal sediment flux, we found that sediment flux through the Bohai Strait in wintertime was much higher than that in summertime by one order in magnitude. Therefore, the wintertime should be a primary time window for sediment export to the Yellow Sea from the Bohai Sea.

CONCLUSIONS

Based on the combined data of the ship-based observations in the Bohai Sea in May and November, 2012, MODIS-derived SSC and the ocean currents simulation from HYCOM, this paper presented sediment dispersal patterns in the Bohai Sea, estimated the annual net sediment flux through the Laizhou Bay transect and the Bohai Strait and its possible mechanisms were discussed.

Under the influence of seasonal variation of the Huanghe sediment discharge and the hydrodynamic condition (*e. g.* wave height, ocean current), the sediment dispersal patterns and the monthly net sediment flux presented evident seasonal variability. In summertime, the river-derived sediment primarily accumulated within the subaqueous delta although more than 80% of the Huanghe sediment was discharged to the sea during that time. Only fine-grained sediment might be transported to the central Bohai Sea as favored by the river plume and was then exported to the Yellow Sea through the middle Bohai Strait. As a result, the net sediment flux in summertime was estimated to be about 0.23 Mt. Nevertheless, the net sediment flux in wintertime increased significantly to 4.84 Mt, one order higher than that in summer time, as a result of the combined effects from strong coastal resuspension and enhanced coastal currents. The Laizhou Bay seemed to be a major pathway for the anti-clockwise transport of resuspeded sediment. The annual sediment flux to the Yellow Sea might vary largely year by year due to the impacts from the sea ice coverage in the coastal region of the Bohai Sea.

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