Periodic Oscillation of Sediment Transport Influenced by Winter Synoptic Events, Bohai Strait, China

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Abstract: Instruments on two bottom-mount platforms deployed in the Bohai Strait during a cruise from January 6–13, 2018 recorded an intense northerly wind event. The responses of hydrodynamic and hydrographical characteristics in Bohai Sea and Yellow Sea to the wind event were analyzed aided by the wind, wave, sea surface suspended sediment concentration and sea surface height datasets from open sources. It is shown that the strong wind event had a significant impact on the redistribution of sea surface height, regional wave conditions, regional circulations and the accompanying sediment transport pattern. Specifically, the sediment transport through the Bohai Strait may be divided into two chronological phases related to the wind event: (1) the enhanced sediment transport phase during the buildup and peak of the wind event when both the Northern Shandong Coastal Current and regional suspended sediment concentration were sharply increased; and (2) the relaxation phase when the northerly wind subsided or even reversed, accompanied by the enhanced Yellow Sea Warm Current with lowered suspended sediment concentration. Such results at synoptic scale would improve our capability of quantifying sediment exchange between the Bohai and Yellow sea, through the Bohai Strait and provide valuable reference for the study of other similar environments worldwide.

Keywords: Bohai Strait; synoptic events; sediment transport; volume transport; winter season

Highlights:
• One typical, intense winter wind event was captured by in situ measurements in the Bohai Strait.
• The patterns of circulations and sediment transports around the Bohai Strait were not always constant in winter, but shown oscillating processes corresponding to the synoptic events.
• A new conceptual model of sediment transport through Bohai Strait in winter was established to reveal the underlying mechanism more clearly.

1. Introduction

A strait is a natural channel that connects two large bodies of waters between which water and particle material are exchanged. Such exchanges of material (water, nutrients, sediment, etc.) and energy (heat) play a critical role in redistribution of heat, salt, pollutants and sediments—as well as regionally biogeochemical cycles [1–3].
The Bohai Strait (BHS) between Shandong and Liaodong peninsula is the only pathway connecting two epeiric seas in the northern China, the Bohai Sea (BH) and the North Yellow Sea (NYS) (Figure 1). The ~104 km wide BHS is the shallowest in the southern end, growing deeper northward with a channel as deep as 70 m offshore Liaodong Peninsula [4] (Figure 1). BH is a semi-enclosed shallow (<18 m) marginal sea that is located to the west of BHS [5]. The surface sediment distribution of the BH is characterized by fine-grained sediment covering the southwestern area and coarser sediment covering the east [6]. In BHS, the coarse silt covers the south and it gradually becomes coarser in the north with coarse sand and gravel. The sedimentation rate of the BH is lower than 0.3 cm/yr, except for the central mud area which is ~2 cm/yr [7]. The tidal regime in the BH is dominated by mixed semidiurnal tide with two main tidal constituents of K₁ and M₂. The maximum tidal current occurs in the north of the BHS with the velocity of 1 m/s [8]. The tidal range in the BHS is lower than 2 m [9]. The residual currents in the BHS are mainly impacted by seasonal monsoon activates and thermal/saline stratifications [10]. The winter circulation in the BH and Yellow Sea (YS) are mainly driven by the intense winter monsoon, while the circulations in summer are maintained by the tilting thermohaline as the wind is much weaker and heat flux is much stronger. Due to the prevailed strong northerly winds, the regional dynamics in winter are significantly stronger than those in other seasons [11]. As a densely populated and important economic zone, the state of the marine environment of BH has been of great concern. Several rivers discharge large amounts of nutrients, pollutants and other terrestrial materials into the BH. In particular, the Yellow River, the second largest river in terms of riverine sediment, transported about 1.2 Gt of terrestrial sediments into the BH annually [12–15]. Such terrestrial sediments not only accumulated quickly near the estuary, but also transported to the open ocean, through the BHS, contributing to the marine environmental and the geological evolution of the East China Sea [11,16–18]. Therefore, accurately characterizing the flux of water and sediment through BHS is of great importance.

**Figure 1.** A local bathymetric map showing the location of the observation sites (red stars). The red solid line is the transect across The Bohai Strait. The dotted contour lines are the iso-thickness of the Holocene mud in North Yellow Sea (the contour interval is 10 m; the thickness is about 40 m at the top of the deposit) [19]. The red and blue arrows indicated the Yellow Sea Warm Current (YSWC) and the Northern Shandong Coastal Current (NSCC) respectively [20].

In the past decades, numerous studies attempted to quantify the sediment transport using various methods such as sedimentary records [21], in situ observation [22], numerical models [23,24] and satellite remote sensing [25] and produced different and sometimes opposite results. The sediment...
transport is closely related to the regional circulation structure and the water exchange processes in BHS [11,26,27]. The traditional view of the BHS circulation structure is “inflow in the north and outflow in the south” [20]. The north of the strait is dominated by the Yellow Sea Warm Current (YSWC) [28], while the south by the Northern Shandong Coastal Current (NSCC) [24,29] (Figure 1). This circulation structure changes with seasonal monsoons, more evident in winter than in summer [11,25]. Previous studies mostly focused on the monthly or seasonal variation of the circulation using observations or numerical models [28,29]. However, recent studies showed that certain synoptic events, such as winter storms or summer typhoons, can significantly modulate the circulation system and sediment transport patterns (e.g., [30–33]). Due to lack of enough temporal (long, continuous time-series) and spatial (synchronized measurements at multiple locations) coverage of field data, how synoptic events such as the strengthening and weakening of winter storm winds alter the sediment transport patterns in the BHS is still unclear.

Here, we present the results and analyses based on field data from an 11-day in situ observation at two locations in BHS in January 2018, during which a typical intense northerly wind event occurred. Based on analyzing the variations of current fields and suspended sediments responding to the different wind conditions, aided by satellite remote sensing and numerical models, the mechanism of sediment transport through BHS affected by the synoptic events is explored and a new conceptual model of sediment transport in the winter is developed.

2. Data and Methods

The field data came from both moored time-series (Tripod, Bottom Mount and Moorings) and shipboard hydrographic surveys (25 h anchor stations) from January 2 to January 13, 2018. Bottom mounted platforms and subsurface moorings for time-series measurements were placed at two stations in the BHS, with T01 in the south at 30 m water depth and T02 in the north at 50 m water depth (Figure 2). The various type of instruments, their settings and placements are listed in Table 1.

| Period | Sampling | Interval | Depth (m) |
|--------|----------|----------|-----------|
| 6 January 9:00 to 7 January 10:00 | 1 h | 0.2, 0.4, 0.8 depth | 3/- |

Table 1. Instruments placements in this study and the details on their setup.

![Figure 2](image-url)  
**Figure 2.** A schematic drawing showing the instrument placements at the site T01 (a) and site T02 (b) respectively.
Table 1. Instruments placements in this study and the details on their setup.

| Stations | Observation Method | Instruments | Measurement Period | Sampling Interval | Depth (m) | Sampling Levels/Vertical Bin Size (m) | Blind Zone (m) |
|----------|--------------------|-------------|--------------------|-------------------|-----------|--------------------------------------|----------------|
|          | Anchor station     | Water samples | 6 January 9:00 to 7 January 10:00 | 1 h | 0.2, 0.4, 0.8 depth | 3/-          | - |
| T01      | Tripod             | CTD         | 6 January 9:00 to 13 January 12:00 | 1 min | 30 | 1/-                                    | -                |
|          |                    | ADCP        | 6 January 9:00 to 13 January 12:00 | 20 min, 1 h | 30 | 64/0.75 (velocity), 1/- (wave) | 1.55           |
|          |                    | ADV         | 6 January 9:00 to 13 January 12:00 | 10 min | 30 | 1/-                                    | -                |
|          | Subsurface mooring | TU          | 1 January 9:00 to 13 January 12:00 | 1 min | 15 | 1/-                                    | -                |
|          |                    | CTD         | 1 January 9:00 to 13 January 12:00 | 1 min | 15 | 1/-                                    | -                |
| T02      | Anchor station     | Water samples | 6 January 9:00 to 7 January 10:00 | 1 h | 0.2, 0.4, 0.8 depth | 3/-          | - |
|          | Bottom mount       | CTD         | 1 January 9:00 to 13 January 11:00 | 1 min | 50 | 1/-                                    | -                |
|          |                    | ADCP        | 1 January 9:00 to 13 January 11:00 | 20 min, 1 h | 50 | 64/0.75 (velocity), 1/- (wave) | 1.55           |
|          | Subsurface mooring | TUs         | 1 January 9:00 to 13 January 11:00 | 1 min | 22, 44 | 2/-                                    | -                |
|          |                    | CTDs        | 1 January 9:00 to 13 January 11:00 | 1 min | 22, 44 | 2/-                                    | -                |

Notes: ADCP: 600 kHz Acoustic Doppler Current Profiler with wave module; ADV: Acoustic Doppler Velocimeter; CTD: conductivity/temperature/pressure sensor; TU: turbidity sensor; Depths are relative to the sea level and 0.2, 0.4 and 0.8 mean 20%, 40% and 80% of the local water depth respectively.
In addition, a 25-hour (January 6, 10:00, UTC + 8 to January 7, 11:00, UTC + 8) synchronized casts were conducted from two vessels anchored at T01 and T02 (Table 1). Instruments mounted for the casts included a conductivity/temperature sensor (CT), a turbidity sensor (TU) and one Laser In situ Scattering Transmissometer profiler (LISST). Water samples were collected with Niskin bottles at 3 heights (0.2, 0.4 and 0.8 of total water depth) every hour. The water samples were pumped through pre-weighted micropore filter pairs with 450 µm pore size and 47 mm diameter to be filtered. The filters were first washed three times with distilled water to remove the sea salt, then dried in an oven at 60°C for 24 hours and then weighed with a high-precision electronic balance. The suspended sediment concentration (SSC) was calculated using the sediment weight and the filtered water volumes [25].

Auxiliary data used in this study were downloaded from various open sources. Wind data are the hourly time-series products from National Centers for Environmental Prediction Climate Forecast System Version 2 (NCEP/CFSv2) with a horizontal resolution of 0.205° × 0.204° over BHS. In previous studies, the NCEP/CFSv2 wind products performed well in East China Sea [34]. Gridded hourly sea surface height (SSH) data with a map spacing of 0.083° × 0.083° were obtained from the Copernicus Marine and Environment Monitoring Service (CMEMS) global ocean physical analysis and forecasting products. For shallow and coastal waters, the correlation coefficients between the CMEMS products and tide gauge series ranges between 0.78 and 0.82 [31,35]. Sea surface SSC data were obtained from the Geostationary Ocean Color Imager (GOCI) L2 products with high spatial and temporal resolution. In coastal waters, GOCI-derived turbidity variation was reliable and can efficiently reflect the temporal dynamics of the turbidity [36]. Significant wave height data were derived from NOAA WAVEWATCH III global model which was widely used in study areas [11,37].

The in situ current profiles from the ADCPs during the observation are shown in Figure 3. In order to better describe the responses of hydrodynamic processes of BHS to the synoptic events, this study only focused on the subtidal current and residual water level. Specifically, the following processing methods were used to remove the tidal signals. First, we used the T_Tide [38] toolbox to predict the time series tidal current during the observation period. Then, the predicted tidal currents were subtracted from the raw current field to remove the tidal component. Lastly, the residual currents were smoothed by moving average with a 1-hour window to filter the high frequency variability. The residual currents were considered as the subtidal currents. Meanwhile we used the bottom pressure records to retrieve the water level which was then processed using the same method to obtain the residual water level.

In addition, we use the relationship between backscatter voltage (V_{rms}) and SSC proposed by Thorne and Hurther (2013) for inversion calculation to obtain SSC profiles with higher vertical and temporal resolution [39]:

$$SSC_i = \frac{(V_{rms} \cdot \phi(r) \cdot r)^2}{K_t \cdot K_s} \cdot e^{A(\alpha \cdot r)}$$  (1)

$V_{rms}$ is calculated by the backscatter intensity (E) measured by ADCP according to $V_{rms} = 10^{K_c \cdot E/20}$. $K_c$ is the conversion number of raw backscatter from a dB scale to a voltage scale. $\phi(r)$ is the near-field correction related to $r$ (distance from the measuring point to the transducer), the radius of the transducer and the signal wavelength; $K_t$ is a constant and is a measure of the instrument sensitivity; $K_s$ is the parameter of the scattering properties of sediment with mixed mineralogy, which depends on the particle size, particle distribution characteristics and backscattering of suspended particles; $\alpha$ is the absorption of sound by seawater, which depends on temperature, salinity, depth and pH (during observation: temperature is 7°C, salinity is 32 PSU and pH is 8). In this study, the calculated $\alpha$ was 0.019 nepers/m. In order to validate the accuracy of SSC obtained by inversion, we fitted the inversed SSC (SSC_{inv}) with the measured SSC (SSC_{obs}), their relationship shown in Figure 4c. SSC_{inv} and SSC_{obs} have a good relationship (determination coefficient ($R^2$) is 0.75), which means that SSC_{inv} can replace the real SSC during observation. The inversed SSC profiles are shown in Figure 4a,b.
Figure 3. Time-series of in situ current profiles (b) of site T01 (a) and site T02 (b) respectively during observation.

Figure 4. Time-series of inversed SSC profiles of site T01 (a) and site T02 (b) respectively during observation; (c) Comparison of the observed SSC (obtained by the water samples) and the inversed SSC at site T01 and site T02 respectively.

3. Results

3.1. Wind and Wave Conditions

The period from January 6 to January 13, when measurements were available at both stations, was selected for investigating the hydrological and hydrodynamic responses to the different wind conditions. A gale level wind event was captured from January 8 to January 11 (Figure 5a). Before the intense wind, a gradually subsided northerly wind prevailed around the BHS on January 6 and finally shifted to southerly wind on January 7. The overall wind speed was below 5 m/s. After that, the intense northwesterly wind dominated this area, which reached a gale level for a short period of time with the maximum speed of over 16.7 m/s. After January 11, the wind weakened and shifted to westerly or southwesterly. During the observation, there was a period of wind relaxation or reversal either before or after the intense wind respectively. According to the wind condition (both wind speed and direction), the observation period was divided into three phases, which are two wind relaxation or reversal phases (Figure 5: phase 1 (P1), phase 3 (P3)) and the intense northerly wind phase (the
northerly wind with the speed over 10.8 m/s (Figure 5: phase 2 (P2)). In this study, the northerly wind is broadly defined (including northerly and northwesterly).

![Wind Speed Diagram]

Figure 5. (a) Hourly wind vectors and magnitude (NCEP/CFSv2) of 10 m above the sea surface over the Bohai Strait January 6 to 13, 2018. Time-series of significant wave height (b), peak period (c) and peak direction (d) recorded by the ADCPs at site T01 and T02 respectively.

Wave had an obvious response to the wind with a lag of 3–6 hours (Figure 5b–d). The peak of wind occurred between 1 pm and 3 pm on January 8, 2018, while the peak of significant wave height \( (H_s) \) occurred between 6 pm and 7 pm on January 8, 2018. During P1, the \( H_s \) in the BHS was overall lower than 1 m and gradually decreasing, the peak period \( (T_p) \) was about 4 seconds and the peak direction \( (D_p) \) was relatively chaotic. As the intense wind was coming, the \( H_s \) significantly increased with the maximum of greater than 3 m on January 8 and the \( H_s \) in T01 was overall higher than that in T02 during the P2. The \( T_p \) also increased to 7-8 seconds. The \( D_p \) was stable and rotated clockwise along with the winds. As the northerly wind subsided, \( H_s \) gradually decreased, as did the \( T_p \). Until the wind turned to westerly or southwesterly, the \( H_s \) rose to 2 m again. At this moment, the \( H_s \) of T02 was higher than that of T01. The \( D_p \) remained stable and consistent with the wind direction.

3.2. Hydrological Characteristics during the Observation Period

During observation, as the water column of T01 and T02 was well mixed, the depth-averaged temperature, salinity and excess density were used to describe the temporal variation of hydrological characteristics and the differences between the northern and southern stations (Figure 6). Under the influence of YSWC in winter, the temperature of the northern side was about 0.5–1 °C higher than that
of the southern side, ranging from 5.5–7 °C in T01 and 6.4–7.5 °C in T02 respectively (Figure 6a). Salinity of the northern side was slightly lower than that of the southern side, ranging from 32.3–32.35 PSU in T01 and 32.25–32.28 PSU in T02 (Figure 6b). The density of T01 was slightly higher than that of T02 with the combination of temperature and salinity (Figure 6c). However, the water in this area could be considered uniform since the difference was so tiny that the baroclinic effect was negligible. During the observation period, both northern and southern sides showed a continuously decrease in temperature and increase in salinity. In T01, the temperature and salinity varied sharply during the intense wind, while became more stable with the obvious tidal signals after the wind subsided or shifted. In T02, the seasonal cooling and the tide were the main forces behind the changes of temperature and salinity instead of the wind.

![Wind: northerly wind](image)

**Figure 6.** Time-series of hydrological characteristics (temperature (a), salinity (b) and excess density (c)) in T01 and T02 during observation).

3.3. Water Level and Current Variation Responding to the Wind

The variation of the water level was consistent with that of the wind (Figure 7a). During P1, the water level was continuously rising about 0.3 m within two days under the effect of the weak wind. In the beginning of P2, the overall water level of BHS plunged about 0.8 m in one day affected by the intense wind and then gradually recovered with a periodic fluctuation during the later phase of P2 and throughout P3. As the circulations around BHS were barotropic processes in winter [32], only depth-averaged currents were used. Figure 7b,c shows the variation of the cross-strait subtidal current at T01 and T02 respectively. The variation of subtidal currents also corresponded well with the wind.

During P1, both southern strait and northern strait showed a weak inflow, with a relatively low velocity of ~0.1 m/s. In the initial phase of P2, as the wind increased significantly, both the north and south of the strait showed intense outflow, with a velocity of about ~0.27 m/s on the south and ~0.1 m/s on the north. As the wind continued, the southern side continued to be dominated by the strong outflow, while the northern side shifted to a fluctuating inflow with a period of 2–3 days. At this moment, the circulation in BHS showed a traditional pattern: "inflow in the north and outflow in the south". During P3, as the wind gradually subsided and shifted, both the north and south of the strait were dominated by inflow again, with the flow velocity of the north stronger than that of the south. The results showed the P1
and P3 had some similarities that the water level of the strait was continuously rising accompanied by a consistent inflow during the wind relaxation or reversal. The outflows mainly appeared during the intense wind and dominated the southern strait. Consequently, on the synoptic scale, the circulation structure of BHS was incredibly sensitive to the oscillation of the wind condition, rather than simply "inflow in the north and outflow in the south". The underlying mechanism of variation of circulation modulated by synoptic events would be discussed in the following sections.

**Figure 7.** The variation of residual water level (a) during different wind conditions (the dashed arrows indicate the varied trend). The variation of depth-averaged subtidal velocity of cross-strait component at site T01 (b) and site T02 (c) during different wind conditions.

### 3.4. The Variation of SSC and Transport through BHS

The distribution of SSC at surface, middle and bottom layers in BHS were shown in Figure 8a,b. SSC showed high values in the south and low values in the north overall. In the water column, SSC showed a decreasing tendency from the bottom to the surface and the bottom layer was significantly higher than the surface and the middle. The temporal variation of SSC had significant fluctuations corresponding to the tidal currents in T02, which gradually decreased from the beginning to the end (spring tide to neap tide) (Figure 4). During P1, the SSC in T01 and T02 had similar variation trend. A peak, which slightly lagging behind the maximum ebb, appeared in both sides of BHS on January 7 with the value of 15–20 mg/L in T01 and ~10 mg/L in T02. During the intense northerly wind (P2), SSC in the south and north had different responses. SSC in southern BHS increased significantly, 2–5 times of the other periods with the maximum value exceeding 50 mg/L (Figure 8a). The northern side was opposite, where SSC had no obvious signal corresponding to the wind, even lower than the average value of mere 3–6 mg/L (Figure 8b). After the wind relaxation or reversal, the SSC was back to a relatively low value in both T01 and T02.

With the current velocities and sediment concentration, both from the ADCP measurements, the unit-width cross-strait water flux (WF) and SSC flux (SSF) can be easily calculated respectively:

\[
WF_x = \frac{\sum_{t=1}^{T} \sum_{i=1}^{n} H_{it} C_{ix}}{T}
\]
where $C^x$ is the $x$ component (cross-strait) current velocity; $T$ is the number of ADCP ensembles for each phase; $H = 0.75$ m is the bin size, $n$ is the total number of layers, units are /m.

The net water and sediment fluxes through BHS in different phases are shown in Figure 9. During P1, under the weak northerly or southerly wind, the net water and sediment both transport to BH at a relatively low level. The fluxes of the northern side was higher than that of the southern side (Figure 9a). In P2, however, the water and sediment transport reversed to out of BH due to the enhanced northwesterly wind. It was notable that the net water and sediment fluxes on the southern side significantly increased, which was an order higher than before. In comparison, the fluxes of the northern side were much lower than the southern side (Figure 9b). P3 is similar to P1 in that the transport direction shifted into BH again after the wind subsided and reversed in both sides of BHS (Figure 9c).

\[
SSF_x = \frac{\sum_{i=1}^{T} \sum_{j=1}^{n} H_{ij} C_{ij}^x \cdot SSC_{ij}}{T}
\]  

(3)

**Figure 8.** The variation of SSC at surface, middle and bottom layers at site T01 (a) and site T02 (b) during different wind conditions.

**Figure 9.** The unit-width water flux (red arrows) and suspended sediment flux (blue arrows) at observed depths at site T01 and T02 under different wind conditions. (a) Weak northerly or southerly wind (P1); (b) intense northerly wind event (P2); (c) wind relaxation or reversal (P3).

Based on the previous results, we concluded the typical characteristics of water and sediment transport affected by the synoptic events as follows: 1. The total transport (both water and sediment) of the whole observation through the BHS was consistent with the traditional views: “inflow in the north and outflow in the south” (Table 2). However, the transport situations in different phases of wind
conditions varied greatly; 2. The phases of the intense northerly wind were the main period of water and sediment transporting out of the BH through the southern BHS (Table 2); 3. After the wind died down or reversed, the outward transportation of water and sediment gradually disappeared and even some sediments were back to BH with the backflow. In summary, in terms of synoptic scales, the water and sediment transport processes in the BHS are not constant, but the periodic processes which are more sensitive to the variation of wind conditions. Thus, the underlying mechanisms of the transport processes would be discussed in the next sections.

Table 2. Total transport quantities during observation.

| Stations (+/-: Out/in) | Phase 1 | Phase 2 | Phase 3 | Total |
|------------------------|---------|---------|---------|-------|
| T01 Water (×10⁵ m³/m)  | −1.28   | 11.3    | −1.64   | 8.38  |
| Suspended sediment     | −1.27   | 13.75   | −0.78   | 11.7  |
|                       |         |         |         |       |
| T02 Water (×10⁵ m³/m)  | −2.14   | 3.71    | −3.92   | −2.35 |
| Suspended sediment     | −1.80   | 1.44    | −0.55   | −0.91 |

4. Discussion

4.1. Changes in BHS Circulations due to the Synoptic Events

Previous sections had shown that the hydrological and sedimentary pattern through BHS were sensitive to winter synoptic events. To better illustrate underlying mechanisms of the wind effect on the circulations around BHS, SSH data from CMEMS and the daily wind data from NCEP were employed in this study.

From January 6 to January 7, a weak southerly wind lingered around the BH and YS, the SSH in the area was gradually recovering from south to north (Figure 10a,b). During this period, a consistent inflow dominated the entire BHS (Figure 7b,c). Notably, a relatively high SSH propagated northward along the west coast of the Korean Peninsula. On January 7, the SSH in BH reached the peak value of the observation period, even higher than it in the YS (Figure 10b). During January 8 and January 9, the intense northerly wind swept over BH and YS and the SSH dropped by about 0.6 m rapidly from north to south (Figure 10c,d). The water rapidly escaped BH towards YS in a short time with an intense outflow through BHS. During January 10 to January 11, as the intense wind continued, the SSH of BH remained at a low level (Figure 10e,f). The relatively high SSH was distributed along the coast of Shandong Peninsula. In BHS, an "inflow in the north and outflow in the south" structure of the circulation appeared (Figure 7b,c). On January 12, the northerly wind weakened and shifted to the westerly wind and southwesterly wind. The SSH in BH and YS gradually recovered with a relatively high SSH propagated northward along the west coast of the Korean Peninsula (Figure 10g). On January 13, a southerly wind dominated the BH and YS, the distribution of SSH showed by the high level in the north and the low level in the south (Figure 10h). At this moment, a continued inflow predominated the entire BHS (Figure 7b,c).

We compared the three synoptic events that the variation of currents showed some obviously traceable characteristics and had a tight link with the regional distribution of SSH. Influenced by the East Asian Monsoon, the northerly wind prevails in winter [11,25]. The oscillation of the wind had a significantly impact on the redistribution of regional SSH, thereby causing the periodic variation of circulation in the BHS. Combined with our results and previous studies, these processes could be summarized as follows. At the initial stage of the intense northerly wind, the water rapidly exited of BH and the SSH decreased rapidly. The changed spatial distribution of the SSH formed a northward pressure gradient field. Meanwhile, the relatively high SSH was distributed along the northern Shandong Peninsula, along with strong NSCC enhanced by geostrophic balance [32,33]. Correspondingly, the BHS was characterized by the strong outflow (i.e., from BH to NYS). After the wind relaxed or reversed, the northward pressure gradient established by precedent winter gales was released and created a northward compensation flow [40]. The YSWC was generated. Besides,
the intense northerly wind triggered a coastal-trapped shelf wave (CTW) propagating northward with a relatively high SSH along the west coast of the Korean Peninsula [32]. The YSWC was also facilitated by the CTW [41,42]. During this period, BHS was dominated by the inflow. In other words, the winter circulations around BHS was not constant on the synoptic scale, but sensitive to varied wind conditions. Furthermore, according to wind conditions, circulation processes could be classified into two situations, one is under intense northerly wind and the other is after the wind relaxed or reversed.

![Figure 10](https://rda.ucar.edu/datasets/ds094.1/). Spatial distribution of wind field and sea level height from January 6, 2018 to January 13, 2018. The data of sea surface height is available at CMEMS: http://marine.copernicus.eu/services-portfolio/access-to-products; the data of wind field is available at https://rda.ucar.edu/datasets/ds094.1/.

### 4.2. Changes of SSC in BH and BHS due to Synoptic Events

Our previous results showed that the SSC had different responses to the different wind conditions. In general, the resuspension of sediment is controlled by both internal and external factors including sediment grain size, topography and hydrodynamic characteristics (current and wave), etc. [43]. Among these factors, the sediment grain size and the topography were relatively stable for years or longer. Meanwhile—as typical of marginal seas—BH was significant affected by the tidal current. Therefore, the different responses of suspended sediment to different wind conditions can be attributed to the variation of the wave and tidal current. We employed the spatial distribution of wave field from the WAVEWATCHIII global model and sea surface SSC from GOCI products to illustrate the spatial variation of sediment in BH during winter, 2018 (November 2017 to March 2018). Based on the wind conditions, the variation of wave and sediment were separated into two regimes: one was affected by the intense northerly wind (regional averaged wind speed ≥ 8 m/s) and the other was when the wind relaxed or reversed. The variation of wave and sea surface suspended sediment in different situations are shown in Figure 11a–d. During the action of intense northerly wind, the wave was enhanced more than that in periods of wind relaxation or reversal. The averaged $H_s$ was ~1.2 m under intense wind conditions, while it was only half that value when the wind subsided or shifted (Figure 11a,b). Correspondingly, the sea surface SSC had different characteristics in the two synoptic situations (Figure 11c,d). In winter seasons, the high SSC in BH was mainly concentrated in the vicinity of the Yellow River estuary, the Bohai Bay and the Liaodong Bay. The center of BH and northern BHS had relatively low SSC. During the intense northerly wind, the SSC in the Laizhou Bay and the northern coast of Shandong Peninsula increased significantly, forming a belt of high turbidity along the Shandong Peninsula from the Laizhou Bay and extending eastward around the Chengshantou (Figure 11c). After the wind subsided, except the Yellow River estuary, the SSC of the Laizhou Bay was back to a relatively low level. The turbid belt became indistinct and the high SSC was only distributed around the southern BHS and Chengshantou (Figure 11d). The variation of sea surface SSC affected by
the intense wave mainly reflected in the shallow waters such as Laizhou bay and northern coast of Shandong Peninsula, with amplification of about 36% and 56% respectively (Figure 11e). The northern side of BHS and the center of BH were less affected by the intense wind, with slight increases of about 25% and 15% respectively (Figure 11e). While the variation in Liaodong Bay and Bohai Bay were negligible with only 0.04% and 0.03% (Figure 11e). Besides the sea surface layer, the SSC in the middle and bottom layers could also increase several times or dozens of times during the extreme weather in winter in the shallow waters [26,44]. In general, besides the wind intensity, the growth of wave also depends on the wind duration and fetch [45]. During the northerly wind in winter, the southern BH had the longer fetch which was better for wave growth. In addition, due to the lower temperature and salinity, the sea ice could last ~105–130 days with a coverage extending offshore over ~70 km in Liaodong Bay which formed a natural barrier to the air-sea interaction [46,47]. Therefore, these factors combined with the depth of water made the shallow water in southern BH a sensitive area of the variation of SSC under intense northerly winds, rather than the northern BH.

Figure 11. Spatial distribution of significant wave height during different wind conditions on winter 2018: (a) during intense wind; (b) wind relaxation or reversal. Spatial distribution of sea surface SSC during different wind conditions on winter 2018: (c) during intense wind; (d) wind relaxation or reversal. The significant wave height are available at WAVEWATCHIII Global model: http://ww3.cimh.edu.bb/. The data of sea surface SSC are available at GOCI: http://kosc.kiost.ac.kr/eng/p10/kosc_p11.html. (e) The variation of sea surface SSC in different regions during different wind conditions. Northern Shandong Peninsula (NSDP), Laizhou Bay (LZB), Northern Bohai Strait (NBHS), Liaodong Bay (LDB), Bohai Bay (BHB) and Center of Bohai Sea (CBS). The percentage in the dashed frames indicate the variation rate.

To further illustrate the control factors of different responses of SSC on the southern and northern sides of BHS during different wind conditions, we employed the empirical formulas for bottom shear stress calculation proposed by Soulsby (1995) [48] and Van Rijn (1993) [49]:

\[ \tau_{bw} = \rho \omega \gamma \omega U^2 \]
\[ C_{bw} = \left( \frac{0.4}{\ln \left( \frac{H}{\lambda} \right)} + 1 \right)^{10} \]
\[ \tau_{w} = 0.5 \rho \omega f \omega U_\omega^2 \]
\[ \tau_{bw} \approx \frac{1 + 1.2 \left( \tau_{bw} + \tau_{w} \right)}{7.6} \]

Where \( \tau_{bw} \) is the wave-induced shear stress, \( C_{bw} \) is the wave-induced shear stress coefficient, \( \rho \) is the density of water, \( \omega \) is the angular frequency of the wave, \( f \omega \) is the Coriolis parameter, \( U_\omega \) is the wind speed, and \( \lambda \) is the wavelength of the wave.
stress calculation proposed by Soulsby (1995) [48] and Van Rijn (1993) [49] to calculate wave-induced shear stress ($\tau_w$), current-induced shear stress ($\tau_c$) and combined wave and current shear stress ($\tau_{cw}$):

$$\tau_c = \rho C_D \bar{U}^2$$  \hspace{1cm} (4)

$$C_D = \frac{0.4}{1 + \ln \left( \frac{D}{z_0} \right)^2}$$  \hspace{1cm} (5)

$$\tau_w = 0.5\rho f_w U_w^2$$  \hspace{1cm} (6)

$$\tau_{cw} = \tau_c \left[ 1 + 1.2 \left( \frac{\tau_w}{\tau_c + \tau_w} \right)^{3.2} \right]$$  \hspace{1cm} (7)

$\rho$ is water density; $C_D$ is the drag coefficient (applicable to depth-averaged current); $z_0$ is the bed roughness length; $\bar{U}$ is the depth-averaged current speed; $H$ is the water depth; $f_w$ is the wave friction factor; $U_w$ is the wave orbital velocity amplitude at sea bed. The results showed that the SSC in the both sides of BHS were obvious consistent with the $\tau_{cw}$. Before the intense wind, the peak of SSC in both T01 and T02 was dominated by the $\tau_c$ (Figure 12a,b). During the intense wind, the enhanced wave caused a significant increase of $\tau_w$ in the southern side of the BHS. The current in the south was also enhanced by the intense wind, which also caused the increase of $\tau_c$. The superimposed effect of wave and current caused the significant increase of $\tau_{cw}$, facilitating the obvious increase of SSC (Figure 12a). Conversely, during this period, although the wave on the northern side of BHS significantly increased, the $\tau_w$ was still small due to the deeper water depth. Meanwhile, the period of the intense wind was during neap-tide, so the $\tau_c$ also decreased. This was why the SSC on the northern side even decreased during the intense wind (Figure 12b). In summary, the resuspension of sediment was dominated by the combination of current and wave in the southern strait, while only by the tide in the northern strait.

![Figure 12](image_url)

**Figure 12.** The bottom currents and shear stress of current, wave and wave-current combination at site T01 (a) and site T02 (b) during the observation.

### 4.3. Suspended Sediment Transport through BHS by the Winter Wind Event

Most of the terrigenous materials carried by the large rivers of BH were deposited around the estuaries in summer [38] and substantial quantities of sediments were transported over long distance by NSCC to form distal mud patches in winter [25]. Previous studies summarized this typical feature as “storage in summer and transport in winter” [13,41]. In the past decades, most of previous simulated studies of sediment transport in BH and YS were focused on the seasonal variation by using monthly or seasonal averaged wind data (e.g., [43,50–52]). Such an approach is undoubtedly feasible for the study
of mean climatology conditions. Nevertheless, sometimes intense northerly wind or weak southerly wind episodically occur during winter and such synoptic events related processes would be obscured. In fact, the winter monsoon was an oscillating activity in which the intense northerly wind events and the wind relaxation or reversal events occurred alternately. Our observation showed that both the sediment carriers (NSCC and YSWC) and sediment themselves were sensitive to the intense northerly wind and the sediment transport processes through BHS were also shown the oscillating processes corresponding to the wind conditions. Therefore, we divided the sediment transport processes though BHS in winter into two patterns according to wind conditions:

1. The intense northerly wind caused the water piling up to south while the SSH in BH fell significantly, effectively forming a northward pressure gradient. A large quantity of the water escape from BH to YS through BHS. Meanwhile, the relatively high SSH is distributed along the northern coast of the Shandong Peninsula and NSCC is markedly enhanced because of geostrophic balance. Furthermore, intensified waves facilitates the rapid increase of SSC in the shallow water of southern BH, which is then carried out of BH by NSCC. This period is the main transport stage of the sediments from BH (Figure 13a).

2. After the wind weakened or shifted, the preceding accumulation of SSH was unleashed, forming a northward compensatory flow. The wind-triggered CTW carried a high-water level propagated northward along the western coast of the Korean peninsula and facilitated the YSWC [41]. During this time, the relatively high SSH in the northern BHS is geostrophically balanced by an inflow from YS to BH. Meanwhile, SSC decreased due to the weak wave and a small part of sediment is brought back to BH (Figure 13b).

Our study also showed that there would be co-existence of the two patterns when the intense wind lasted a longer time (Figure 7a,b). Study on the two decisively separated patterns would help us understand the underlying mechanism more clearly and serve as a basis for more accurate quantitative estimation of sediment transport. Moreover, there have been a number of studies on numerous straits around the globe (e.g., Gibraltar, Otranto, Taiwan and Tsushima Straits) [53–55] that show the transports of water and sediment have significant seasonal variations affected by the monsoon activities [56–59]. Meanwhile, some episodic synoptic events do not follow the original transport pattern or are even contrary to previous results [31,32,60–62], e.g., typhoons could cause the strong southward transport in Taiwan Strait, which temporarily changed the general direction of Taiwan Strait northward transport [63]. Ko et al. had shown the transport reversal in Taiwan Strait affected by the northerly winter wind bursts [64]. These results of transport processes in worldwide straits, including the BHS, on synoptic scales had some similar phenomenon with our findings. Affected by the episodic synoptic events, the transports through straits were not always constant, but shown the oscillation processes corresponding to the wind. In summary, the establishment of the conceptual model of water and sediment transport is not only nonnegligible for the accurate quantitative study of transport processes in the BHS, but also valuable reference for the study in other similar environments worldwide.
5. Conclusions

During the winter cruise from January 6 to January 13, 2018, an intense northerly wind event was captured using the in situ observation systems at the key stations in the north and south of BHS. Combined with satellite remote sensing and model data, the responses of hydrodynamic and hydrological characteristics in BH and YS to the intense wind events and the accompanying wind subsided events were analyzed. Based on the results, we came to the following conclusions:

(1) The distribution of SSH in BH and YS was sensitive to the synoptic events. The regional variation of SSH would significantly modulate the winter circulation structures around the BHS. According to the wind conditions, circulation processes around the BHS could be classified in two situations: one is dominated by outflow during intense northerly wind, the other is dominated by inflow after wind relaxation or reversal.

(2) Similarly, the wave condition in BH and YS was also sensitive to the synoptic events. The different wave conditions had significant impact on the variation of SSC mainly in shallow waters around southern BH and northern coast of Shandong Peninsula. During the intense northerly wind, SSC sharply increased in these regions. In BHS, resuspension of sediment in the south was controlled by the combination of current and wave, while it was only controlled by the current in the north.

(3) The volume and sediment transport processes through the BHS were not always constant in winter, but shown an oscillating pattern corresponding to the synoptic events. According to the different wind conditions, the sediment transport through BHS in winter were divided into two periods, each with its pattern. One was the main sediment transport period with enhanced NSCC and SSC by the intense northerly wind, the other was the recovery period with enhanced YSWC and lower SSC when the wind was relaxed or shifted. The established conceptual model of water and sediment transport help us understand the underlying mechanism more clearly. This is necessary for the accurate quantitative study of transport processes in the BHS and provide valuable reference for the study of other similar straits in the world.

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