The features and mechanisms of the North Shandong Coastal Current: a case study in 2014

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Abstract

The North Shandong Coastal Current (NSCC) is an important transporting route for sediment, drifting algae, and spilled oil from the Bohai Sea to the Yellow Sea. This study investigated the features and formation mechanism of the NSCC using observational data of current velocity and a numerical coastal ocean model. Our results confirmed the existence of the NSCC in the sense of climatological current in winter when northerly wind prevails in the Bohai Sea and Yellow Sea. The magnitude of the NSCC in the monthly time scale ranged 0.07–0.12 m/s and the current direction was parallel to the coastline. The detided residual current on the pathway of the NSCC was unstable, but variable with the local wind speed. The residual current was well correlated with northerly wind speed and tended to be parallel to coastline with the increase of wind speed. Strong wind plays key roles in the formation of eastward mean flow on the pathway of the NSCC in winter. We found that strong wind can generate a stronger eastward current in the southern side of the northern Yellow Sea, but a smaller westward return flow during the strong wind relaxation period. The asymmetry of wind-related residual current during and after strong wind events accounts for the formation of the eastward NSCC. A momentum analysis was performed using the numerical model results during strong wind events. We found that the barotropic pressure gradient was the dominant driving force of the residual current both during and after a strong wind event.

Keywords The North Shandong Coastal Current · North Yellow Sea · Observational current velocity data · Winter large wind events · Momentum analysis

1 Introduction

The Bohai Sea and Yellow Sea form a semi-closed marginal sea surrounded by the coast of China and Korean Peninsula. With seasonal variation in climate, the sea water properties and circulation can change significantly (Lu et al. 2011; Yuan and Hsueh 2010; Yue et al. 2000). In winter, an anti-clockwise gyre occurs in the circulation pattern in the Bohai

Sea and Yellow Sea (Fig. 1a). It consists of a coastal current from the Bohai Sea to Yellow Sea in the southern and western sides; and northward warm current from the Yellow Sea to Bohai Sea in the eastern and northern sides (Xiong 2012). The North Shandong Coastal Current (NSCC), also called the Lubei Coastal Current, is a segment of the coastal current in the southern part of the north Yellow Sea. It flows eastward and is parallel to the coastline of Shandong Peninsula in the north. The NSCC is obvious from October to February when the prevailing wind is from the north in the Bohai Sea and Yellow Sea (Zhang et al. 2018; Xiong 2012).

The Yellow River is the largest river entering the Bohai Sea and Yellow Sea. It transports huge amount of freshwater and sediment into the Bohai Sea, which significantly affects the salinity and suspended sediment concentration in the coastal water around the river mouth. The low-salinity water and highly turbid water belt in the coastal water of the north coast of Shandong Peninsula can indicate the influence area of the NSCC. The bottom mud belt lies along the northern and eastern coastline of the Shandong Peninsula is related

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Fig. 1 **a** Circulations in the Yellow Sea during winter. The blue arrows indicate the pathway of the coastal current around Shandong Peninsula; the red arrows indicate the pathway of a warm current (redrawn according to Xiong (2012)). **b** Locations of the observation sites (B1, B2, M1 and N1)

to the NSCC (Lee et al. 2020). The sediment flux from the Bohai Sea to the Yellow Sea is higher in winter than in summer because of the high suspended sediment concentration and the NSCC (Bi et al. 2011; Yang et al. 2011). In general, about 80% of the sediment transported from the Bohai Sea to the Yellow Sea occurs during winter. In winter, the low-salinity water adjacent to the Yellow River mouth is transported to the east. It flows out of the Bohai Strait to the northern Yellow Sea. Then, the low-salinity water is transported by the NSCC which forms a low-salinity tongue in the north of Shandong Peninsula (Zhang et al. 2010).

The NSCC begins from the outflow in the southern Bohai Strait between the Bohai Sea and Yellow Sea (Li et al. 2015; Xiong 2012). Typically, water flows out of the Bohai Sea through the southern part of the Bohai Strait, and flows into the Bohai Sea through the northern part of the Bohai Strait in winter (Song et al. 2017; Huang et al. 1998; Wan et al. 2015). Winter monsoon is the dominant factor which regulates the water exchange through the Bohai Strait (Yuan and Hsueh 2010). Under the influence of prevailing northerly or northwesterly wind in winter, sea water accumulates in the Laizhou Bay (in the southern part of the Bohai Sea). The higher water level of the Laizhou Bay generates an outflow in the southern Bohai Strait (Li et al. 2015). Once water flows out of the Bohai Sea, it continues to flow along the north coast of Shandong Peninsula and forms the NSCC. In addition, the northerly wind also causes sea water to accumulate along the north coast of Shandong Peninsula. It forms a northward gradient of water level which contributes to the eastward NSCC due to the geostrophic effect (Zhang et al. 2018). Large amount of current velocity data has been used to investigate the sea water exchange in recent years. These analyses indicated that the current in Bohai Strait can be unstable; and can fluctuate with synoptic-scale wind speed. Different from the general perception, Wu et al. (2019) reported a westward residual flow in the southern part of Bohai Strait. By analyzing the observed current velocity at a fixed site in the northern part of the Bohai Strait, Wan et al. (2015) found that the detided current velocity can respond strongly with high wind speed and water level

fluctuations. Wang et al. (2020) indicated that the sediment outflow through the Bohai Strait can be greatly enhanced during winter storms. Song et al. (2017) suggested that strong wind in winter can significantly increase the water exchange between Bohai Sea and Yellow Sea. Since the NSCC connects the outflow in the southern Bohai Strait, the NSCC could be related to the synoptic weather conditions.

Current understanding about the NSCC is either based on numerical models or indicators (e.g., sediment and salinity). To the best of our knowledge, observational analysis on the pathway of the NSCC is still absent. Besides, previous studies mainly focused on the long-term features of the current using numerical models (Yue et al. 2000) or indirect observations, such as suspended sediment concentration from satellite remote sensing images (Bi et al. 2011; Liu et al. 2020). With limited observations, the variation of current velocity in the northern coastal water of Shandong Peninsula during winter is poorly understood.

More recently, we have collected some observations (e.g., current velocity, sea level and wind) along the pathway of the NSCC during winter. In this paper, we aim to: (1) verify the existence of the NSCC in winter as a climatological current; (2) analyze the magnitude of the NSCC; and (3) investigate the mechanism of the NSCC formation using the observed data and a numerical ocean model. This paper is organized into five sections. Section 2 explains the data and methods used in this study. Section 3 analyzes the observations and shows the simulation results. Section 4 discusses the mechanism of the NSCC formation. We conclude our research findings in Sect. 5.

2 Data and methods

2.1 Observed data

Two buoys (B1 and B2) were deployed off the coast of Shandong Peninsula on the pathway of the NSCC (Fig. 1b). The water depths at B1 and B2 were about 19 m. A downward-looking 600 kHz Nortek Aquadopp ADCP (Acoustic

Doppler Current Profilers) was mounted on the two buoys. They were used to measure the current velocity in the water columns below the two buoys. The first bin of measured current profile was 1.5 m below the sea surface. The current velocity at B1 was monitored from October 10, 2014 to January 5, 2015. At B2 (i.e., to the southeast of B1), the current velocity was recorded from October 10 to October 28, 2014. The time interval of current velocity data was 10 min at B1 and B2. The current velocity measurements at B2 were interrupted after October 28 due to equipment failure. The bin size of ADCP-measured current velocity was 1 m at B1 and B2.

An up-looking RDI 300 kHz ADCP was deployed at the seabed of N1 (refer to Fig. 1b). N1 was located in the northern part of the northern Yellow Sea, just opposite to B1 and B2. The water depth at N1 was about 57 m. Current velocity at 10 min intervals was measured at N1. The bin size of current velocity was 1 m. The first bin was 3.17 m above seabed, and the last bin with valid data was about 46 m above seabed. The current velocity data at N1 was available from October 5 to November 16, 2014. The instruments were redeployed at N1 on December 23, 2014. Current velocity was recorded until January 6, 2015. At the same time, a CTD (conductivity, temperature, depth) (model: SeaBird 37) at the same location measured the variation of sea level. N1 was far from the pathway of the NSCC. The observed data at N1 was used for understanding the mechanism of the NSCC formation.

A CTD (model: SeaBird 37) was deployed on the seabed at M1 (refer to Fig. 1b) approximately 2 km away from the coastline. We measured the sea level variation every 10 min from December 22, 2014 to January 8, 2015. The CTD measured sea level data was relative to the height of the CTD sensor. To make comparison with modelled sea level, the measured sea level was processed by subtracting the mean sea level over the observation period at each site.

Automatic weather stations at both buoys (B1 and B2) recorded meteorological data (wind speed, air pressure, air temperature and relative humidity) at 10 min intervals the same period as the current velocity.

The convention for wind directions differs from the convention for the direction of ocean currents. Meteorological

convention was used to denote the wind direction, i.e., the direction from which the wind is blowing. While the ocean direction denotes, where the current is going towards. The current direction is clockwise in the range -180° to 180° and north is 0 (by definition, direction of southward current is -180° , westward current -90° and northward current 0).

Prior to using these data, we have performed quality controls (e.g., spike removal, missing data filling). Values of the observed variables out of valid ranges were sorted out and marked as invalid values. Then all invalid and missing data were filled with linear interpolation. Table 1 summarizes the details of all data used in this study.

2.2 Numerical modelling

In this paper, an unstructured-grid, Finite-Volume, free-surface, three-dimensional (3-D) primitive equations Community Ocean Model (FVCOM) (Chen et al. 2007) was used to study the formation mechanism of the NSCC. In the simulation, we set the model domain to cover the entire Yellow Sea and Bohai Sea (see Fig. 2a). The boundary between the Yellow Sea and East China Sea was the open boundary of the model. The mesh resolution near the open boundary was about 15 km, and was increased to about 1 km in the coastal water of the Shandong Peninsula. The bathymetry data applied in the model were extracted from nautical charts. There were 13 uniform sigma layers in the vertical direction. At the open boundary, we added the hourly water level forecasted by TPXO 7.0 (Egbert and Erofeeva 2002). Data of wind 10 m above sea surface and air pressure at mean sea level provided by ERA5 (the fifth generation ECMWF atmospheric reanalysis of the global climate.) were used as surface forcing for the model. The ERA5 data was generated by a global atmosphere model with a spatial resolution 0.25° and time interval of 1 h (Copernicus Climate Change Service 2017). The simulation started on October 1, 2014 and ended on January 10, 2015, covering the observation period.

Table 1 Summary of observed data in this study

Site	Parameters	Instruments	Duration	Interval
B1	Current velocity	ADCP	2014-10-10 to 2015-01-05	10 min
	Wind speed	Automatic weather stations		
B2	Current velocity,	ADCP	2014-10-10 to 2014-10-28	10 min
	Wind speed	Automatic weather stations		
M1	Sea level	CTD	2014-12-22 to 2015-01-08	10 min
N1	Sea level	CTD	2014-10-05 to 2014-11-16	10 min
	Current velocity	ADCP	2014-12-23 to 2015-01-06	

Fig. 2 **a** Unstructured model mesh and water depth of the FVCOM model. The red dashed line denotes the open boundary for the model; **b** zoom-in plot of the model mesh in part of the Bohai Sea and the northern Yellow Sea

3 Results

3.1 Monthly averaged current on the pathway of the NSCC

Since the NSCC is a climatological current, we calculated the time-averaged current velocity for each month from October to December 2014. Figure 3 shows the monthly mean flow in the vertical layers at B1 in October, November and December 2014; and at B2 in October 2014. It should be noted that the monthly averaged current in October 2014, was for the period October 12–31 because data were not available before October 12; and the mean flow of December included the first five days of January 2015.

At B1, the magnitude of monthly mean flow decreased from 0.09 m/s in the upper layers to 0.02 m/s at the bottom in October 2014. Mean flow in most layers ranged 0.06–0.07 m/s. The magnitude was almost homogenous, except that the bottom current was much weaker than that in the upper layers. The current directions at depth above 15 m ranged 132° – 149° (i.e., southeastward), while that at bottom turned to south and southwest. In November 2014, the current magnitude and directions over the water

column at B1 were similar to those in October 2014. In December 2014, the mean flow magnitude of most layers significantly increased to 0.12 m/s, while the flow direction maintained southeastward.

At B2, the current velocity data were only available in October 2014. Figure 3d displays the mean flow of October in vertical layers. The current magnitude of the upper and middle layers ranged 0.05–0.07 m/s. The current magnitude gradually declined to 0.02 m/s at the bottom layer. The current directions of most layers were within the range 80° – 90° (i.e., eastward over the water column at B2).

3.2 Low-pass filtered residual current

Figure 4 displays the power spectrum density of the depth-averaged current velocity at B1. There were three notable peaks in the frequency domain. Two of them were caused by the semi-diurnal and diurnal tidal signals. The third peak was at 5.35 days (128 h), which was likely to be driven by the synoptic scale features. There was a trough at 34 h, indicating that the diurnal tidal signals might have minor effect on current velocity with period larger than 34 h. As wind is the dominant driver of winter circulation in the Bohai Sea and the Yellow Sea (Ding et al. 2019), primary tidal

Fig. 3 Monthly mean flow in vertical layers at B1 for **a** October 12–31, 2014; **b** November 1–30, 2014; **c** December 1 2014–January 5 2015; and mean flow in vertical layers at B2 for October 12–30, 2014 (**d**)

Fig. 4 Power spectral density of the east (solid line) and north (dashed line) components of the depth-averaged current velocity at B1 from October 12 2014 to January 5 2015. (CPD denotes cycles per day)

components of the current velocity were removed in the following analysis using a 4-order Butterworth low-pass filter with a cut-off time at 34 h (Roberts and Roberts 1978). The low-pass filtered current was called residual current hereafter for brevity. As displayed in Fig. 3, the mean flow of October, November and December 2014 were almost homogenous in vertical direction. Thus, we only analyzed the residual current on three representative layers.

Figure 5 shows the residual current in October, November and December 2014 at B1 in an upper (2.5 m below the sea surface), middle (9.5 m below the sea surface) and bottom (17.5 m below the sea surface) layers, respectively. The residual current on the three layers showed strong temporal variability with periods about several days. Current magnitude on the middle layer was comparable to the surface current. The bottom current was obviously weaker than the current in middle and surface layers. The maximum current

magnitude from October to December in 2014 was 0.8 m/s, which occurred on December 1 at surface and middle layers. The bottom current hit 0.6 m/s at the same time. Each time the current reached a peak, the current direction was southeastward and roughly parallel to the local coastline. The northwestward current during this period was generally weak. However, relatively strong northwestward current appeared in the middle and bottom layers on December 1 and 12 after a strong southeastward current.

At B2, which is to the east of B1 and also on the pathway of the NSCC, the low-pass filtered residual current is shown in Fig. 6 from October 10–28, 2014. There were two notable current velocity peaks over this period. One was on October 12, where the maximum current velocity was 0.44 m/s. The other peak occurred on October 21 and the maximum current velocity was about 0.2 m/s. When the current peaked on October 12 and 21, the current velocity was roughly eastward (90° – 100°).

3.3 Correlation between wind and residual current

Wind speed was monitored by the automatic weather station at B1 from October 2014 to early January 2015. Based on these data, we prepared a wind rose diagram in Fig. 7a. During this period, winds from northwest, southwest and northeast were the three most frequent wind directions, but strong wind events were from the north, northwest or northeast (wind speed > 14 m/s). Wind speed over the northern Yellow Sea presented synoptic-scale variation (Fig. 7b, c). Strong wind events occurred every 1–2 weeks. From October 2014 to early January 2015, there were totally eight strong wind events with instantaneous peak wind speed above 14 m/s at B1. The duration of large wind (> 9 m/s) ranged from 15 to

Fig. 5 Vectors of 34 h-low-pass-filtered current velocity in the surface (a), middle (b) and bottom (c) layers at B1 from October 11, 2014 to January 5, 2015 (black arrows). Solid lines denote the current velocity magnitude in the surface, middle and bottom layers at B1 during the same period

Fig. 6 Vectors of 34 h-low-pass-filtered current velocity in the surface (a), middle (b) and bottom (c) layers at B2 from October 10 2014 to October 28 2014 (black arrows). Solid lines denote the current velocity magnitude in the surface (a), middle (b) and bottom layers (c)

Fig. 7 **a** Wind rose diagram at B1 from October 2014 to early January 2015; **b** time series of east (blue line) and north (red line) components of wind speed at B1; positive north component is northward, and positive east component is eastward **c** time series of wind magnitude at B1

67 h in these wind events (Table 2). The maximum wind speed (21.1 m/s) occurred on December 1, 2014. Local wind directions were northwest, north or northeast at B1 during these wind events.

Table 3 illustrates the correlation coefficients between the east and north components of wind, and two components of vertically-averaged residual current velocity at B1 and B2. At B1, the correlation coefficient between east component of current and north component of wind was -0.71 , while the correlation coefficient between north component of current and north component of wind was 0.83 . There was almost no correlation between the two components of current and the east component of wind. At B2, the correlation coefficients between north component of wind and the two components

of current were -0.71 and 0.81 , respectively, which were also higher than the correlation coefficients between east component of wind and the current velocity. As shown in Fig. 7, the frequency and intensity of northerly wind (negative sign) were high in winter. The high correlation between north component of wind and east component of current indicates the strong relation between the eastward (positive sign) longshore NSCC and the north component of wind in winter. In October, November and December, the monthly-averaged north components of wind at B1 were -1.5 m/s, -1.7 m/s and -3.5 m/s, respectively. Therefore, northerly wind in December was the strongest among the three months. This should explain the higher mean flow at B1 in December (as demonstrated in Fig. 3).

Table 2 Eight strong wind events at B1 from October 10 2014 to January 03 2015

ID	Start time	End time	Time of maximum wind speed	Maximum speed (m/s)	Duration (h)
1	10-12 06:00	10-14 01:00	10-13 07:00	17.27	67
2	10-15 15:00	10-16 06:00	10-15 22:00	14.44	15
3	10-26 07:00	10-27 09:00	10-26 09:00	15.20	26
4	11-11 21:00	11-13 18:00	11-12 06:00	16.06	45
5	11-30 13:00	12-02 04:00	12-01 04:00	21.11	39
6	12-02 12:00	12-05 02:00	12-04 16:00	17.48	62
7	12-15 20:00	12-17 14:00	12-16 11:00	16.62	42
8	12-30 22:00	01-01 16:00	12-31 16:00	17.36	42

Table 3 Correlation coefficients between wind and vertically-averaged residual current at site B1 and B2

Site		Wind_east	Wind_north
B1	Current_east	0.11	−0.71
	Current_north	−0.09	0.83
B2	Current_east	−0.49	−0.71
	Current_north	0.64	0.81

“east” and “north” after “_” denote the east and north components of current velocity or wind speed

Figure 8 shows the frequency diagrams of the residual current directions with different wind magnitude ranges at B1 (Fig. 8a–c) from October 2014 to early January 2015; and at B2 (Fig. 8d–f) from October 11 to October 28, 2014. For weak wind (< 6 m/s) at B1, residual current directions were distributed in a relatively wide range. When the wind speed magnitude increased to 6–12 m/s, current directions concentrated in the range of $[130^\circ, 150^\circ]$. When the wind speed exceeded 12 m/s, more than 90% of residual current directions were in a narrow range ($120^\circ, 140^\circ$). At B2, the current directions under weak wind (< 6 m/s) were distributed in a wide range of ($-50^\circ, 150^\circ$). With the increase of wind speed, the current direction focused in the range of ($90^\circ, 110^\circ$). For wind speed above 12 m/s, the current direction was in the narrow range ($90^\circ, 110^\circ$). Figure 8 indicates that, with the increase of wind speed, the frequency of south-eastward/eastward current increased and most of the current directions tended to be parallel to the coastline during very strong wind.

At B1, the summation of flow over the whole period from October to December 2014 were 157.3 m/s and -274.7 m/s, respectively. The summation of flow over the eight storm events were 142.4 m/s and -149.7 m/s, respectively. While the total duration of these events represented only 16% of the whole period, the strong wind induced eastward residual current velocity accounted for 90% and the southward flow accounted for 55% in the NSCC formation.

3.4 Residual current during and after the strong wind events

Since strong wind events played prominent roles in the NSCC formation, we comprehensively investigate the strong wind induced current. Figure 9a1–c1 depicts the wind speed vectors during the early stages of the strong wind events 1, 4 and 8 (Table 2). Figure 9a2–c2 displays the wind speed vectors when the wind speed magnitude was maximum at B1. At that moment, wind all over the Bohai Sea and Yellow Sea blew towards south or southeast almost homogeneously. For the period indicated in Fig. 9a3–c3, wind speed at B1 was 9 m/s, and the wind direction over the Bohai Sea and Yellow Sea was northerly or northwesterly. In Fig. 9a4–c4, the strong wind relaxed, wind speed magnitude declined and wind direction was more spatially variable. Figure 10 illustrates the variations of longshore residual current at B1 and N1 during the three strong wind events. On top of the residual current velocity during strong wind periods, we also consider the current velocity over 24 h during storm relaxation to evaluate the subsequent effect of strong wind on residual current. Moreover, we investigate the residual current at N1 (Fig. 10g–i), which is in the northern part of the northern Yellow Sea in comparison with the current at B1 on the pathway of the NSCC (Fig. 1).

In Fig. 10a–c, the red dashed vertical lines represent the separating time between strong wind periods (> 9 m/s) and strong wind relaxation periods (< 9 m/s) of the three strong wind events. Before the separating time, the wind speed peaked and exceeded 9 m/s at B1. After the separating time, the storms relaxed and wind speed turned weaker. At B1, the peak values of longshore residual current ranged 0.4–0.6 m/s during the three strong wind events (Fig. 10d–f). When strong wind relaxed, the longshore residual current became weaker, and the current direction reversed to northwest. The reversed northwestward residual current lasted less than 14 h, and the peak values of the reversed residual current during these storm events ranged 0.05–0.11 m/s, which were much weaker than the eastward residual current.

Similar to B1, residual current at N1 was sensitive to wind speed. However, the current at N1 responded differently to the strong wind in winter (Fig. 10g–i). In response to the increase of wind speed during the strong wind periods (wind speed > 9 m/s), the eastward residual current at

Fig. 8 Frequency of current direction under different ranges of wind speed at B1 (a–c) from October 12, 2014 to January 3, 2015; and at B2 (d–f) from October 11 to October 28, 2014

Fig. 9 Wind fields (ERA5 wind data) during and after strong wind event 1 (a1–a4), event 4 (b1–b4) and event 8 (c1–c4). In subfigures a1, b1 and c1, strong wind events started in the northern Yellow Sea. In subfigures a2, b2 and c2, wind speed peaked at b1. In subfigures a3, b3 and c3, strong wind events just ended in the northern Yellow Sea. In subfigures a4, b4 and c4, strong wind events have relaxed

N1 has also increased. During the three storm events, the peaks of the eastward current were 0.07 m/s, 0.18 m/s and 0.32 m/s, respectively. The residual current reversed after the wind speed peaked. The reversed westward current at N1 increased as the wind speed decreased. During the strong wind relaxation, the peak values of the westward current were 0.39 m/s, 0.31 m/s and 0.37 m/s, respectively.

They were much higher than those of the reversed westward current at B1. In addition, the reversed westward current lasted longer than the eastward current during the strong wind events 1 and 4; the duration of westward current was comparable to the eastward current during the strong wind event 8.

Fig. 10 Time series of **a** wind speed during and after the strong wind event 1; **b** wind speed during and after the strong wind event 4; **c** wind speed during and after the strong wind event 8; **d** vertical-averaged longshore residual current during and after the strong wind event 1 at B1; **e** vertical-averaged longshore residual current during and after the strong wind event 4 at B1; **f** vertical-averaged longshore residual current during and after the strong wind event 8 at B1; **g** vertical-averaged longshore residual current during and after the strong wind event 1 at N1; **h** vertical-averaged longshore residual current during and after the strong wind event 4 at N1; **i** vertical-averaged longshore residual current during and after the strong wind event 8 at N1

Fig. 11 Comparison of low-pass filtered sea level between observational data (black line) and model results (gray line) at M1 (**a**) and N1 (**b**)

3.5 Model validation

Figure 11 compares the modelled and observed 34 h-low-pass filtered sea level at M1 and N1. At these sites, the root mean square deviations (RMSDs) between the modelled and observed sea level were 0.20 m and 0.15 m, respectively; and the correlation coefficients between them were 0.9 and 0.8, respectively. Figure 12 shows the modelled and observed 34 h-low-pass filtered depth-averaged current velocity at B1, B2 and N1. The RMSDs of residual current between the model and observation were smaller than 0.12 m/s. The correlation coefficients between modelled and observed residual current at the three sites were generally above 0.7. Only at N1, the modelled and observed north component of the residual current were poorly correlated ($R=0.11$), probably due to the weak residual current before the strong wind event 8. The model errors were most likely from the barotropic assumption, wind stress parametrization and wind data accuracy. Nevertheless, the model captured three main characteristics of the residual current variation during the strong wind events. First, the residual current was significantly enhanced during the strong wind events at the three sites. Second, strong northwesterly or northerly wind generated eastward or southeastward longshore current during large wind events. Third, at B1 and B2, the residual current was much weaker than that at N1 during strong wind relaxation.

Overall, the model has reasonably reproduced the variation of current velocity at the three sites, especially during strong wind events. Thus, the model results can be used to study the mechanism of the residual current influenced by strong winter wind.

3.6 Momentum analysis

We adopted momentum analysis to investigate the mechanism of residual current influenced by the strong wind in winter. As shown in Fig. 10, the variation pattern of residual current was similar during different strong northerly wind events in winter. Here we take the strong wind event 4 (see Table 2) as an example for the momentum analysis. The analysis utilizes the model results from Nov. 11 to Nov. 14 in 2014, including a strong wind period and a wind relaxation period (Fig. 10b). The vertically averaged zonal (1) and meridional (2) momentum balance equations are shown below:

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} = fv - g \frac{\partial \eta}{\partial x} + \frac{\tau_{sx}}{\rho_0 D} - \frac{\tau_{bx}}{\rho_0 D} + K_h \nabla^2 u, \quad (1)$$

$$\frac{\partial v}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y} = -fu - g \frac{\partial \eta}{\partial y} + \frac{\tau_{sy}}{\rho_0 D} - \frac{\tau_{by}}{\rho_0 D} + K_h \nabla^2 v, \quad (2)$$

Fig. 12 Comparison of east component and north component of residual current between observational data (black line) and model results (gray line) at the site B1 (a, b), B2(c, d) and N1 (e, f)

where u and v are the zonal and meridional components of depth-averaged residual current, respectively; f is the Coriolis parameter; τ_s and τ_b are the surface and bottom stresses, respectively; η is the sea level; g is the acceleration of gravity; and K_h is the horizontal diffusion coefficient. The subscripts x and y denote the zonal and meridional directions of surface or bottom stress. On the left-hand side of Eqs. (1) and (2), the first term is the local acceleration term (LA), and the summation of the second and third terms is the advective term (ADV). On the right-hand side, they are the Coriolis force (CF) term, barotropic pressure gradient term (BTPG), wind stress term (WS), bottom friction term

(BF) and horizontal diffusion term (DIF). All the terms are obtained from the FVCOM model output.

Table 4 shows the mean values of the momentum terms at B1, B2 and N1 from Nov. 11 to Nov. 14. The ADV and DIF at these sites were six times smaller than the LA, reflecting their minor roles in driving the residual current. Other terms were either comparable or greater than the LA. Therefore, we exclude the advective term and diffusion term in the subsequent analysis. At these sites, the BTPG term was the dominant term and COR was the second largest term. The magnitudes of WS at B1 and B2 were two times greater than that at N1 due to the lower depths at B1 and B2.

Table 4 Magnitudes (10^{-5} m/s^2) of momentum terms at B1, B2 and N1 during the strong wind event 4

	ADV	COR	BTPG	DIF	WS	BF	LA
B1	0.15	1.93	2.75	0.003	1.05	0.51	1.00
B2	0.01	1.76	3.16	0.004	1.19	0.54	1.33
N1	0.01	1.19	1.66	0.005	0.04	0.65	0.61

Fig. 13 Time series of **a** depth averaged current and local acceleration term at B1; **b** primary momentum terms at B1; **c** depth averaged current and local acceleration term at N1; **d** primary momentum terms at N1; **e** modelled low pass filtered sea level at B1 and N1 during the strong wind event 4

Figure 13 shows the vectors of depth averaged residual current and primary momentum terms, as well as the low-pass filtered sea level at B1 and N1 during and after the strong wind event 4. At B1 (which is on the pathway of the NSCC), during the strong wind period, the dominating momentum was the BTPG with maximum value up to $6.5 \times 10^{-5} \text{ m/s}^2$, and the direction of the BTPG was northeastward, approximately along the cross-shore direction (see Fig. 1). With the increase of northwesterly wind on November 12, 2014 (indicated by the WS term in Fig. 13b), the northeastward BTPG has increased along with the enhanced CF and WS; and generated the southeastward LA and a southeastward residual current (Fig. 13a). The WS, BTPG and the residual current at B1 have peaked almost at the same time. The CF term was almost opposite to the BTPG with slightly smaller magnitude. The WS and BF terms were secondary to the BTPG and CF even when the wind speed reached the highest levels. During the wind relaxation period, the BTPG turned southwest and their magnitudes were significantly reduced relative to that during the strong wind period. The southwestward BTPG together with the CF generated the westward LA. Thus, a westward residual current was formed. However, it was much weaker than that during the strong wind period.

At N1, which is far from the NSCC, the residual current and momentum terms evolved differently compared to those at B1. During the strong wind period, the residual current at N1 was eastward, and the maximum magnitude was 0.15 m/s, which was much smaller than that at B1. Nonetheless, during the strong wind relaxation, the reversed westward residual current increased to 0.25 m/s, which was much stronger than the reversed current at B1 (Fig. 13c). As illustrated in Fig. 13d, during the strong wind period, the BTPG at N1 was northward, generating an eastward residual current, but its magnitude was only one-fifth of the BTPG at B1. The BTPG has experienced a notable increase during the wind relaxation period, forming a strong westward BTPG. The BTPG then turned to the southwest and continued to increase. The northward CF was caused by a westward residual current. It was rising, and at 00:00 on November 14 the southward BTPG was balanced by the northward CF. After that, the BTPG pointed to the southeast and weakened the westward residual current. During the wind relaxation period, the WS and BF terms were small. The BTPG and CF formed the westward LA term, resulting in the westward residual current at N1.

Figure 13e shows the sea level variations at B1 and N1. The strong wind event has led to sea level drop up to 0.9 m. When the strong wind died away, the sea level recovered to the normal sea level (around 0 m) within 24 h. The sea level variations at B1 and N1 were consistent with the BTPG. During the strong wind period, sea level at B1 was always higher than that at N1, indicating sea water accumulation in

the north coast of Shandong Peninsula and the northward pressure gradient. During the wind relaxation period, sea level at B1 was lower than N1, resulting in a southward pressure gradient.

4 Discussion

4.1 The mechanism of the NSCC formation

Despite the extensive discussions about the NSCC in previous studies (Liu et al. 2020; Qu 2014; Wan et al. 2015; Xiong 2012), the long-period observations of current velocity on the pathway of the NSCC are rare. Current study utilized observed current velocity data on the pathway of the NSCC to analyze the features of the NSCC in winter. We can now confirm the existence of the NSCC as a climatological current (see Sect. 3.1). The magnitude of the mean flow at B1 and B2 ranged 0.07–0.12 m/s from October to December, 2014, and the vertical variation of the mean flow was weak. We also find that the magnitude and direction of the mean flow in this study are consistent with earlier simulation studies (Liu et al. 2020; Ma 2014).

It is widely accepted that the NSCC is related to the winter monsoon in the eastern Asia. Based on climatological data, Zhang et al. (2018) proposed that the NSCC could be a result of a quasi-balance state between wind stress, Coriolis force and pressure gradient force. In recent years, researchers realized the episodic strong wind events had substantial influence on the circulation in the Bohai Sea and Yellow Sea (Li et al. 2015; Wan et al. 2015; Hu et al. 2017; Ding et al. 2019). In this study, we re-evaluated the formation mechanism of the NSCC from a new perspective.

Driven by the stronger wind and sea surface cooling after September, the water density stratification in the Bohai Sea and Yellow sea in autumn and winter is generally weaker than that in summer. The density induced current can be ignored, and the residual current is mainly induced by wind in winter (Naimie et al. 2001). Winter wind in the northern China is characterized by intermittent strong northerly wind (including northwesterly or northeasterly) with a time scale of several days. The residual current on the pathway of the NSCC was well correlated with local wind speed, more precisely, with the north component of wind speed. During strong wind events, strong northerly wind can trigger considerable eastward coastal current along the north coast of Shandong Peninsula. Such phenomenon in this region was also reported in simulation studies (Li et al. 2015; Ding et al. 2019; Liu et al. 2020). Along with the longshore current, sea level drops abruptly. Upon the end of the strong wind event, sea level starts to recover together with a westward return flow on the pathway of the NSCC. However, the return flow is not as strong as the eastward flow during the

strong wind period. Therefore, the mean flow over a strong wind period and its relaxation period is eastward. During a calm-weather period between two strong wind events, wind speed can turn weaker and the wind field might not exhibit a definite pattern. Thus, wind during calm weather may generate a residual current weaker than that during strong wind events. Although the total period of strong wind is short in the entire winter, the residual current induced by large wind can represent most of the climatological residual current in winter. Hence, the mean flow over a period of monthly time scale in winter (i.e., the NSCC) tends to be eastward (as shown in Fig. 3).

We also investigated the residual current during strong wind periods at N1 on the northern side of the Bohai Strait, just opposite to the NSCC. Our results indicated that the strong wind induced eastward residual current both in the northern side and the southern side of the north Yellow Sea. However, the current magnitude in the southern side can be stronger than that in the northern side. During the relaxation of large wind, the reversed westward current can also occur at N1 and the reversed current was more pronounced than that at B1 (as shown in Fig. 10). Therefore, in the northern side of the northern Yellow Sea, the westward residual

current during the strong wind relaxation period can be greater than the eastward current during strong wind which can lead to a net westward mean flow.

Momentum analysis revealed the importance of barotropic pressure gradient in forming the eastward strong residual current during strong wind periods on the pathway of the NSCC (relative to the local wind stress). The barotropic pressure gradient is probably the only driving force of the return flow during the relaxation of strong wind. The barotropic pressure gradient is related to the sea level distribution. The Bohai Sea and Yellow Sea form a semi-closed marginal sea with an outlet in the south. When a typical northerly or northwesterly winter storm sweeps through the Bohai Sea and Yellow Sea (e.g., strong wind event on November 12, 2014), sea water can be transported roughly from north to south. Figure 14 shows the sea level distribution over the Bohai Sea and the Yellow Sea during and after the strong wind event 4. Under the influence of the strong northwesterly wind, sea water was accumulated along the north coast of Shandong Peninsula (Fig. 14a, b), forming a strong northward pressure gradient in this region. Strong eastward flow was generated off the northern coast of Shandong Peninsula. As the large wind

Fig. 14 Distribution of low-pass filtered sea level and depth averaged residual current (arrows) at four representative moments during and after the strong wind event 4

impacted the Bohai Sea and Yellow Sea, sea level continued dropping. At 8:00 on November 13, 2014 (Fig. 14c), the sea level in the whole Bohai Sea and northern Yellow Sea was notably lower than that in the southern Yellow Sea. At that moment, the strong northerly wind has relaxed, and was unable to transport sea water towards south. Northward flow (about 0.3 m/s) was formed in the middle of the Yellow Sea due to the northward pressure gradient. After that, the sea level of the Bohai Sea and northern Yellow Sea began to recover. The sea level in the eastern and northern parts of the Yellow Sea increased much faster than its western and southern parts. At 20:00 on November 13 (Fig. 14d), the sea level in the northern part Yellow Sea was higher than that in its southern part, resulting in a southward pressure gradient (see Fig. 13d). A notable westward flow was formed in the middle part of the Bohai Strait. While in the southern part (i.e., off the northern coast of Shandong Peninsula), the southward sea level gradient was smaller, generating a weaker westward return flow.

The sea level fluctuation during the relaxation of large northerly wind events was basically the result of a coastal trapped wave (CTW) propagating over the Yellow Sea and Bohai Sea (Hu et al. 2017; Jacobs et al. 1998; Ding et al. 2018; Li and Huang 2019). Once the large wind relaxed, the sea level variations propagate cyclonically in the entire Bohai Sea and Yellow Sea. Sea level in the eastern side of the southern Yellow Sea recovers earlier than the western side, forming a westward sea level gradient and northward flow (Fig. 14c). Then the sea level in the northern part of the northern Yellow Sea recovers, and earlier than the southern part in the northern Yellow Sea, forming a southward pressure gradient and thus a westward geostrophic current in the north Yellow Sea (Fig. 14c).

The relatively weak return flow on the pathway of the NSCC could be an important factor for the formation of the eastward NSCC. The return flow right after a storm in different parts of the Yellow Sea has been reported by previous researchers. By analyzing the observational data of current velocity, Wu et al. (2019) and Ding et al. (2019) reported a westward flow in the southern part of the Bohai Strait, which was inconsistent with the general view of the flow direction in this region. The Yellow Sea Warm Current (YSWC) in the trough of the southern Yellow Sea is also related to the winter monsoon. After a winter storm with strong northerly wind, a notable northward/northwestward current can be formed, which can be stronger than the southward current during storms (Ding et al. 2018). Lie et al. (2001) argued that the YSWC could be an intermittent current induced by strong northerly wind. The return flow might not be limited to the Bohai Sea and Yellow Sea, and could be found in the Taiwan Strait after a strong northerly wind in winter (Shen et al. 2019).

4.2 Implications for the water exchange through the Bohai Strait and the transporting of drifting substances of the NSCC

The water exchange between the Bohai Sea and Yellow Sea through the Bohai Strait has been extensively studied (Ji et al. 2019; Guo et al. 2016; Song et al. 2017; Zhang et al. 2018; Wei et al. 2003). The water exchange rate has notable seasonal variability (Zhang et al. 2018; Wei et al. 2003). During winter, the conventional view about the mean flow direction through the Bohai Strait is “inflow in the northern part and outflow in the southern part”. Earlier numerical experiments suggested that winter monsoon plays some important roles in the water exchange through the Bohai Strait. In this study, we have found that typical winter storms can cause eastward flow in the southern part and westward flow in the northern Yellow Sea. While the finding in this study relied on observational data at two fixed locations in the northern Yellow Sea, it is generally in agreement with the conventional view of water exchange through the Bohai Strait.

In recent years, many studies have recognized that synoptic storm events can induce notable synoptic variations of residual current in the Bohai Strait (Ju et al. 2020; Li et al. 2015; Wan et al. 2015). As demonstrated in current study, westward flow occurred during strong wind relaxation periods. In this sense, it is reasonable to expect a synoptic-scale inflow in the southern part of the Bohai Strait (Wu et al. 2019; Ding et al. 2019).

More recently, *Sargassum horneri* bloom broke out on the coast of Jiangsu Province, China and South Korea in the southern Yellow Sea (Kim et al. 2019; Xing et al. 2017). The bloom of *Sargassum horneri* has led to the so-called golden tide and severely affected the coastal tourism and aquaculture. The sources of *Sargassum horneri* in the southern Yellow Sea have not been identified so far. Some studies proposed that the most probable source of *Sargassum horneri* was the benthic *Sargassum horneri* adjacent to the islands in the Bohai Strait (Huang et al. 2018). Our study confirmed that there is a potential transporting route of *Sargassum horneri* from the Bohai Strait to the southern Yellow Sea in winter, providing one scientific evidence to support the argument of Huang et al. (2018).

5 Conclusions

Based on the observational current velocity data on the pathway of the NSCC, we analyzed the features of the coastal current. We confirmed the existence of an eastward mean flow in winter roughly parallel to the north coast of the Shandong Peninsula, which is consistent with previous studies. The monthly mean flow of the NSCC ranged 0.07–0.12 m/s.

The detided longshore residual current could reach 0.8 m/s during strong wind with an eastward current direction.

The residual current on the pathway of the NSCC had a good correlation with the north component of local wind speed. With the increase of wind speed, residual current magnitude on the pathway of the NSCC has increased and current directions tended to be parallel to the coastline and southeastward or eastward. Strong northerly winter wind played a vital role in the NSCC formation, as the eastward mean flow on the pathway of the NSCC was mainly formed during strong wind events. Northerly stormy wind caused sea water to pile up along the north coast of Shandong Peninsula, generating a high northward barotropic pressure gradient. The northward barotropic pressure gradient force was the dominant driving force of the detided residual current, producing a strong eastward residual current along with Coriolis force and local wind stress. When storms relaxed, sea level in the Bohai Sea and northern Yellow Sea recovered, generating a reversed westward flow. The westward return flow after a storm on the pathway of the NSCC was weaker than the eastward flow during storms. Therefore, we deduce that the eastward mean flow (the NSCC) is formed largely due to the asymmetrical flow during and after a typical winter large wind event. This finding enhances our understanding of the NSCC formation, and provides a clue to investigate the annual variation of the NSCC.

In this study, time series of current velocity at only two sites on the pathway of the NSCC were applied. However, the spatial variation of current velocity and the extent of the NSCC remain unknown. Limited by available observations, we focused on the NSCC features from October to December 2014. In future study, observational data need to be collected for January and February so that we could fully understand how the NSCC evolves in these months.

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