Nonlinear tide-surge-wave interaction at a shallow coast with large scale sequential harbor constructions

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\textbf{A R T I C L E   I N F O}

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Nonlinear dynamics
Wave-induced surge
Harbor construction
Delft3D

\textbf{A B S T R A C T}

The southwestern part of Bohai Bay in northeastern China is a shallow-water coast with a long fetch for water to pile up to produce large storm surge under strong wind action during the extreme weather condition. In addition, the coastline along the bay has experienced significant environmental impacts from large scale harbor constructions in the past two decades. Consequently, there is a pressing need to better understand the effects of two local large scale sequential harbor constructions on storm surge and coastal vulnerability in the bay area. The extreme cold front weather on 10-13th October 2003 caused a 1.31 billion Yuan damage. A two-way coupled tide-surge-wave Delft3D model is used to investigate the impact of the harbor constructions from 2003 to 2016 on the interaction of tide, storm surge and wave during a storm like that. The wind field by the newly-released global reanalysis wind product ERA5 of European Centre for Medium-Range Weather Forecasts (ECMWF) has been improved by assimilation with field observations at a higher resolution than previous version and is used to drive the tide, surge and wave modelling framework. The model results indicate that the storm surge in the study area is dominated by the wind-induced surge before and after the constructions whereas the maximum contribution from wave-induced surge (wave setup) is increased from 5%–15% to 8%–20% by the harbor constructions between 2003 and 2016. It is found that semi-diurnal modulation of storm surge is generated by nonlinear tide-surge interaction, which is mainly attributed to local tidal acceleration in the offshore zone and bottom stress in the nearshore zone respectively. The harbor constructions affect the coastal storm surge mainly through nonlinear tide-surge-wave interaction. In addition, the quarter-diurnal variation of storm surge induced by the harbor constructions is due to the influences of the harbor constructions on the local quarter-diurnal tidal constituents and their modulation of wave momentum transfer to coastal circulation.

1. Introduction

A storm surge, an abnormal increase of sea surface driven by meteorological and wave forcing, consists wind-, pressure- and wave-induced components (Wolf, 2009; Wu et al., 2018a). The atmosphere induced storm surge is a complex physical process dependent not only on wind direction and speed, storm propagation speed and direction relative to the coast, duration, size and path of storm (Irish et al., 2008; Li et al., 2013; Mo et al., 2016; Sahoo and Bhaskaran, 2018), but also on geometric and topographic features of the coast (Zhao and Jiang, 2011; Hu et al., 2015; Ding and Wei, 2017). When storm surge coincides with an astronomical high tide and large wave, extreme high water level occurs at the coast (Prandle and Wolf, 1978; Horsburgh and Wilson, 2007; Feng et al., 2016), which damages coastal defences, inundates low-lying areas and threatens life and property (Zou et al., 2013; Needham et al., 2015). The coastal vulnerability to severe storms will be further exacerbated by the projected rising sea level due to climate change (Xie et al., 2019). To protect coastal community, it is critical to better understand the interaction between tide, surge and wave in order to improve the accuracy of coastal inundation forecasts.

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Before 1950’s, the storm tide, i.e., total water level, was taken as the sum of tidal level and atmospheric storm surge ignoring the nonlinear tide-surge-wave interaction. This approach is able to capture the general features of storm tide, however, it fails to capture the magnitude and timing of surge peaks properly, or the nonlinear tidal and wave modulation of storm surge (Rossiter, 1961; Johns et al., 1985; Qin et al., 1994; Jones and Davies, 2008). Subsequently, numerous studies have reported that the nonlinear tide-surge interaction is significant especially in the shallow water regions (Johns et al., 1985; Quinn et al., 2012; Lydon et al., 2018). The nonlinearity of tide-surge interaction can be traced back to the nonlinear terms in the momentum equations of ocean circulation (Proudman, 1957; Prandle and Wolf, 1978; Parker, 1991). In addition, it is conjectured that the nonlinear interaction increases towards the coast (Johns et al., 1985; Yang et al., 2019; Zhang et al., 2017), possibly due to the enhanced nonlinearity by the decreasing water depth (Speer and Aubrey, 1985; Parker, 1991).

There are two main storm surge features associated with nonlinear tide-surge interaction (Horsburgh and Wilson, 2007). One feature is that the surge is reframed from peaking at high tide and prefers to appear on rising or falling tide (Rossiter, 1961; Horsburgh and Wilson, 2007; Feng et al., 2016). The timing of surge peak is mainly caused by the phase shift of tidal signal due to increasing water depth by surges. For example, a positive surge would increase the propagation speed of tidal wave ($gh^2/2$) and decrease the bottom friction due to the increasing water depth, which leads to an advance of tidal phase; in contrast, a negative surge would retard tidal propagation (Rossiter, 1961; Wolf, 1981). The timing of surge peaks is also related to the characteristics of tidal wave propagation and transformation along the coast. In a region where progressive tidal waves prevail, such as the eastern coast of UK, surge peaks tend to coincide with rising tide as indicated by the long-term statistics of observations (Rossiter, 1961; Prandle and Wolf, 1978; Horsburgh and Wilson, 2007). In contrast, in a region where standing tidal waves prevail, the surges tend to peak during the falling tide (Proudman, 1957; Feng et al., 2016).

The other surge feature due to tide-surge interaction is the tidal modulation of storm surge, whose intensity is stronger at low tide than that at high tide (Horsburgh and Wilson, 2007). As a result, the storm surge tends to oscillate with time at the same frequency as local dominant astronomic tide, most likely a semi-diurnal M2 tide (Horsburgh and Wilson, 2007; Valle-Levinson et al., 2013; Feng et al., 2016). Therefore, the tidal modulation of storm surge is also called semi-diurnal residuals or surges (Valle-Levinson et al., 2013; Feng et al., 2016). Moreover, both tidal elevation and current contribute to the tidal modulation of surge (McInnes and Hubbert, 2003; Horsburgh and Wilson, 2007; Zhang et al., 2010a; Idier et al., 2012; Valle-Levinson et al., 2013). Since the coastal hydrodynamics is driven by meteorological, tidal and wave forcings, and altered by geometry, bathymetry and topography of the coast, it is not surprising that the mechanism for nonlinear tide-surge interaction is site- and event-dependent. It is proposed that semi-diurnal surge comes primarily from the nonlinear parameterization of bottom friction (e.g., Tang et al., 1996; Bernier and Thompson, 2007; Horsburgh and Wilson, 2007; Zhang et al., 2010a; Idier et al., 2012). At a region with a strong current, the nonlinear advection term may also play a key role in the nonlinear tide-surge interaction (Proudman, 1957; Wolf, 1978; Rego and Li, 2010; Yang et al., 2019). Recently, it is recognized that wind stress (Yang et al., 2019) and Coriolis accelerations due to alongshore current (Valle-Levinson et al., 2013) may also have profound impact on tidal modulation of storm surge.

Including the nonlinear tide-surge interaction in the model, therefore, can improve the accuracy of storm surge forecasts (Zhang et al., 2017; Lyddon et al., 2018; Yang et al., 2019). However, waves are often neglected in storm surge forecasts, because wave modelling is relatively time-consuming, and wind stress and atmosphere pressure have been considered to be the primary factors for storm surge (Jelemsinski, 1972; Jelemsinski et al., 1992). To compensate for neglected wave effects, some researchers tune the wind drag coefficient $C_d$ to achieve the optimal model results of storm surge (Wu et al., 2018a). This calibration method, however, does not account for enhanced bottom roughness in shallow water by wave and therefore the bottom friction induced semi-diurnal surge. In addition, numerous studies have demonstrated that wave-induced surge, i.e., wave setup (Longuet-Higgins and Stewart, 1962, 1964), is inversely proportional to the water depth and relates to the slope of sea floor (Nayak et al., 2012; Ji et al., 2018). As a result, in coastal regions the relative importance of wave-induced surge to overall storm surge can reach over 15% (e.g., Kim et al., 2010; Sheng et al., 2010; Kennedy et al., 2012; Wu et al., 2018b), so that the wave contribution to surge in those regions cannot be neglected. In fact, the quality of surface wind data dictates the accuracy of storm surge and wave forecasts, as the uncertainty is amplified drastically while propagating from the atmospheric wind field forecast to ocean and wave predictions (Tolman, 1998; Zou et al., 2013; Sahoo et al., 2019). Numerous data assimilation methods based on a concept of “observation constraint” are therefore proposed and applied to improve the performance of reanalysis wind data (Mazaheri et al., 2013; Lv et al., 2014; Li, 2017; Fan, 2019) or alleviate the systematic biases in coupled climate models (Breugem and Stephenson, 2015; Huang and Ying, 2015; Li et al., 2016).

The main purposes of this study are 1) to estimate semi-diurnal modulation of storm surge in an extensive shallow-water coast, southwestern (SW) Bohai Bay, during an extreme cold front event in October 2003; 2) to explore the mechanisms of nonlinear tide-surge interaction and the relative contribution from wave-induced surge to overall surge; 3) to assess the responses of storm surge to local large scale seasonal harbor constructions and elucidate the underlying mechanism.

The rest of the paper is organized as follows: In Section 2, we introduce the background of study area southwestern Bohai Bay and extreme cold front event in October 2003 and the data for model calibration and validation. In Section 3, we provide a brief description of the coupled tide-surge-wave Delft3D model with calibrated surface wind input and wind drag coefficient and model validation. Section 4 presents the model results of the cold front event and the features of semi-diurnal modulation of surge and momentum terms along a cross-shore section. Section 5 discusses the contribution of wave-induced surge to overall storm surge, and elucidates physical mechanisms of tide-surge-wave interaction and impacts by local harbor constructions. Finally, conclusions are drawn in Section 6.

2. Field site and data

2.1. Study area and the cold front event in October 2003

The Bohai Bay, located in the west of Bohai Sea of northeastern China (see Fig. 1), is known to be vulnerable to storms due to the geometric, bathymetric and topographic features in this region and frequent intensive northerly cold fronts (Sun et al., 1979, 1980; Sun, 1984; Yin et al., 2001; Zhao and Jiang, 2011; Feng et al., 2012, 2018; Mo et al., 2016). Unlike tropical cyclone that features cyclonic wind and low pressure at the center, cold front often appears in high-latitude regions accompanied by high wind (>10.8 m/s) and cooling (Huler, 2004; Zhao and Jiang, 2011). Hence the cold front is a high-pressure system that produces a small negative surge, whose contribution to overall storm surge is dependent on water depth (Mo et al., 2016). The cold front in the Bohai Sea is a process of cold-air outbreak from north to south that is often coupled with extratropical cyclone (Mo et al., 2016), which is susceptible to other large scale weather systems, e.g., the Arctic Oscillation, Siberian High, East Asian Winter Monsoon and East Asian jet stream (Wang et al., 2013, 2016). And it is characterized by a spatially uniform, unidirectional and long lasting wind field. The Huanghua-Binzhou coast (Fig. 1c) is situated at the southwest of Bohai Bay against the prevailing wind direction of regional cold fronts. Nonlinear dynamics of tide-surge interaction in local is expected to be pronounced due to the long stretch shallow averaged water depth of 13
m and the mildly-sloping seabed of 1:3000 (Kuang et al., 2019). The cold front event during 10–13th October 2003 coincided with spring tide and was one of the worst storms in the bay in the past 50 years (Wang et al., 2004). It passed through the Bohai Sea from northeast to southwest, and generated a storm tide up to 3.29 m and a storm wave over 4 m in the southwest of Bohai Bay, which caused a total economic loss of 1.31 billion Yuan (Bulletin of China Marine Disaster, 2003). It is therefore of practical significance to reproduce the process of tide-surge-wave interaction during this event as the surge during cold front event has drawn little attention from researchers (McInnes and Hubbert, 2003; Mo et al., 2016), but has catastrophic effect for the Bohai Sea.

Due to its geographical location, the southwestern Bohai Bay is deemed one of the most important harbors of China, and the Huanghua and Binzhou harbors are constructed at the west (belong to Hebei province) and east (belong to Shandong province) part of the study area, respectively, as shown in Fig. 1a. The scale of these two harbors was small as the jetty was less than 8 km long in 2003 when the extreme cold front event occurred. With the rapid growth of local economy and demand for cargo capacity, these two harbors are pressured to provide more land and deeper waterway. Large-scale land reclamation and extremely long jetty are therefore constructed, which results in a dramatic increase of artificial coastline over 80 km in 2016 (Fig. 1c). The nonlinear interaction of tide with surge and wave during extreme weather conditions is further complicated by local large-scale harbor constructions.

Overall, this area serves as an excellent case study site to investigate the tide-surge-wave interaction, because 1) the meteorological forcing of cold front is simple as the wind field is steady and unidirectional and the effect of atmospheric pressure on surge is negligible; 2) the surface elevation due to tide and storm surge is significant contribution to total water level, therefore, strong tide-surge interaction is expected; 3) the geometry of the study area is modified considerably by the constructions of local large-scale harbors, so that the tide-surge-wave interaction in turn is altered by human interventions.

2.2. Data

Surface wind data from atmospheric reanalysis products of global model are often used to drive oceanic models. In the present study, the atmospheric reanalysis products European Centre for Medium-Range Weather Forecasts (ECMWF)-Interim, Cross-Calibrated Multi-Platform (CCMP) and ECMWF-ERA5 are selected and compared to observation. The ECMWF-Interim is one of the most commonly used atmospheric reanalysis product and the CCMP data product is provided by NASA. The ECMWF-ERA5 is the newly released fifth generation ECMWF atmospheric reanalysis product with a temporal resolution up to every hour. The time period of data coverage, spatial and temporal resolutions and source of these surface wind data are summarized in Table 1.

The meteorological station of Huanghua Harbor (location refer to Fig. 1c) recorded the wind speed and direction hourly during the storm event from 18:00 10th to 06:00 13th October 2003. Meanwhile, sea surface elevation was measured by the tide gauge of Huanghua Harbor at same location as the meteorological station during 10–13th October 2003 by the Tianjin Research Institute for Water Transport Engineering, Ministry of Transport, China, except for the time period in 03:00-06:00 11th and 18:00 11th-06:00 12th. There was a lack of field observations of wave conditions during this cold front event, so that the research institute deployed two SBA3-2 acoustic wave gauges in the study site and captured another extreme event on 5–9th November 2003 (Zhao, 2007). Only the observation of wave gauge at the deeper water indicated by the red square in Fig. 1c is used in the present study as the two wave gauges are close to each other and give similar results.

3. Methodology

3.1. Model set up

The tide-surge-wave coupled model adopted in the present study was

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Fig. 1. (a) Geographic location of Bohai Sea in the northeastern China (black dashed box). (b) A zoom-in view of the model domain of the tide-surge-wave coupled Delft3D model. (c) Topography of Huanghua-Binzhou Harbor and harbor layouts in 2003 (black solid line) and 2016 (red solid line). The red dot is the tide gauge and meteorological station of Huanghua Harbor and the red square denotes the acoustic wave gauge location. The blue solid line indicates the cross shore section AB used for analyzing the cross-shore variation of tide, surge and momentum flux. The white dot indicates the location of maximum storm surge along the section AB. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
The model configurations and the use of high-resolution data are essential features of the wave model evaluations. The model has been validated against observational data and other models, demonstrating its ability to simulate coastal wave conditions accurately. Future research should focus on improving the model's ability to capture long-term trends and interannual variability in coastal wave conditions.

## Table 2

**Table 2**

<table>
<thead>
<tr>
<th>Description</th>
<th>Time period</th>
<th>Resolution</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECMWF-Interim</td>
<td>1979.01-2019.08</td>
<td>6 h</td>
<td>0.125 x 0.125</td>
</tr>
<tr>
<td>CCMP</td>
<td>1987-2011.12</td>
<td>6 h</td>
<td>0.250 x 2.500</td>
</tr>
<tr>
<td>ECMWF-ERA5</td>
<td>1979.01-present</td>
<td>1 h</td>
<td>0.250 x 2.500</td>
</tr>
</tbody>
</table>

As indicated by previous studies, waves may have significant effects on 2-D and 3-D simulation results of storm surge or tide (Sheng et al., 2010; Roland et al., 2012). This primarily due to the vertical structure of wave-current interactions (Wu et al., 2018a). The present model successfully captures the wave-current interaction, and our model better reproduces the wave-current interactions.

## 3.2. Wind data assimilation and model validation

### 3.2.1. Surface wind

According to the studies using integrated atmosphere-ocean-coast modelling framework, the uncertainty in the surface wind is amplified drastically while propagating from the meteorological forcing to storm surge, wave and coastal flood risk prediction (Tolman, 1998; Zou et al., 2013; Sahoo et al., 2019). Accurate surface wind data is key to reproduce storm surge during 10–13 October 2003 successfully. Since three reanalysis products have different temporal and spatial resolutions (shown in Table 1), the surface wind data is linearly interpolated in space and time to obtain the hourly wind data at the Huanghua Harbor meteorological station for comparison and calibration (solid lines in Fig. 2). To quantify the performance of the model, the Pearson’s correlation coefficient ($r$) is adopted to evaluate the collinearity and the ratio of root-mean-square-error and standard deviation of observation (RSM) is used to estimate the discrepancy.

It is evident that the reanalysis surface wind speed generally follow the trend of observation with correlation coefficients $r$ of 0.71, 0.64 and 0.87 for ECMWF-Interim, CCMP and ECMWF-ERA5, respectively. As noted by previous studies (Lv et al., 2014; Fan, 2019), however, the wind speed at Bohai Sea tends to be underestimated by these global reanalysis products with RSM of 1.13, 0.90 and 0.65 for ECMWF-Interim, CCMP and ECMWF-ERA5, respectively, in particular around the peak wind speed (cf. Fig. 2a). In comparison, the reanalysis wind directions (Fig. 2b) perform well in the range of 0–90° during the cold front, with higher correlation in trend ($r$ 0.69–0.76) and smaller discrepancy in magnitude (RSM 0.89–0.94). Overall, the newly released ECMWF-ERA5 captures the observed surface wind best, which is partly due to its higher temporal resolution of hourly. Besides, both Bernier and Thompson (2007) and Xie et al. (2019) find that increasing sampling rate in time of meteorological forcing (e.g., from 3 or 6 h to 1 h) may significantly improve storm surge forecasts.

The modelling of the reanalysis wind by data assimilation of the observation is regarded as a robust technique to improve the accuracy of storm surge and wave simulations. Mazaheri et al. (2013) proposes that...
the improvement of wind data can be achieved by adjusting wind velocity component with a correction coefficient derived from linear regression between reanalysis data and observation, i.e., regression coefficient. This method has been applied to the regional modelling at Bohai Sea with spatially varying correction coefficient based on several observations along the coast (Lv et al., 2014; Li, 2017; Fan, 2019). Despite that this approach can indeed improve the wind through rescaling the wind vector, the discrepancy between reanalysis and observed data (i.e., the intercept obtained from linear regression) is not fixed because its inclusion may cause the direction of wind to change to the opposite direction. During the period of this study, there is little change in the wind direction which remains within a quadrant (0–90°). Thus, the intercept has been used to further improve the performance of reanalysis wind without switching to the opposite direction, which can be encountered when wind directions fall in different quadrants.

Each wind velocity component is corrected based on the linear regression between reanalysis and observed wind in Fig. 3. As it can be seen in Fig. 2c and d, the data assimilated reanalysis wind at Huanghua station are in better agreement with the observations. The ECMWF-ERA5 wind remains the best wind data as the correlation \( r \) of wind speed increases to 0.91 and the discreteness RSR decreases to 0.44. Fig. 4 shows the comparison of original and assimilated wind field of ECMWF-
ERAS at Bohai Bay at peak wind and it indicates that the assimilated wind field remains its original spatial pattern and fixes the underestimation of wind speed. It is noted that storm surge in a semi-enclosed bay could be more prone to the spatial than temporal resolution of wind field (Zhong et al., 2010). Regarding the relative importance of wind field, local wind forcing may account for 80% of the storm surge, while regional wind forcing and other effects only contributes to 20% of the storm surge (Mo, 2018). As a result, the data assimilated wind field of ECMWF-ERA5 will be used to drive our coupled tide-surge-wave model in the following sections. The data assimilation adopted here for a bay and that for a regional basin (Mazaheri et al., 2013; Lv et al., 2014; Li, 2017; Fan, 2019) can significantly improve the performance of ocean model. Moreover, recent studies have also attempted to reduce the uncertainty in climate projections by correcting the systematic biases in ensemble atmospheric models based on the concept of observational constraint (Bracegirdle and Stephenson, 2013; Huang and Ying, 2015; Li et al., 2016).

3.2.2. Wind drag coefficient

Wind stress is a quadratic function of surface wind speed relevant to the momentum transfer from atmosphere to ocean:

\[ \tau^* = C_{d} \rho_{a} U_{10}|U_{10}| \]  

(1)

where \( \rho_{a} \) is the air density and \( U_{10} \) represents the wind velocity above 10 m of the sea surface; the wind drag coefficient \( C_{d} \) represents the roughness of the sea surface and the momentum transfer rate. Large amount of pioneering studies (e.g., Garratt, 1977; Smith, 1980; Large and Pond, 1981; Wu, 1982) were conducted to establish the relationship between surface wind velocity and wind drag coefficient, as following (Guan and Xie, 2004):

\[ C_{d} = a b \left( \frac{U_{10}}{10} \right) \]  

(2)

where \( a \) and \( b \) are the empirical parameters determined by observation.

In atmospheric and oceanic modelling, the wind drag coefficient \( C_{d} \) acts as a determining factor for the accuracy of the predicted storm surge. Although lots of studies have been dedicated to improve the value of \( C_{d} \), the optimal wind drag coefficient remains to be a site and event specific. Therefore, based on the widely used expression proposed by Wu (1982) with \( a = 0.80 \) and \( b = 0.065 \) in Eq. (2), the above assimilated wind field is applied to reproduce the cold front event in October 2003. It is seen in Fig. 5 that the default wind drag (\( b = 0.065 \)) underestimates the total water level by about 0.8 m. This may be due to the fact that we neglect the enhancement of the drag coefficient by the increased roughness by the presence of large waves (Zou, 1998). It may also due to the fact that we assume the storm surge boundary condition at the offshore boundary of the circulation model is negligible. According to a series of sensitivity studies, the optimal wind drag coefficient for the study area during the cold front in October 2003 is achieved by an adjusted parameter \( b \) to 0.123, whose \( C_{d} \) is generally within the cap of 0.0035 prescribed by Garratt (1977) and Wu (1982).

3.2.3. Water level and surface wave

The total water level predicted by the model is in good agreement with the observation, with a high correlation of 0.97 and a small discrepancy of 0.27 (Fig. 5). Specifically, the coupled model shows great fitness with the observed water level during and after the storm (18:00 10th-00:00 14th), however, it underestimates the water level before the storm. The tidal boundary condition of the coupled tide-surge-wave model is forced by the tidal table predicted by the National Marine Data and Information Service of China, and the predicted tidal level without storm agrees with the tidal table (dashed line in Fig. 5) reasonably well. Thus, the mismatch of tidal level during time 00:00 10th and 18:00 10th is possibly due to the tidal forcing input or a datum shift of observation record before the storm because the model agrees fairly well with the observed tidal level during 00:00 13th-00:00 14th after the storm. Lacking wave observations during the cold front event wave simulation is validated against the observation during the following storm on 5–9th November 2003. The corresponding surface wind input from ECMWF-ERA5 is corrected based on the same method in Section 3.2.1. Fig. 6 depicts the simulated wave height and period against observation in 5–9th November 2003. The comparison suggests that the performance of simulated significant wave height is generally better than that of wave period, with higher collinearity \( r (0.95 \text{ vs. } 0.89) \) and smaller discreetness \( RSR (0.36 \text{ vs. } 0.77) \). As expected, the coupled tide-surge-wave model with a minimum grid resolution of 90 m is capable to reasonably capture the wind-wave process over this shallow and mildly-sloping coast.

Overall, the coupled tide-surge-wave model accurately reproduces the observed water level and wave height and period during extreme weather conditions, with an overall collinearity (\( r \) 0.89) and discreetness (\( RSR \) 0.77). The discrepancy of water level mainly occurs before the storm, therefore, is considered to be acceptable. But the underestimate of water level at the beginning of the storm, as found in Zhang et al., 2010b, is possibly due to the underestimated wind speed even after the data assimilation. The validation of wave condition suggests that it is plausible to drive the Bohai Sea wave model by wind forcing only, i.e., neglecting the wave at the offshore boundary, to reproduce the storm wave within Bohai Bay.

3.3. De-tiding and model runs

Following the definitions of previous studies (Banks, 1974; Pugh, 1987; Sinha et al., 2008), the storm tide \( \zeta \) represents the total observed

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**Fig. 4.** Comparison between (a) original and (b) assimilated reanalysis wind field of ECMWF-ERA5 in the Bohai Bay at 06:00 11th October 2003, at the peak wind speed during the extreme cold front event.
water level due to all the physical processes in coastal ocean during the storm. The storm surge $\xi_s$ represents the de-tiding/non-tidal water level that is calculated by subtracting harmonic tidal predictions $\xi_T$ from the storm tide $\xi$, namely, $\xi_s = \xi - \xi_T$. The storm surge $\xi_s$ can be further decomposed into the surge due to meteorological forcing only without tidal effect $\xi_S$ and nonlinear tide-surge interaction $\xi_I$, i.e., $\xi_s = \xi_S + \xi_I$. The nonlinear interaction residual $\xi_I = \xi - \xi_T - \xi_S$ is taken as a direct measure of the interaction between tide and surge (Bernier and Thompson, 2007; Zhang et al., 2010a; Mo et al., 2016; Zou and Xie, 2016; Yang et al., 2019).

Water elevation components $\xi$, $\xi_T$ and $\xi_S$ can be derived from the model runs forced with both wind and tidal forcing (case 1), tidal forcing only (case 2), and wind forcing only (case 3) respectively. In case 3, the surge $\xi_S$ not only includes the surge induced by wind but also the surge induced by wind-generated wave (i.e., wave-induced surge), which was frequently neglected in some previous studies (e.g., Lin et al., 2012; Mo et al., 2016; Sahoo and Bhaskaran, 2018; Yang et al., 2019). To assess the contribution by waves, we conduct an additional model run (case 4) by excluding the wave model from case 1. The intervention from local large-scale sequential harbor construction is considered by applying the hydraulic structures in Delft3D model, e.g. the jetty and reclamation are treated as “thin dam” and “dry point” during simulation respectively. These non-erodible “obstacles” can be used to represent the artificial coastline formed by harbor constructions, where water, energy and particle are not permitted to transfer through the hydraulic structures (Kuang et al., 2019). Based on model runs under harbor layout 2003 (case 4), the hydraulic structures of Huanghua-Binzhou Harbor in 2016 are incorporated (case 5–8) to estimate the impacts of local harbor constructions on the tide-surge-wave interaction. More details about the model runs are summarized in Table 3.

4. Model results

4.1. Cold front on 10–13th October 2003

Under the influences of large-scale weather system such as Siberian High amplification (Mo et al., 2016; Feng et al., 2018), the cold air passes through Bohai Sea from north to south during 10–13th October 2003. As illustrated by the wind vectors in Fig. 7, unlike tropical cyclone characterized by cyclonic wind, cold front exhibits a large-scale sustained wind field with little change in wind direction. According to the observation at Huanghua harbor (Fig. 2), the wind speed increases abruptly from 8 m/s at 13:00 10th to a maximum of 23.6 m/s at 06:00 11th (Fig. 7b–d). After that, the wind speed fluctuates around a speed of 20 m/s for about 18 h with direction changed slightly by 20 (Fig. 7e and f) and then tapers off (Fig. 7g–k). The negative surge induced by the atmosphere pressure in cold front system is negligible at Bohai Sea (Mo et al., 2016). During the cold front event, the atmosphere pressure gradually increases from 1015 hPa at 00:00 11th to 1030 hPa at 14:00 12th, as documented by Hu et al. (2005). Based on the expression $P_{\mu gh}$, the maximum increase of pressure of 15 hPa within 40 h only leads to a decrease of sea surface by 0.15 m. The change of pressure-induced surge per hour is smaller than that of wind-induced surge (Fig. 7), therefore, can be neglected. Since Bohai Sea is a shallow-water region with a mean water depth of 18 m (Jiang et al., 2000), the wind speed plays a major role in driving the storm surge based on the following simplified expression proposed by Pugh (1987):

$$\eta_{wind} \propto L W^{\frac{3}{2}} H$$

(3)

where $\eta_{wind}$ denotes the wind-induced surge, $L$, $W$ and $H$ are the continental shelf width, wind speed and mean water depth, respectively, $C$ is the constant value associated with gravity, density and drag.

Table 3

<table>
<thead>
<tr>
<th>No.</th>
<th>Description of model runs.</th>
</tr>
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<tbody>
<tr>
<td>Case 1</td>
<td>Circulation model driven by wind and tidal forcing with a coastline in 2003</td>
</tr>
<tr>
<td>Case 2</td>
<td>Circulation model driven by tidal forcing only with a coastline in 2003</td>
</tr>
<tr>
<td>Case 3</td>
<td>Circulation model driven by wind forcing only with a coastline in 2003</td>
</tr>
<tr>
<td>Case 4</td>
<td>Circulation model driven by wind and tidal forcing with a coastline in 2003</td>
</tr>
<tr>
<td>Case 5</td>
<td>As in the Case 1, but with the addition of hydraulic structures in 2016</td>
</tr>
<tr>
<td>Case 6</td>
<td>As in the Case 2, but with the addition of hydraulic structures in 2016</td>
</tr>
<tr>
<td>Case 7</td>
<td>As in the Case 3, but with the addition of hydraulic structures in 2016</td>
</tr>
<tr>
<td>Case 8</td>
<td>As in the Case 4, but with the addition of hydraulic structures in 2016</td>
</tr>
</tbody>
</table>
Due to the northeasterly wind, a positive storm surge occurs in the southwestern Bohai Sea, whereas a negative storm surge is encountered in the northeastern Bohai Sea as indicated by the contour map in Fig. 7. It is evident that Bohai Bay and Laizhou Bay experience the most significant surge during the storm partly due to their C-shaped geometry, which is favorable for water to pile-up due to funneling effect (Sahoo and Bhaskaran, 2018; Yang et al., 2019). More specifically, when wind speed increases at the initial stage of the event (Fig. 7a–d), the northeasterly wind pushes the water in Bohai Sea westward to pile up in Bohai Bay to increase the surge to an average of 0.95 m. Subsequently, the sustained strong wind (Fig. 7e and f) forces the surge in Bohai Bay and Laizhou Bay to increase continuously to a same peak value of about 2.25 m at 11:00 11th and 01:00 12th, respectively. After that, the wind speed decreases and wind direction further turns south (Fig. 7g–k), so that the surge in Laizhou Bay surpasses that in Bohai Bay. By 21:00 13th (Fig. 7l), the influence of cold front on surge almost vanishes.

4.2. Storm surge

According to the time series of storm surge along the cross shore section AB indicated in Fig. 1c under the actions of tide, wind and wave (see Fig. 8a), that is, ζSL, this major storm event causes a storm surge ranging from 0.50 m to 2.25 m in the study area. As expected, the sustained onshore strong wind during 20:00 10th-18:00 12th produces a significant positive surge over 0.5 m (Fig. 8a), with a peak surge at station C at 2 m-depth and 6 km away from the shore indicated in Fig. 1c. The storm surge in the nearshore zone appears to have longer duration and stronger magnitude than that in the offshore. It is because that wind-induced surge (Pugh, 1987) and wave-induced surge (Longet-Higgins and Stewart, 1962, 1964) are both inversely proportional to water depth.

Fig. 8b demonstrates the storm surge without wave action, i.e., ζSL excl. Comparing Fig. 8b with Fig. 8a, there is small wave contribution to overall storm surge in the study area. In combination with the results at station C (Fig. 9a), the storm surge can reach a peak value of 2.22 m in coast with a significant tidal modulation with semi-diurnal M2 period (12.4 h). Excluding wave causes only a slight decrease of the surge by ~0.10 m (see further discussions in Section 5.1). Moreover, these two cases of tide-surge interaction indicate that tide seems to be responsible for the semi-diurnal oscillation of storm surge as the maximum/minimium surge appears at the low/high tide (cf. Fig. 8a and b with Fig. 8d, black and red solid lines with grey dashed line in Fig. 9a). Then, the tidal effect is excluded from the coupled model (case 3) and results in the surge ζS generated by wind stress and wind-waves shown in Fig. 8c, which follows similar trend as those with tidal effect (Fig. 8a and b). However, the comparison of model results at station C suggests that excluding tidal effect leads to mismatch of the surge peaks during tidal cycles (blue line in Fig. 9a) due to nonlinear interaction between tide and surge, which will be further discussed in Section 5.2.

4.3. Momentum balance

The model results of momentum terms are next used to estimate the relative importance of physical processes in the variation of storm surge due to tide-surge interaction. Following previous studies (Hench and Luetich, 2003; Valle-Levinson et al., 2013; Yang et al., 2019), one-dimensional (cross-shore direction) momentum balance during the cold front event is given in the following Eq. (4) assuming that the horizontal advection, atmosphere pressure and viscosity are negligible.

\[
\frac{\partial u}{\partial t} + f v + \frac{\partial (u u)}{\partial x} = \rho \frac{\partial h}{\partial x} \eta + \frac{1}{\rho} \frac{\partial \tau_t}{\partial h} - \frac{\partial \tau_z}{\partial h} + \frac{1}{\rho} \frac{\partial S_{\eta \eta}}{\partial x} = 0
\]

ACC COR PRE BSTR WND WAV

\[
\begin{align*}
\text{ACC} & = 0.10, \quad \text{COR} = 0.09, \quad \text{PRE} = 0.11, \\
\text{BSTR} & = 0.20, \quad \text{WND} = 0.20, \quad \text{WAV} = 0.20
\end{align*}
\]
gravitational alongshore where (a) Fig. 8. Time series of storm surge along the section AB indicated in Fig. 1c, due to the action of (a) tide, wind and wave (ζθ); (b) tide and wind (ζSI(station)); and (c) wind and wave (ζu). (d) Time series of tidal level along the section AB in tidal only situation (ζ).

Fig. 9. (a) Time series of storm surge under the impacts of different forcing, i.e., ζθ (black solid lines), ζSI(station) (red solid line) and ζu (blue solid line), scaled tidal elevation 0.25ζT (grey dashed line) and nonlinear tide-surge interaction ζT (black dashed line) at the coastal station C indicated in Fig. 1c. (b) Time series of wave-induced surge at the coastal station C under the harbor layout of year 2003 (red solid line) and year 2016 (black solid line). Fall/rise means the falling/rising tide. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

where u and v denote the velocity components in cross-shore and alongshore direction, respectively, f is the Coriolis parameter, g is the gravitational acceleration, ρ is the water density, h is the mean water depth, θ and τs denote the bottom and surface stresses, respectively, Sxx indicates the radiation stress, ACC (acceleration of tidal current), COR (Coriolis force), PRE (pressure gradient), BSTR (bottom stress), WND (wind stress), WAV (wave forcing).

The fully coupled model results (case1) of six primary momentum terms in cross-shore direction at the cross-shore section AB are demonstrated in Fig. 10. The momentum terms ACC, PRE, BSTR, and WND contribute the most to the local momentum balance, with five times larger magnitude than those of COR and WAV (note that scales are different in Fig. 10). Due to tide-induced change in water depth and current flow, the momentum terms also exhibit semi-diurnal modulation. Moreover, all these terms are in phase with each other along the section except for the COR which is associated alongshore current. The phase shift in COR in cross-shore direction is possibly due to the flow diversion by the coastline (Kuang et al., 2019) and the tidal distortion by shallow water effect (Dyer, 1973; Li et al., 2012; Song et al., 2013). The momentum terms BSTR and WND relating to total water depth H d ζ show considerable variations towards the shore during the period of interest (Fig. 10b and d). It appears that dominant pairs of momentum balance is different in space and time. In the calm weather, the predominant PRE is mainly balanced by ACC and COR in the offshore, but by BSTR in the nearshore zone due to decreasing water depth, which are in accord with the findings of previous studies (Speer and Aubrey, 1985; Hench and Luettich, 2003). However, during the storm event, the PRE is primarily balanced by the intense WND in both nearshore and offshore zones, which reflects the relative importance of wind stress in the shallow water coast. Interestingly, BSTR becomes weaker in the nearshore zone during the storm as the remarkable positive surge increases the total water depth, whereas the COR is intensified by the strong alongshore wind-induced current. WAV seems to be less affected by tide and increases onshore, but its contribution is limited to momentum balance even in the shallow region. The response of ACC to the storm event is weaker than other terms.

5. Discussion

5.1. Wave-induced surge

Wave breaking introduces additional momentum flux from wave to current (e.g., Longuet-Higgins and Stewart, 1962, 1964; Phillips, 1977). The wave-induced surge or so called wave setup produces the pressure gradient to balance the extra momentum flux induced by wave in the cross-shore direction (Longuet-Higgins and Stewart, 1964). Previous section has demonstrated that the wave-induced surge is not as large as the wind-induced storm surge in southwestern Bohai Bay (Figs. 8 and 9a). The time series of wave-induced surge is presented in Fig. 9b, with a peak value of only 0.13 m under the harbor layout of 2003. This peak value is quantitatively consistent with that predicted by our numerical model forced with a constant 19 m/s easterly wind (Song et al., 2019) and by a well-validated empirical formula (Ji et al., 2018). As shown in Fig. 9b, the wave-induced surge is modulated by tide through not only water depth but also the momentum flux from tidally modulated wave to flow (Brown et al., 2013; Zou and Xie, 2016; Song et al., 2019). As indicated by Zou et al. (2013), at shallow enough water depth, the wave is strongly modulated by tide and surge. Therefore, the contribution of wave-induced surge to overall storm surge increases/decreases in the falling/rising tide by 5%-15% (Fig. 9a and b). In practice, the contribution of wind- and wave-induced surges can be diagnosed by the following simplified 1-D steady-state storm surge balance from neglecting the unimportant terms in Eq. (4), i.e., ACC, BSTR and COR, based on the results shown in Fig. 10, which is in accordance with that proposed by Dean and Darymple (1991) without considering the air pressure term, as following:
Consequently, over early 2017 fetch. a more overall positive value indicates the shoreward momentum flux.

\[
\frac{g}{\eta} \frac{\partial h}{\partial x} + \frac{\tau_x}{\rho h \eta} - \frac{\partial S_{sw}}{\partial x} \tag{5}
\]

PRE WND WAV

The long fetch of northeasterly wind in Bohai Sea, in conjunction with local shallow water depth produces large wind-induced surge which may be calculated by integrating the term WND over the wind fetch. Wave transformation mainly depends upon bottom slope and water depth change (Schulz et al., 2012; Parvathy and Bhaskaran, 2017). Because of the gentle slope of 1:3000, the storm wave breaks early in the offshore and deforms gradually towards the shore, resulting in a broad surf zone (Zhao, 2007; Zhang et al., 2010b; Song et al., 2019). The radiation stress gradient \(\frac{\partial S_{sw}}{\partial x}\) in term WAV in Eq. (5), therefore, is small over such a broad surf zone, which leads to small wave-induced surge. As a result, it is reasonable to neglect the wave contribution to the overall storm surge on this shallow and mildly-sloping coast to some extent. However, this might not be the case in the coast with steeper slope, in which case the integration of the dominant term WND is smaller since the water depth becomes deeper, therefore, the wind-induced surge is decreased. In contrast, the storm wave tends to break closer to the shore, so that larger radiation stress gradient is generated over a narrower surf zone which leads to larger wave-induced surge. As reported by Parvathy and Bhaskaran (2017), wind-wave propagating on a steeper slope will have a severer energy dissipation over a narrower surf zone as compared to that on a gentler slope. Consequently, the contribution of wave can account for up to 15%–40% or more of storm surge in regions with steeply-sloping topography (e.g., Kim et al., 2010; Sheng et al., 2010; Kennedy et al., 2012; Wu et al., 2018a). In addition to the bed slope, the intensity of storm also plays a role in the contribution of wave to surge (Wu et al., 2018a).

5.2. Nonlinear tide-surge interaction

5.2.1. General features

The model results in Figs. 8 and 9 shows significant semi-diurnal modulation of storm surge with a period of the dominant astronomic tide, due to nonlinear tide-surge interaction (McInnes and Hubbert, 2003; Horsburgh and Wilson, 2007; Zhang et al., 2010a; Idier et al., 2012; Valle-Levinson et al., 2013). The intensity of nonlinear tide-surge interaction increases towards the shore due to amplification of tidal amplitude and storm surge (Horsburgh and Wilson, 2007; Feng et al., 2016), as shown in Fig. 8. Nonlinear interaction residual \(\zeta\) is adopted by numerous researchers to quantify the nonlinear interaction. As shown in Fig. 9a, the nonlinear residual \(\zeta\) displays a M2-period oscillation during the storm, and furthermore, it is always out of phase with the tide \(\zeta_T\) (cf. black dashed line with grey dashed line). This result suggests that nonlinear tide-surge interaction acts as a “damper” to the highest water elevation at peak positive surge. As a result, the nonlinear residual \(\zeta\) and its resulting storm surge \(\zeta_{SI}\) are to attain their maximum and minimum value at low and high tide, respectively, which is consistent with those of previous studies (Rego and Li, 2010; Feng et al., 2016). In particular, the residual \(\zeta\) due to nonlinear tide-surge interaction varies between 0.32 m and 0.59 m leading to a 0.81 m change in water level (Fig. 9a), which is about 32.4% of the local tidal range of about 2.5 m. It is worth noting that here the surge peak occurs at the low tide, instead of rising or falling tide found by some studies (Rossiter, 1961; Horsburgh and Wilson, 2007; Feng et al., 2016). The storm surge modulation due to nonlinear tide-surge interaction relates to meteorological forcing (Rego and Li, 2010) and bottom slope (Nayak et al., 2012), therefore, the timing of surge peaks varies by storm events and by sites. The nonlinear tide-surge interaction may occur due to two generation mechanisms (Feng et al., 2016): 1) phase delay/advance of the observed tide relative to the predicted astronomic tide causes surge to peak during the falling/rising tide; 2) attenuation of the observed tide by surge causes surge to peak at low tide. The predominant timing of surge peak at the low tide in this study may be ascribed to the dominant role of second mechanism by local surge modification over the first mechanism by the phase shift.

5.2.2. Generation mechanisms

In tidal only case, nonlinearity comes from the nonlinear terms in momentum equation due to horizontal advection and bottom stress and nonlinear terms in continuity equation (Parker, 1991). However, during extreme weather, the nonlinear processes becomes more complicated and nonlinear term WND becomes important as shown in Fig. 10. These nonlinear processes lead to not only nonlinear water level (vertical tide) but also current velocity (horizontal tide). As a result, the momentum

Fig. 10. Cross-shore momentum balance terms along the cross-shore section AB from the fully coupled tide-surge-wave model (case1). (a) ACC (acceleration of tidal current); (b) BSTR (bottom stress); (c) PRE (pressure gradient); (d) WND (wind stress); (e) COR (Coriolis force); (f) WAV (wave forcing). Note that scales are different and positive value indicates the shoreward momentum flux.
residual of linear term, calculated by the method proposed by Yang et al. (2019), can be non-zero and influences the nonlinear tide-surge interaction as well. For example, the COR associated with alongshore current is significant during storm events (Valle-Levinson et al., 2013; Yang et al., 2019) and is recognized as the primary cause of the semi-diurnal surge in the US eastern seaboard (Valle-Levinson et al., 2013). Here, the momentum residuals of six primary terms are compared to the nonlinear interaction residual $\zeta_I$ at offshore station A (Fig. 11a) and nearshore station B (Fig. 11b) (locations indicated by Fig. 1c), in order to pinpoint the dominant physical process for nonlinear tide-surge interaction there. In the offshore, the semi-diurnal modulation of nonlinear residual $\zeta_I$ can be mostly contributed by the PRE residual that is mainly balanced by the ACC residual (Fig. 11a), which is also the case in Tieshan Bay (Yang et al., 2019). The significance of ACC in the offshore suggests a strong nonlinear interaction of tidal current with storm-induced current. As water depth decreases towards the shore, the BSTR residual becomes dominant over the ACC residual offsetting the PRE residual and governs the semi-diurnal modulation of surge, consistent with previous findings (e.g., Tang et al., 1996; Bernier and Thompson, 2007; Horsburgh and Wilson, 2007; Zhang et al., 2010a; Idier et al., 2012). It is interesting that the predominant WND in momentum balance (see Fig. 10d) only plays a secondary role in the balance of momentum residual, thus has a limited contribution to the nonlinear tide-surge interaction (Fig. 11). The PRE residual is able to account for most but not all the evolution of nonlinear interaction residual. On one hand, the discrepancies are partly attributed to the nonlinear free surface process in continuity equation (Sheng and Wang, 2004). On the other hand, this comparison can only represent the correlation between the momentum terms and nonlinear residual in a qualitative sense (Kuang et al., 2019).

The mechanisms for nonlinear tide-surge interaction may also be explained in analog with the interactions among astronomic tides in shallow waters since the storm surge can be treated as long waves (not a freely propagating Kelvin long wave) (Rego and Li, 2010; Valle-Levinson et al., 2013). Accordingly, the momentum and energy transfer/redistribution between tidal constituents and the storm surge long wave are expected to occur in the coastal region (Horsburgh and Wilson, 2007; Jones and Davies, 2008; Rego and Li, 2010; Sahoo et al., 2019). For examples, the energy is possibly to be transferred from low-frequency component (i.e., storm long wave) to high-frequency component (e.g., semi-diurnal tide $M_2$ and higher harmonics $M_4$ and $M_6$) via nonlinearity (Gallagher and Munk, 1971; Parker, 1991; Speer and Aubrey, 1985; Jones and Davies, 2008). However, this kind of energy redistribution and wave-wave interaction may not be detected by the commonly used tools of harmonic analysis, e.g., $T_{\text{TIDE}}$ (Pawlowski et al., 2002), which should be an interesting subject for the future study.

Nonlinear tide-surge-wave interaction may also occur through wave-current interaction due to (1) depth averaged and depth dependent wave radiation stress (e.g., Longuet-Higgins and Stewart, 1962, 1964; Zou et al., 2006; Ardhuin et al., 2008; Mellor, 2005, 2008); (2) bottom stress (e.g., Grant; Zou, 2004); and (3) ocean surface stress modification by waves (e.g., Johnson et al., 1998; Taylor and Yelland, 2001; Moon et al., 2004a, b; Haus, 2007).

### 5.3. Effects of harbor constructions

Coastal structures such as long jetty and large-scale reclamation, may remarkably modify the current pattern but not the water level, which is at the order of $O(10^{-1})$ m (Pelling et al., 2013; Park et al., 2014; Guo et al., 2018; Kuang et al., 2019). Fig. 12a demonstrates the spatial distribution of storm surge difference due to the difference in harbor layouts in 2016 and 2003 at 11:30 11th October 2003, at the storm surge peak. It is evident that the water pushed westward is markedly blocked by the Huanghua Harbor in 2016, resulting in an increase of storm surge up to 0.20 m on the east and a decrease of about 0.10 m on the west. The increased storm surge is significant in the region between the two harbors, especially in the nearshore zone where local tide-surge-wave interaction is strong. In general, the time evolution of storm surge $\zeta_{\text{ST}}$ at the nearshore station C (Fig. 13a) suggests the change by local harbor constructions in 2016 is limited since the storm with long wavelength can diffract over the obstacles as astronomic tides do (Song et al., 2013; Wu et al., 2018b). Nonetheless, coastal storm surge in layout 2016 still appears some interesting features that are different from those in layout

![Fig. 11. Time series of different components of cross-shore momentum residual and nonlinear interaction residual $\zeta_I$ at the (a) offshore station A and (b) nearshore station B (locations indicated in Fig. 1c). The momentum residual is calculated following the method proposed by Yang et al. (2019).](image-url)

2003. The time series of storm surge difference between layout 2003 and 2016 (black solid line in Fig. 13b) indicates that the storm surge in layout 2016 shows a little more significant and frequent modulation during the storm. The possible reason for this variation of storm surge by coastal structures is quite complex, as it not only relates with the changes in surge induced by wind and wave but also change in wave height, tidal amplitude and water piled-up due to geometric changes by the construction. As concluded in Section 5.2, the semi-diurnal modulation of storm surge is generated by nonlinear tide-surge interaction. Fig. 13b shows that the variation of nonlinear interaction residual $\zeta_{I}$ explains most of the change in storm surge $\zeta_{SI}$ by the harbor constructions (cf. black dashed line with black solid line). Exceptions occur around the peaks of storm surge between 11:00 and 17:00 11th October, as marked in Fig. 13. This discrepancy is ascribed to the increase of storm surge forced by wind forcing only $\zeta_{S}$ (blue solid line) and nonlinear interaction residual $\zeta_{I}$ (black dotted line). (c) Difference induced by the harbor construction between 2016 and 2003 in wave-induced surge (red solid line) and wave height difference between offshore and nearshore (black solid line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 13. (a) Time series of storm surge at nearshore station C for the harbor layout in 2003 and 2016. (b) Difference induced by the harbor construction between 2016 and 2003 in storm surge $\zeta_{SI}$ (black solid line), storm surge forced by wind forcing only $\zeta_{S}$ (blue solid line) and nonlinear interaction residual $\zeta_{I}$ (black dotted line). (c) Difference induced by the harbor construction between 2016 and 2003 in wave-induced surge (red solid line) and wave height difference between offshore and nearshore (black solid line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Regarding the wave-induced surge in the nearshore zone, generally, the construction of local harbor further intensifies its magnitude (cf. black solid line with red solid line in Fig. 9b), and its maximum contribution to the overall storm surge is increased to 8%–20% in layout 2016. The intensification of wave-induced surge can be explained by the following two possible reasons: 1) the semi-closed geometry of layout 2016 provides a more favorable conditions for water piled-up (as in Fig. 12b); 2) more wave momentum flux is transferred onshore. The wave momentum transferred to coast is associated with the gradient of radiation stress, which can be indicated by the difference of significant wave height between nearshore and offshore (Brown et al., 2013). It has been reported that the southeastward transport of local dominant $M_2$ tidal wave is severely obstructed by Huanghua Harbor in layout 2016, which causes a pronounced decrease of tidal amplitude between two harbors (see Kuang et al., 2019). Then, the decreased tidal amplitude could result in a weaker tidal modulation of coastal wave height (Moon, 2005; Song et al., 2019), while the modulation of offshore wave height remains unchanged. Consequently, the cross-shore difference of wave
height in layout 2016 experiences a general increase (black solid line in Fig. 13c) and suggests that more momentum flux is brought to the coast, therefore, leading to a larger wave-induced surge (red solid line in Fig. 13c).

The storm surge in layout 2003 and 2016 (Fig. 13a) are similar to each other. However, the mechanisms for the nearly quasi-diurnal variation of nonlinear interaction residual $c_\xi$ (Fig. 13b) is worth investigation. The construction of large-scale coastal structure may significantly change the local nonlinearity and quasi-diurnal tides (e.g., $M_2$, $M_4$, $M_6$, and $M_{2n}$) even in tidal only situation (Gao et al., 2014; Li et al., 2018; Kuang et al., 2019). The harbor construction has significant effects on quasi-diurnal tides during extreme weather event due to enhanced nonlinearity and wave energy, therefore, on the quasi-diurnal modulation of nonlinear tide-surge interaction. In addition, local wave-induced surge was found to be modulated by quasi-diurnal due to the phase difference between tide and wave momentum flux by Song et al. (2019). The same phenomenon may also be found in this case study and even amplified by the larger harbor layout in 2016 (Fig. 9b). As a result, the modification of wave-induced surge by harbor displays a quasi-diurnal modulation (red solid line in Fig. 13c) which in turn affects the nonlinear tide-surge interaction (Fig. 13b).

The long-term bathymetric variation between year 2003 and 2016 may trigger change in water level comparable to that induced by harbor construction changes (Guo et al., 2018) but is neglected in the present study. Its inclusion will further complicate the driving mechanisms for tide-surge-wave interaction. Moreover, the extreme weather event is expected to affect sediment transport and morphological evolution which in turn would alter the water depth, wave, tide, surge and their interactions. These are the potential research topics in the future work. Nevertheless, the case study of Huanghua-Binzhou Harbor here provides a direct comparison of storm surge hydrodynamics before and after large scale cross-shore oriented harbor constructions. It would be of practical significance for similar scenarios where harbor situate in a coastal zone susceptible to sedimentation and has cross-shore long jetties such as the Tianjin Harbor, in the west of Bohai Bay.

6. Conclusion

A 2-D depth-averaged tide-surge-wave coupled model (Delft3D) is applied to study the nonlinear tide-surge-wave interaction in a shallow and mildly-sloping coast at southwestern Bohai Bay in Northeastern China, during the extreme cold front event on 10–13th October 2003. The present study investigates the generation mechanisms of nonlinear tide-surge-wave interaction based on momentum and energy balance and transfer among wind, tide, surge and wave, and estimates the relative contribution of wave-induced surge (wave setup) to overall storm surge. Furthermore, a special attention is paid to the impacts of large scale harbor constructions on nonlinear tide-surge-wave interaction processes.

The wind data derived from atmospheric reanalysis products of global model ECMWF-Interim, CCMP and ECMWF-ERA5 are improved through data assimilation of the field observations using linear regression. It is found that the newly-released ECMWF-ERA5 with the highest temporal resolution performs the best in reproducing the observed surface wind field. The optimal wind drag coefficient during the cold front in 2003 is found to be $c_d = 0.8 \times 0.123U_{10}^{-1}$. The southerly traveling cold front during 10–13th October 2003, produces a sustained southwestward wind field with little change in direction (within 0°–90°). The wind stress is effective in raising water level by piling water against the coast due to shallow water depth and long fetch and unidirection of wind in southwest Bohai Bay. The model results indicate that the intensity of storm surge increases rapidly towards the coast to 2.22 m, as the surges induced by wind and wave are inversely proportional to total water depth. The contribution of wave-induced surge to the overall storm surge is limited due to a gentle bottom slope, and increases and decreases during falling and rising tide respectively, by 5%–15% at most.

The semi-diurnal modulation of storm surge is mainly due to nonlinear tide-surge interaction that dampens and restrains the extreme high sea surface at the peak of storm surge. The contribution of nonlinear tide-surge interaction to the storm surge is found to increase towards the coast by up to 0.81 m, which is about 32.4% of tidal range. According to the momentum distribution analysis in the cross-shore direction, the momentum residual balance in the offshore is primarily between pressure gradient and flow acceleration, which implies the nonlinear tide-surge interaction is caused by the flow acceleration associated nonlinearity by current. However, in the nearshore zone, the pressure gradient is balanced by bottom stress, which strongly influences the nonlinear tide-surge interaction. In contrast, the predominant momentum term due to wind stress only plays a secondary role in generating the nonlinear tide-surge interaction.

The construction of Huanghua-Binzhou Harbor gives rise to a significant quasi-diurnal modulation of storm surge. It relates to the changes in storm surge, wave and water piled-up due to geometric modifications by the harbor constructions. The quasi-diurnal surge modulation may also be attributed to the change in quasi-diurnal tides during the extreme weather event due to the effect of harbor construction on the nonlinearity and energy. In addition, the quasi-diurnal modulation of wave-induced surge due to phase difference between tide and wave momentum flux may also contribute to the quasi-diurnal storm surge. The construction of Huanghua-Binzhou Harbor forms a semi-closed region between them which provides an optimal condition for local water to funnel and piled-up to produce surge. Consequently, this region becomes the most vulnerable area with a peak storm surge increase of 0.20 m. Moreover, local wave-induced surge is increased by up to 0.13 m so that its maximum contribution to overall storm surge increases to 8%–20%, due to more momentum flux transported onshore by the harbor construction.

This study may be further improved by nesting a regional meteorological model such as WRF with the global climate models, considering the feedbacks of bathymetric variation to tide-surge-wave interaction or evaluating the uncertainty cascade from atmosphere to ocean to coastal models using an ensemble modelling approach. Nevertheless, the case study of Huanghua-Binzhou Harbor here provides new insights for the impacts of large-scale cross-shore oriented harbor constructions on storm surge hydrodynamics, which is of practical significance for similar scenarios at other sites of the world.

Declaration of competing interest

The authors declare no competing interests.

CRediT authorship contribution statement


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