LETTER

Storm surge risk under various strengths and translation speeds of landfalling tropical cyclones

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Abstract

Landfalling tropical cyclones (TCs) frequently occur with strong intensity in most coastal areas, and storm surges are likely to occur in response to extreme sea level (ESL) growth. However, the level of ESL growth under various wind conditions, coastline geometries and tide-surge interactions has not been clarified. In the Pearl River Estuary and Daya Bay, observations of landfalling TCs have indicated an increasing frequency of intense and rapid landfalls in the 2010s as compared to the 2000s, accompanied by a noteworthy increase in storm surge. Based on a large ensemble (≃0.5 million storm surge events with various tracks, maximum wind speeds, maximum wind radiuses, translation speeds and tidal conditions) obtained from well-validated model simulations, the ESL growth in the study area is further quantified as follows: (a) ESL growth is more sensitive to the acceleration effect of landfalling TCs than to the strengthening effect of landfalling TCs since the effect of low acceleration (+3 m s\(^{-1}\)) is comparable to that under notable strengthening (+10 m s\(^{-1}\)); (b) ESL growth is strongly modulated by coastline geometry, especially in flared or arching coastline areas. ESL growth mainly occurs along flared coastline areas when landfalling TCs strengthen into severe TCs or typhoons but can also occur along arching coastline areas for stronger landfalling TCs, such as severe typhoons or supertyphoons; and (c) ESL growth could be increased or decreased by approximately 10% under the effect of tide-surge interactions. Both the large-ensemble method and the above ESL growth characteristics are worthy of attention in risk assessment and rapid prediction of storm surges in shallow waters.

1. Introduction

Storm surge disasters caused by landfalling tropical cyclones (TCs) occur with rapid rises in sea surface level and greatly threaten human lives and infrastructure in low-lying areas of affected coastal regions (Peduzzi et al 2012). This threat may even be worse under the increasing frequency and intensity of strong TCs (Elsner et al 2008, Bender et al 2010, Knutson et al 2010). Recent studies have shown that the storm surge threat in areas with intense human activities is closely related to the extreme sea level (ESL) during a storm surge event (Sterl et al 2009, Rashid et al 2019). Statistics on ESL growth at various conditions of landfalling TCs can be used to estimate the storm surge risk under intensified TCs. However, these ESL statistics require data on storm surge events that cover all tide and wind conditions, e.g. the track,
maximum wind speed, translation speed and maximum wind radius of landfalling TCs, which are not supported by historical data even in areas with frequent storm surges. Hence, it is essential to build a large ensemble according to various landfalling TC conditions using numerical methods to further improve risk-resilient development options and the forecasting capability, as indicated by Rao et al. (2020).

In shallow waters, ESL during a typical storm surge event is mainly driven by wind, tide, bottom friction and advection according to the momentum equation (Flather 2001, Chen et al. 2007). In this study, we considered four major factors, namely, wind, tide, coastline geometry (Dube et al. 1982) and tide-surge interaction (Heaps 1983, Wolf 2009), to analyze ESL growth because the coastline geometry and tide-surge interaction are related to both bottom friction and advection and are more commonly considered in ESL assessments (Horsburgh and Wilson 2007, Dinopoli et al. 2020). Wind-driven currents tend to transport large amounts of water to near-coast areas and play a dominant role in storm surges; e.g. the ESL could increase by approximately 3–6 m in gulf s of the South China Sea when the TC strength is higher than a typhoon (Mori et al. 2014). The most dangerous wind direction points toward the mouth of an estuary or bay, which is different from that attributed to the Coriolis force because the surface and bottom stress in shallow waters exceeds the Coriolis force (Weisberg and Zheng 2006). The tidal elevation provides a background sea level so that the ESL probably occurs near the high position of the spring tide (Brown et al. 2010, Park and Suh 2012, Choi et al. 2018). The effect of the coastline geometry can cause a regional difference in ESL of more than 3 m in affected bays (Yang et al. 2017, Bass et al. 2018). Two typical coastline geometries, namely, a flared coastline with a convergent effect (Zhang et al. 2017, He et al. 2020) and an arching coastline with a lower friction (Rego and Li 2010), both attained higher ESL values at the top of the bay. Tide-surge interactions, which may contribute 80% to the tidal amplitude (Keers 1968, Rego and Li 2010, Xu et al. 2016), can be mainly attributed to the nonlinear advection effect (Rego and Li 2010) and the nonlinear bottom friction effect (Tang et al. 1996, Bernier and Thompson 2007, Zhang et al. 2010). Other factors, e.g. wave and wave-surge interactions (Zhang et al. 2018), are not considered because ESL at timescales larger than 1 h, which excludes most wave processes, is the focus of this study. With respect to the above four major factors, numerous model experiments and large-ensemble analyses are essential for quantifying ESL growth under various conditions of landfalling TCs.

The Pearl River Estuary and its adjacent four bays (figure 1(a), rectangular box area) represent a typical area that can be used to study ESL growth because of the high frequency of TC intrusions. The study area is one of the world’s largest bay areas in terms of gross domestic product, and it is also a low-lying coastal area that suffers from severe storm surges (Syvitski et al. 2009, Wu et al. 2018). Liu et al. (2020) pointed out the increasing destructive potential of landfalling TCs over China and the high frequency of climatologically landfalling TCs over the northern South China Sea and southern coast of South China. Although there is a slowdown of TC translation speed in the western North Pacific (Kossin 2018), the translation speed at TC landfall over the northern South China Sea has accelerated in recent years (Liu et al. 2020). Based on data from the Joint Typhoon Warning Center of the U.S. Naval Pacific Meteorology Oceanography Center in Hawaii, intensified (above typhoon level) landfalling TCs frequently occur in the northern South China Sea (figure 1(b), blue and red points). In the study area, only one intensified landfalling TC occurred between 2000 and 2009 but seven occurred between 2010 and 2019. The translation speed of landfalling TCs, regardless of whether the value is calculated from all TC events (figure 1(c), black solid line) or from TC events above the typhoon level (figure 1(c), black dashed line), increased from 5 m s$^{-1}$ in 2000 to more than 8 m s$^{-1}$ in 2019. Although the difference from one decade is not sufficient to rigorously calculate a trend, landfalling TCs with high intensity levels and rapid translation speeds have frequently occurred after 2000. In particular, the study area includes the two typical coastline geometries of a flared coastline in the Pearl River Estuary and an arching coastline in Daya Bay, which could function as representative areas with high storm surge risk in shallow waters. The questions to be addressed in this paper are as follows: (a) How will ESL growth respond to the various strengths and translation speeds of landfalling TCs? (b) What roles do the major factors of wind, coastline geometry and tide-surge interaction play in ESL growth?

To answer the above two questions, two observation stations in the Pearl River Estuary and Daya Bay are employed to confirm ESL growth under high strength and translation speed of landfalling TCs, and then a quantitative analysis is performed with a finite-volume community ocean model (FVCOM; Chen et al. 2003) and a large-ensemble implementation. Since typhoons and supertyphoons frequently occurred and the translation speed of landfalling TCs increased from 2000 to 2019, the ESL growth responses to the strength and acceleration of landfalling TCs are compared. The roles of the flared coastline in the Pearl River Estuary and the arching coastline in Daya Bay in ESL growth are also compared under various strengths and translation speeds of landfalling TCs. The tide-surge interaction and its mechanism are explored through a comparison of sensitivity experiments with and without tide-wind coupling.
2. Methods

To determine ESL growth, we built a well-validated FVCOM model that considers tide-wind coupling and a large ensemble of ~0.5 million storm surge events under various wind and tidal conditions. To further analyze the tide-surge interaction, another 13 680 wind-driven tests and 36 tidal-driven tests were established for comparisons to the tide-wind coupling results.

2.1. Tide-wind coupling model

The tide-wind coupling model simulated tides, storm surges and tide-surge interactions during various storm surge events. Fine grid resolutions (0.1–3 km, figure S1 available online at stacks.iop.org/ERL/16/124055/mmedia), 20 vertical layers, and high-resolution topography (<0.1 km), were used in the study area. A bottom friction coefficient of 0.005 and a bottom roughness of 0.002 m were applied in our simulations. The tidal conditions were specified along open boundaries with harmonic constants of 11 major tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, and MN4) based on the Oregon State University global tidal model of TPXO.7.0 (Egbert et al 1994).

A wind construction method (Emanuel 2004, Emanuel and Rotunno 2012) was adopted to generate the wind field through parameterizations of the track, maximum wind speed, translation speed and maximum wind radius in a specified TC. The wind velocity \( U \) at a radius \( r \) is given by the following:

\[
U(r) = \frac{R_m (2CU_m - U_t \sin(\theta)) + \frac{1}{2} R_m^2 f r}{R_m^2 + r^2} - \frac{fr}{2}
\]

where \( R_m \) is the maximum wind radius; \( C \) is a correction factor of the maximum wind speed \( (U_m) \), with a value of \( C = 0.736 \) used for the northern South China Sea (Zhang et al 2016); \( U_t \) is the translation speed of TC; \( \theta \) is the direction of TC translation; and \( f \) is the Coriolis parameter \( (f = 2\Omega \sin\varphi) \), where \( \Omega = 7.292 \times 10^{-5} \) and \( \varphi \) is the latitude.

Wind fields during four typical landfalling TCs at the levels of tropical storms (figure S2), typhoons (figure S3), severe typhoons (figure S4) and supertyphoons (figure S5) showed asymmetric winds primarily varying with the maximum wind speed. Storm surge
events of the above four landfilling TCs were simulated to validate the tide-wind coupling model.

2.2. Large-ensemble simulations and predictions

To build a large ensemble that includes all the wind conditions of the various tracks, maximum wind speed, maximum wind radius, translation speed and tidal conditions, 492 480 storm surge events were simulated with the tide-wind coupling model. Based on typhoon statistics (figure 1(a), blue and red curves), 19 parallel tracks (figure 1(a), dashed lines) were designed from southeast to northwest considering the most likely landfalling angle and an interval of approximately 25 km, which represented a characteristic scale in wind speed variation. These parallel tracks, which were constructed in other typhoon affected areas (Bass et al 2018, Yin et al 2021), covered the entire study area and represented landfalling TCs in any approaching position. Ten maximum wind speed levels (15–60 m s\(^{-1}\)), eight maximum wind radius levels (25–200 km), and nine translation speed levels (3–11 m s\(^{-1}\)) were configured at intervals of 5 m s\(^{-1}\), 25 km and 1 m s\(^{-1}\), respectively. As irregular semidiurnal tidal water patterns occur in the study area, 36 tidal conditions covering three semidiurnal periods of spring, middle and neap tides at 1 h intervals were selected.

To quantify tide-surge interactions for surge events in the large ensemble, following the terminology of Banks (1974), the sea level in the large ensemble can be written as the sum of the tidal level, the pure storm surge produced by the meteorological conditions only, and the residual elevation due to tide-surge interaction. Therefore, pure storm surge models of 13 680 wind-driven tests and 36 tide-driven tests were simulated to calculate tide-surge interactions for all the samples in the large ensemble. The wind-driven tests involved the same wind forcings as those in the tide-wind coupling model, which were constructed based on 19 tracks, 10 maximum wind speed levels, 8 maximum wind radius levels and nine translation speed levels of landfalling TCs. The tide-driven tests also involved the same tidal conditions as those in the tide-wind coupling model.

Based on the large ensemble of storm surges and their related wind and tidal conditions, a statistical forecasting method was designed for the rapid (<1 min) prediction of historical storm surge by searching for its given wind and tidal conditions in the large ensemble. At a forecast time, because the connected storm surges from the large ensemble to the prediction occurred in different storm surge events, a bias of elevation was observed between the two snapshots despite having the same wind and tidal conditions. For example, a comparison of the elevations between the large ensemble and a tide-wind coupling simulation in a snapshot time of Supertyphoon Mangkhut showed a large bias (figures S6(a)–(c)). Therefore, the time derivative of elevation (\(\partial \eta / \partial t\)), which could reduce the bias caused by different storm surge events (figures S6(d)–(f)), was used to construct the elevations in a specified storm surge event. Now, we begin the large-ensemble prediction process based on a specified storm surge event, and it includes major variables of time steps, longitude, latitude, maximum wind speed, translation speed and maximum wind radius. At each time step, we search for \(\partial \eta / \partial t\) from the large ensemble based on the largest weight; this parameter is the product of the distance weight, maximum wind speed weight, translation speed weight and maximum wind radius weight. After determining the \(\partial \eta / \partial t\) value for each time step, \(\eta\) is further derived through a time integration of \(\partial \eta / \partial t\). Finally, storm surges that occurred in response to the 70 historical landfalling TCs (figure 1) in the northern South China Sea were predicted by the proposed large-ensemble prediction method.

2.3. Validation of the numerical model and large-ensemble predictions

Data on the observed wind and elevation at stations in the Pearl River Estuary (figures 2 and S1), Daya Bay (figures 2 and S2) and estuary mouth (figures 2 and S3), from the National Marine Data Center, are used to validate the wind construction method, tide-wind coupling model and large-ensemble prediction results. The mean root-mean-square error of the maximum wind speed is approximately 2.5 m s\(^{-1}\) (figure S7), which is relatively low (relative error of 7.6%) in comparison with the wind speed of typhoons (32.7 m s\(^{-1}\)). The historical elevation retrieved from both the tide-wind coupling model and the large-ensemble prediction is consistent with the observed results during Tropical Storm Nida, Typhoon Vicente, Severe Typhoon Hato and Supertyphoon Mangkhut (figure S8). Furthermore, the elevation errors in the large-ensemble predictions are generally <0.3 m (figure S9(b)), which is less than the effect of tide-surge interactions, indicating that the large-ensemble prediction method can successfully distinguish the tide-surge interaction term. The residual elevation errors may be introduced from wind field construction errors and other neglected storm surge mechanisms, e.g. wave and wave-surge interactions.

3. Results

In this section, we first investigate the storm surge patterns at two hydrologic stations under various strengths and translation speeds of landfalling TCs. Then, an analysis of the large ensemble is performed to quantify each singular impact of the wind, coastline geometry and tide-surge interaction on ESL growth.

3.1. Storm surges at the two hydrologic stations

To represent areas with flared and arching coastlines, observations of the wind speed and water elevation at stations S1 and S2 (figure 2(a)) are adopted to
investigate the storm surges under various landfalling TCs. Fifty-five landfalling TCs, which impacted the Pearl River Estuary and Daya Bay from 2002 to 2019, are selected with varying landfalling locations (figure 2(a), circle centers) and different maximum wind speeds (figure 2(a), color), maximum wind radii (figure 2(a), circles) and tidal conditions (figure 2(b)).

The maximum wind speed observed at both stations exhibits a significant strengthening (significance > 95%), although the maximum wind speeds observed at S1 and S2 (figures 2(c) and (d), respectively, blue curves) are much lower than those retrieved from remote sensing data (figure 1(b)) because the wind speed at a fixed observation location is greatly affected by the distance to the location of the maximum wind radius at landfall. Stronger storm surges (>1 m) at S2 occur once between 2000 and 2009 but seven times between 2010 and 2019, which is related to the number of intensified landfalling TCs (figure 1(a), blue and red points in the study area, respectively). The storm surge duration, calculated as the time with a positive storm surge value, is almost unchanged in the Pearl River Estuary and Daya Bay (figures 2(e) and (f), respectively; blue curves), which means that the storm surge has not lasted longer as it increases in intensity. This result is probably attributed to the increasing translation speed, which increased from 5 m s\(^{-1}\) in 2005 to 8 m s\(^{-1}\) in 2019, thus decreasing the storm surge duration and balancing the effect of the landfalling TCs in 2019 being more intense.

However, the maximum wind radius mostly occurred far from the observation stations (figure 2(a)), and landfalls rarely ensued during the high phase of the spring tide (figure 2(b)), indicating that the storm surge has been underestimated in historical data. In addition, ESL growth under the different wind, coastline geometry and tide-surge interaction conditions is difficult to quantify because of the limited landfalling TC samples (especially intensified landfalling TCs) in historical data.
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3.2. ESL growth under various strengths and translation speeds of landfalling TCs

To quantify the effect of TC strength on the ESL created by landfalling TCs, we calculate the induced ESL and duration at five landfalling TC intensity levels, which are defined using maximum wind speeds as follows: level 1, tropical depression: 15 m s\(^{-1}\); level 2, tropical storm: 25 m s\(^{-1}\); level 3, typhoon: 35 m s\(^{-1}\); level 4, severe typhoon: 45 m s\(^{-1}\); and level 5, super-typhoon: 55 m s\(^{-1}\). ESL growth from levels 2 to 3 and from levels 4 to 5 of landfalling TCs is examined based on the responses to the increased number of typhoons and supertyphoons in figure 1(b). Under linear maximum wind speed growth (figure 3, levels 1–5), the response of ESL growth exhibits notable nonlinearity and varies with the coastline geometry. In the flared coastline area of the Pearl River Estuary, the ESL achieves the fastest growth (1.9 m) when a given landfalling TC strengthens into a typhoon (figures 3(a) and (b), levels 2–3), whereas it exhibits much slower growth (<0.6 m) at higher TC levels, i.e. severe typhoon and supertyphoon levels. In the arching coastline area of Daya Bay, the situation is opposite to that in the Pearl River Estuary, with maximum ESL growth (~1.2 m) at higher levels, i.e. severe typhoons and supertyphoons (figures 3(a) and (b), levels 4–5). Therefore, the ESL is strongly modulated by the coastline geometry, which is more complicated than the wind effect because storm surge growth could be a cubic function of the wind speed (Peng et al 2006). In addition, the storm surge duration generally increases by approximately 3–4 h except from levels 3 to 4 (figures 3(d) and (e)), indicating that the maximum wind radius of landfalling TCs increases with an increased level of landfalling TC.

Comparisons of the ESL and duration between translation speeds of 5 m s\(^{-1}\) and 8 m s\(^{-1}\) are conducted to quantify the effect of accelerated landfalling TCs (figure 1(c)). ESL growths (figure 3(c)) affected by translation speeds are also prominent and sensitive to the different wind levels and shoreline geometries. The mean ESL growth induced by acceleration is 0.55 m (figure 3(c), the numbers at levels 2–5), which is comparable to the mean ESL growth of 0.76 m
induced by the strengthening effect of landfalling TCs (figure 3(a), the numbers inside parentheses). A lower landfalling TC acceleration (+3 m s\(^{-1}\)) contributes to ESL growth that is comparable to that under notable strengthening of landfalling TCs (+10 m s\(^{-1}\)), which suggests that the ESL is more sensitive to landfalling TC acceleration. Comparisons of ESL growth between the strengthening (+5 m s\(^{-1}\) in each level) and acceleration (from 5 m s\(^{-1}\) to 10 m s\(^{-1}\)) of landfalling TCs show that acceleration effect is more than 1.6 times greater than the strengthening effect (table S1). The greatest ESL growth in the Pearl River Estuary and Daya Bay reaches 0.6 m and 0.9 m, respectively, indicating that the arching coastline area yields a higher risk in response to accelerated landfalling TCs. In addition, the duration generally decreases by 2–4 h (figure 3(f)), which is comparable to the increase in the duration of typhoon- and supertyphoon-level landfalling TCs (figure 3(d), levels 3 and 5, respectively). This reduction interprets that the landfalling TC duration is almost unchanged (figures 2(c) and (d)) under the joint effect of strengthening and acceleration of landfalling TCs.

To further evaluate the potential ESL growth, the difference between the ESL during historical landfalling TCs (70 landfalling TCs from 2000 to 2019, figure 1) and the ESL based on large-ensemble simulations (~0.5 million landfalling TCs) is further analyzed. The ESL values during historical landfalling TCs are predicted with the large-ensemble prediction method. Both the ESLs (figure 4(a), heights) and the tide-surge interactions (figure 4(a), color) in the Pearl River Estuary and Daya Bay are severely underestimated, and the risk posed by these conditions is associated with the eastern edges of the maximum wind radius passing by the mouth of the Pearl River Estuary and Daya Bay (figure 4(a), blue and black circles, respectively) in historical data, as indicated by Weisberg and Zheng (2008).

3.3. Tide-surge interaction and its mechanisms

The tide-surge interaction (figures 3(g) and (h)) plays an important role in the ESL in the Pearl River Estuary and Daya Bay, e.g. the magnitude of the tide-surge interaction in the Pearl River Estuary reaches 0.6 m (figure 3(h), level 5), which is approximately 10% of the ESL. Both the magnitude and direction of tide-surge interaction vary with the wind conditions and coastline geometry. In the Pearl River Estuary, the observed tide-surge interaction ranges from positive (levels 1–2) to negative (levels 3–5) and finally reduces the storm surge of level 4–5 landfalling TCs by 10%. The larger negative tide-surge interaction value of level 4–5 landfalling TCs is comparable to the observed ESL growth; therefore, this phenomenon may contribute to the slower ESL growth at higher landfalling TC levels. In Daya Bay, the tide-surge interaction values are generally positive, and the larger values attained at higher landfalling TC levels may contribute to fast ESL growth. A comparison of \( U_1 = 5 \) m s\(^{-1}\) and \( U_1 = 8 \) m s\(^{-1}\) (figure 3(i)) reveals that a large increase (0.3 m) in tide-surge interaction occurs for level 3 landfalling TCs, while a larger decrease (~0.4 m) occurs for level 5 landfalling TCs, indicating that tide-surge interaction in the arching coastline area is greatly affected by landfalling TC acceleration.

The mechanisms of the tide-surge interaction are related to the increase in water surface elevation, and they are further analyzed with the maximum gradient of forcings in the momentum equation (Chen et al 2007). The momentum equation of the barotropic model is vertically integrated to estimate the momentum balance along the water column. Since horizontal diffusion constitutes a comparatively small term, it is neglected for simplicity

\[
\begin{align*}
&\frac{0}{\eta} \frac{\partial \bar{\nu}}{\partial t} + \frac{0}{\eta} \left( \bar{V} \cdot \nabla \bar{V} \right) + \frac{0}{\eta} -2\bar{\Omega} \times \bar{V} \\
= \ -\rho g f h + \rho_d C_D \left( \bar{U} \bar{U} - b_3 \bar{v}_b \bar{v}_b \bar{v}_b \right) + \text{Pressure} + \text{Coriolis} + \text{Wind} + \text{Bottomfriction} \\
&= \text{(2)}
\end{align*}
\]

where \( \bar{V} \) is the velocity, \( \bar{\Omega} \) is the angular rotation velocity of Earth, \( \eta \) is the elevation, \( \rho_d \) is the density of air, \( \bar{U} \) is the wind speed at 10 m above the sea surface, \( C_D \) is the drag coefficient at the sea surface (which varies with the wind speed \( \bar{U} \)), \( b_3 \) is the bottom friction coefficient, and \( \bar{v}_b \) is the simulated velocity at the bottom. Similar to the tide-surge interaction calculation, each forcing related to the tide-surge interaction is calculated based on the forcing in the tide wind tests minus the sum of the forcings in the wind and tide tests. Two stronger storm surge events in the Pearl River Estuary and Daya Bay are considered to reveal the mechanisms of tide-surge interactions. In the Pearl River Estuary, tide-surge interaction exerts a negative impact on the ESL and occurs during the high tide period (figure 4(b)). The negative acceleration of tide-surge interaction (figure 4(d), black curve) is mainly balanced by the bottom friction and wind forcing (figure 4(d)). In Daya Bay, the tide-surge interaction plays a positive role in the ESL and occurs during the low tide period (figure 4(c)). The positive acceleration of the tide-surge interaction is balanced by the effects of advection, bottom friction and wind forcing (figure 4(c)). Therefore, with the strengthening and acceleration effects of landfalling TCs, bottom friction plays a dominant role in the negative tide-surge interaction observed in the flared coastline area of the Pearl River Estuary, while both advection and bottom friction affect the positive tide-surge interaction observed in Daya Bay with an arching coastline.
Figure 4. Assessments of ESL and tide-surge interaction in historical storm surge events with mechanisms of tide-surge interactions in the Pearl River Estuary and Daya Bay. The heights and color barograph in Panel a show the differences in ESL and tide-surge interaction between historical landfalling TCs and large-ensemble simulations, respectively. The blue and black arrows in Panel a indicate the landfalling TCs that cause the highest ESL difference in the Pearl River Estuary and Daya Bay, respectively. Panels b and c show the storm surge, tide and tide-surge interaction during the highest-risk landfalling TCs in the Pearl River Estuary and Daya Bay, respectively. Panels d and e further show the mechanisms of tide-surge interaction in the Pearl River Estuary and Daya Bay, respectively.

4. Conclusion and discussion

Based on observations over the last 20 years and large-ensemble (~0.5 million storm surge events) simulations in the Pearl River Estuary and Daya Bay, the effect of strength and translation speed of landfalling TCs on ESL growth was investigated, and the three major factors of the wind, coastline geometry and tide-surge interaction were highlighted in the nonlinear ESL growth process.

The ESL is more sensitive to the acceleration effect than to the strengthening effect of landfalling TCs, although the increase in constructed wind velocity (equation (1)) induced by acceleration is less than that by the strengthening effect. A low acceleration (+3 m s\(^{-1}\)) contributes to ESL growth is comparable to that under notable strengthening (+10 m s\(^{-1}\)), while the mean effect of acceleration (+5 m s\(^{-1}\)) is more than 1.6 times larger than the mean effect of strengthening (+5 m s\(^{-1}\) in each lev). Furthermore, the acceleration of landfalling TC shortens the disaster response time by nearly half, which greatly improves previous forecasting models.

ESL growth is strongly modulated by the coastline geometry. ESL growth in flared coastline areas mainly occurs when landfalling TCs strengthen into severe TCs or typhoons, whereas ESL growth in arching coastline areas mostly occurs at higher landfalling TC strengths, i.e. during severe typhoons or super-typhoons. Although flared coastline areas present a
higher risk (higher ESL and longer duration) than areas with other coastline geometries, as reported in previous studies (Zhang et al 2017, He et al 2020), the increase in ESL in arching coastline areas is also very significant in response to highly strengthened and accelerated landfalling TCs.

The maximum impacts of the tide-surge interaction on both the total ESL and ESL growth reach approximately 10%, and strong nonlinearity is observed in the tide-surge interaction with varying wind speed and coastline geometry. Our results confirm that the tide-surge interaction value can reach up to 80% of the tidal amplitude and varies with the coastline geometry, as reported in previous studies (Rego and Li 2010, Zheng et al 2020). Furthermore, tide-surge interactions in flared and arching coastline areas are highlighted in this study. The tide-surge interaction value changes from positive to negative under higher landfalling TC strengths in the Pearl River Estuary, while the tide-surge interaction is generally positive in Daya Bay. The mechanisms in higher landfalling TC strengths indicate that bottom friction plays a dominant role in the negative tide-surge interaction value in the Pearl River Estuary, while both advection and bottom friction affect the positive tide-surge interaction value in Daya Bay.

The value of the large-ensemble method has been investigated in risk assessment and rapid storm surge prediction. The most dangerous storm surge in an area occurs particularly when the edge of the maximum wind radius passes by the bay mouth (Weisberg and Zheng 2008), although this phenomenon is difficult to analyze if sufficient historical data are lacking. Therefore, the large-ensemble method combined with various scenarios, such as varying wind and tidal conditions, is useful and necessary. Under accelerated TC landfall, the rapid predictions (<1 min) obtained with the large-ensemble method solve the problem that the disaster response time is shortened by half; thus, they can be well applied in other storm surge models (Cao et al 2014, Lagmay and Kerle 2015, Bilskie et al 2019, Sun et al 2019). The large-ensemble method requires a regional wind construction parameterization scheme and notable computing and storage resources for application in other areas impacted by storm surge disasters.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: http://doi.org/10.5281/zenodo.5069167.

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References

Banks J E 1974 A mathematical model of a river-shallow sea system used to investigate tide, surge and their interaction in ThamesSouthern North Sea region Phil. Trans. R. Soc. A 275 567–609

Bass B, Torres J M, Iraza J N, Proft J, Sebastian A, Dawson C and Bedient P 2018 Surge dynamics across a complex bay coastline, Galveston Bay, TX Coastal Eng. 138 165–83

Bender M A, Knutson T R, Tuleya R E, Sritarut J I, Vecchi G A, Garner S T and Held I M 2010 Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes Science 327 454–8

Bernier N B and Thompson K R 2007 Tide-surge interaction off the east coast of Canada and northeastern United States J. Geophys. Res.–Oceans 112 C06008

Bilskie M V, Hagen S C and Medeiros S C 2019 Unstructured finite element mesh decimation for real-time Hurricane storm surge forecasting Coastal Eng. 156 103622

Brown J M, Souza A J and Wolf J 2010 An investigation of recent decadal-scale storm events in the eastern Irish Sea J. Geophys. Res.–Oceans 115 C05018

Cao Y N, Zhang Z H, Ye Y, Yin J Y, Liu T and Center N M 2014 Sensitivity tests of surface wind fields in typhoon storm surge modeling: cases study in the South China Sea J. Trop. Meteorol. 30 1119–26

Chen C, Huang H, Beardsley R C, Liu H, Xu Q X and Cowles G 2007 A finite volume numerical approach for coastal ocean circulation studies: comparisons with finite difference models J. Geophys. Res.–Oceans 112 C03018

Chen C, Liu H and Beardsley R C 2003 An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: application to coastal ocean and estuaries J. Atmos. Ocean. Technol. 20 159–86

Choi B H, Kim K O, Yuk J H and Lee H S 2018 Simulation of the 1953 storm surge in the North Sea Ocean Dyn. 68 1759–77

Dinapoli M G, Simionato C G and Moreira D 2020 Nonlinear tide-surge interactions in the rio de la plata estuary Estuar. Coast. Shelf Sci. 241 106834

Duhe S K, Sinha P C and Rao A D 1982 The effect of coastal geometry on the location of peak surge Matsu 33 445–50

Egbert G D, Bennett A F and Foreman M 1994 Topex/Poseidon tides estimated using a global inverse model J. Geophys. Res.–Atmos. 99 24821–52

Elsner J B, Kosin J P and Jagger T H 2008 The increasing intensity of the strongest tropical cyclones Nature 455 92
Emanuel K A and Rotunno R 2012 Self-stratification of tropical cyclone outflow Part II: implications for storm intensification J. Atmos. Sci. 68 2236–49

Emanuel K 2004 Tropical cyclone energetics and structure Atmospheric Turbulence and Mesoscale Meteorology vol 8 (Cambridge: Cambridge University Press) pp 165–91

Flather R A 2001 Encyclopedia of ocean sciences Storm Surges (New York: Academic) pp 2882–92

He Z G, Tang Y L, Xia Y Z, Chen B D, Xu J, Yu Z Z and Li L 2020 Interaction impacts of tides, waves and winds on storm surge in a channel–island system: observational and numerical study in Yangshan Harbor Ocean Dyn. 70 307–25

Heaps N S 1983 Storm surges 1967–1982 Geophys. J. Int. 74 331–76

Horsburgh K J and Wilson C 2007 Tide–surge interaction and its role in the distribution of surge residuals in the North Sea J. Geophys. Res.–Oceans 112 C08S03

Keers J F 1968 An empirical investigation of interaction between storm surge and astronomical tide on the east coast of Great Britain Ocean Dyn. 21 118–25

Knutson T, McBride J L, Chan J, Emanuel K, Holland G, Landsea C, Held I, Kossin J P, Srivastava A K and Sugi M 2010 Tropical cyclones and climate change Nat. Geosci. 3 157–63

Kossin J P 2018 A global slowdown of tropical-cyclone translation speed Nature 558 104–7

Lagmaya A M and Kerle N 2015 Typhoons: storm–surge models helped for Hagupit Nature 519 414

Liu L, Wang Y, Zhan R, Xu J and Duan Y 2020 Increasing destructive potential of landfalling tropical cyclones over China J. Clin. 33 3731–43

Mori N, Kato M, Kim S, Mase H, Shibutani Y, Takemi T, Tsuchi K and Yasuda T 2014 Local amplification of storm surge by super typhoon haiyan in leYTE gulf Geophys. Res. Lett. 41 5106–13

Park Y H and Suh K D 2012 Variations of storm surge caused by shallow water depths and extreme tidal ranges Ocean Eng. 55 44–51

Peduzzi P, Chatenoux B, Dassaux D, Bonn A D, Herold C, Kossin J, Manton S and Nordbeck O 2012 Global trends in tropical cyclone risk Nat. Clim. Change 2 289–94

Peng M, Xie L and Pietrafesa L J 2006 Tropical cyclone induced asymmetry of sea level surge and fall and its presentation in a storm surge model with parametric wind fields Ocean Model. 14 81–101

Rao A D, Upadhyaya P, Pansey S and Pouloue J 2020 Simulation of extreme water levels in response to tropical cyclones along the Indian coast: a climate change perspective Nat. Hazards 100 151–72

Rashid M M, Wahl T, Chambers D P, Calafat F M and Sweet W V 2019 An extreme sea level indicator for the contiguous united states coastline Sci. Data 6 326

Rego J L and Li C Y 2010 Nonlinear terms in storm surge predictions: effect of tide and shelf geometry with case study from Hurricane Rita J. Geophys. Res.–Oceans 115 C06020

Sterl A, van Den Brink H, de Vries H, Haarsma R and van Meijgaard E 2009 An ensemble study of extreme storm surge related water levels in the North Sea in a changing climate Ocean Sci. 5 369–78

Sun J C et al 2019 Development of a fine-resolution atmosphere–wave–ocean coupled forecasting model for the South China Sea and its adjacent seas Acta Oceanol. Sin. 38 154–66

Svyitsky J P M et al 2009 Sinking deltas due to human activities Nat. Geosci. 2 681

Tang Y M, Sanderson B, Holland G and Grimshaw R 1996 A numerical study of storm surges and tides, with application to the North Queensland coast J. Phys. Oceanogr. 26 2700–11

Weisberg R H and Zheng L 2006 A simulation of the hurricane charley storm surge and its breach of North Captiva Island Plateau Meteorol. 69 152–65

Weisberg R H and Zheng L 2008 Hurricane storm surge simulations comparing three-dimensional with two-dimensional formulations based on an Ivan-like storm over the Tampa Bay, Florida region J. Geophys. Res.–Oceans 113 C12

Wolf J 2009 Coastal flooding: impacts of coupled wave–surge–tide models Nat. Hazards 49 241–60

Wu Z Y, Milliman J D, Zhao D N, Cao Z Y, Zhou J and Zhou C Y 2018 Geomorphologic changes in the lower Pearl River Delta, 1850–2015, largely due to human activity Geomorphology 314 42–54

Xu J L, Zhang Y H, Cao A Z, Liu Q and Lv X Q 2016 Effects of tide–surge interactions on storm surges along the coast of the Bohai Sea, Yellow Sea, and East China Sea Sci. China Earth Sci. 59 1308–16

Yang J A, Kim S, Mori N and Mase H 2017 Bias correction of simulated storm surge height considering coastline complexity Hydrol. Res. Lett. 11 121–7

Yin C, Zhang W, Xiong M, Wang J, Zhou C, Dou X and Zhang J 2021 Storm surge responses to the representative tracks and storm timing in the Yangtze Estuary, China Ocean Eng. 233 109020

Zhang C, Hou Y and Li J 2018 Wave–current interaction during Typhoon Nuri (2008) and Hagupit (2008): an application of the coupled ocean–wave modeling system in the northern South China Sea Chin. J. Oceanol. Limnol. 36 65–77

Zhang H, Chen D, Zhou L, Liu X, Ding T and Zhou B 2016 Upper ocean response to typhoon Kalmahagi J. Geophys. Res.–Oceans 121 6520–35

Zhang H, Cheng W C, Qiu X X, Feng X B and Gong W P 2017 Tide–surge interaction along the east coast of the Leizhou Peninsula, South China Sea Cont. Shelf Res. 42 32–49

Zhang W Z, Shi F, Hong H S, Shang S P and Kirby J T 2010 Tide–surge interaction intensified by the Taiwan Strait J. Geophys. Res.–Oceans 115 C06012

Zheng P, Li M, Wang C X, Wolf J, Chen X, Dominicis M D, Yao P and Hu Z 2020 Tide–surge interaction in the Pearl River Estuary: a case study of Typhoon Hato Front. Mar. Sci. 7 236