THE ASYMMETRY OF COASTAL WATER LEVEL RESPONSE TO LANDFALLING HURRICANES SIMULATED BY A THREE-DIMENSIONAL STORM SURGE MODEL

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1. INTRODUCTION

Any storm surge model depends critically on the accurate input of the hurricane's wind fields. In ideal experiments, a symmetric parametric wind model is frequently used to drive the storm surge model. However, any mistake of parameterization may lead to serious problems.

For example, when the Holland model (1980) was applied to storm surge hindcast of Hurricane Isabel in 2003 (Fig. 1), the model calculated maximum storm surge, generally, agree well with the observations at the available water level stations (Fig. 2). However, apparent overestimation of sea level fall occurred after the maxima, and this pseudo negative surge may be largely due to the tendency of more sea level drop for an offshore wind.

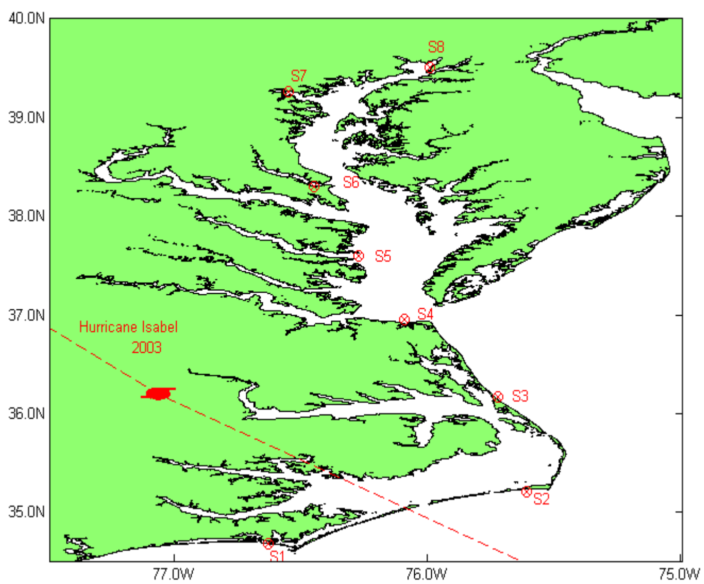

Fig. 1 Track of Hurricane Isabel and the locations of sea level stations

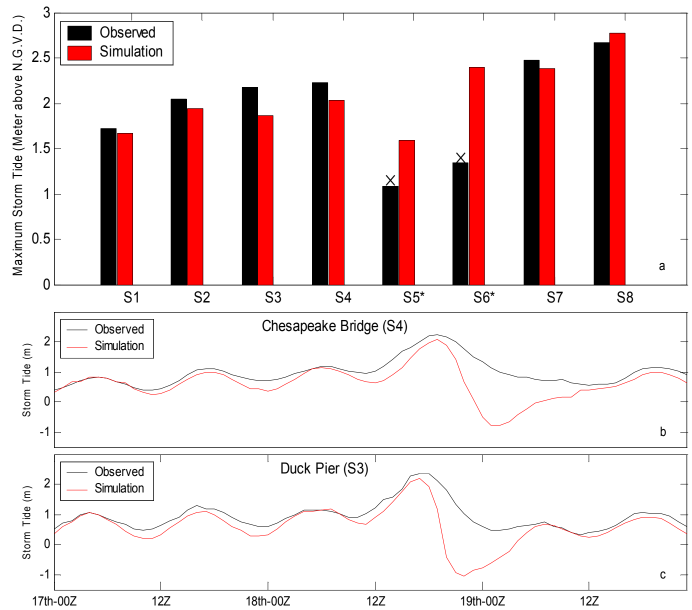

Fig. 2 Upper: observed and simulated maximum storm tide. Lowers: time series at S3, and S4.

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NUMERICAL MODEL

The storm surge model employed in this study is described in details in Xie et al (2004) and Peng et al (2004). The hydrodynamic component of the modeling system is based on the POM Model (Mellor, 1996).

THE ASYMMETRY OF SURGE AND FALL UNDER STEADY WIND FORCES

To investigate the extent of such asymmetry under different symmetric wind forces, steady onshore and offshore winds with the same magnitude apparently offer a perfect and simple symmetric wind force. To make things easy, an asymmetry index is introduced as: $AI = (|fall_{\max}| - surge_{\max}) / surge_{\max} \times 100\%$, where $fall_{max}$ and $surge_{max}$ are respectively the maximum sea level fall in the offshore-wind case and the maximum surge in the onshore-wind case.

A square region of 100 × 100 points with grid size of 5km in both directions is chosen as the study domain. The water depth linearly increases from the coast to the ocean at a slope of 1/10000. Such a slope, which is much smaller than a typical continental shelf, is chosen to emphasize the shallow water effect and make storm surge more striking. In the experiments, 10, 20, 30 and 50m are arbitrarily chosen as the minimum water depth to readjust the original bathymetry. These four cases are respectively named Case1, Case2, Case3 and Case4. In Case1, the water depth is assumed to be homogenously 10m for the region where the original value is less than it. Similar are the other cases. A steady onshore or offshore wind with speed of 30m s^{-1} is the driving force in the experiments.

As indicated in Fig. 3, there is no apparent asymmetry of sea level surge and fall under the assumed wind for Case3 and Case4 (AI is less than 10%). But for the shallow water cases (Cases1, 2), an offshore wind depresses sea level far more efficiently than an onshore wind induces a surge.

To investigate how sea level responds to different wind forces in a shallow region, wind

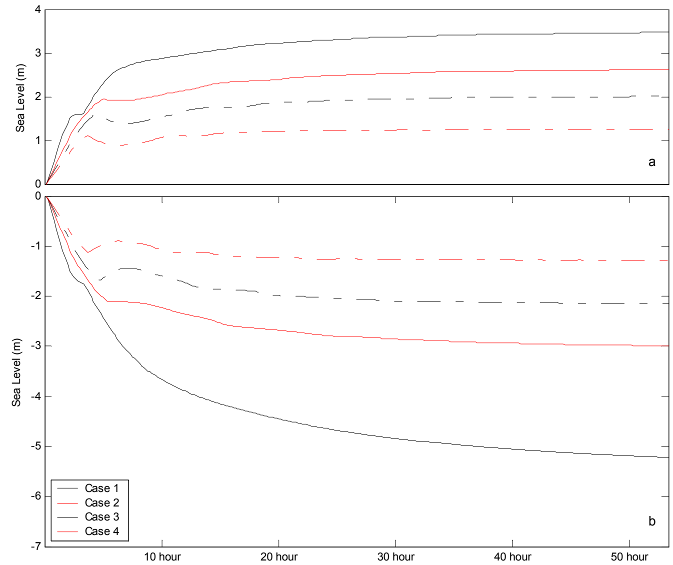

Fig. 3 a) The “spin-up” process at coastal locationwith the steady 30m s^{-1} onshore wind. b) The “spin-down” process with the steady 30m s^{-1} offshore wind.

speeds of 20, 25, 30 and 35m s^{-1} are chosen for the numerical experiments. It is found that the extent of the asymmetry increases distinctly with the wind speed. This is why apparent asymmetry of the sea level surge and fall may exist under most hurricane wind forces (e.g. the minimum wind speed for Category 1 hurricane is 32m s^{-1}). However, stronger hurricane does not necessarily induce larger AI since wind duration of a typical hurricane is not long enough for pressure gradient at a given location to reach a final balance with wind stress.

THE ASYMMETRY OF SURGE AND FALL UNDER HURRICANE WINDS

The parametric wind model

Holland model is the parametric wind model in this study to generate symmetry wind fields. The parametric wind model, assuming to the lowest order, gives a circular wind flow pattern around its center.

Translation speed

To investigate the asymmetry of the hurricane induced sea level surge and fall, the idealized square domain, again, is employed with the hypothetical track running along the coast from south to north with land on the left.

As Fig. 4 indicates, for TCs with a fixed central pressure, the slower the translation speed, the greater the asymmetry of the maximum surge and fall.

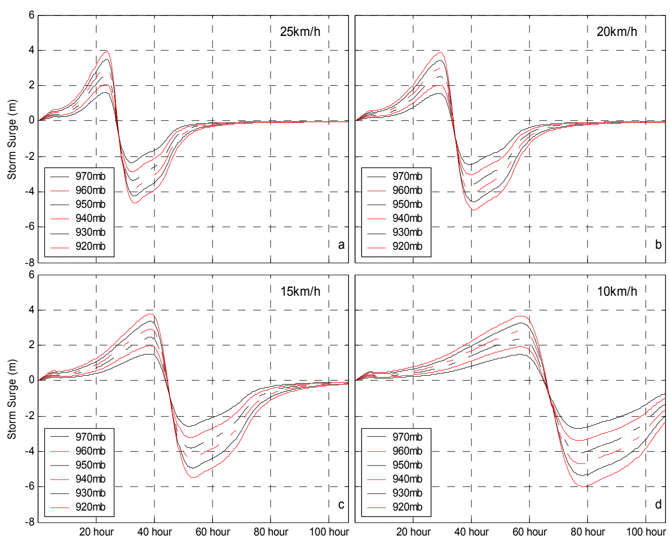

Fig. 4 The effect of hurricane's translation speed on the asymmetry of the surge and fall.

For those with the same translation speed, a weaker TC is expected to gain a higher AI value though its induced maximum surge and fall are relatively smaller.

RMW

Another important parameter in the wind model is RMW (radius of maximum wind) that can greatly influence hurricane induced storm surge.

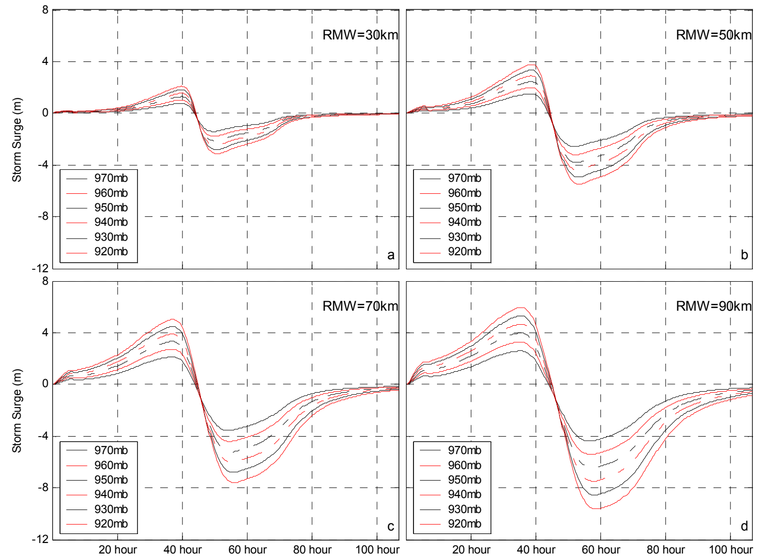

Fig. 5 The effect of RMW on the asymmetry of the surge and fall

For hurricanes with a fixed translation speed, a larger RMW increases not only duration time for both onshore and offshore winds, but also wind fetch. The effect of the latter is important and makes peculiar the relationship between RMW and AI.

As expected, the extent of both surge and fall increases as RMW is enlarged (Fig.5). The apparent correlation between RMW and the maximum surge is due largely to wind fetch variation as RMW changes. For those with fixed RMW, the relationship between central pressure and AI depends on the value of RMW.

Hurricane's inflow angle

Unlike translation speed and RMW, which influence the maximum surge and fall due to the variation of duration or fetch, inflow angle affects the surge and fall extent by changing the asymmetric nature of the lowest-order wind fields. This change and the consequent wind asymmetry are essentially different from the former two parameters in the way to cause asymmetry of storm surge and fall.

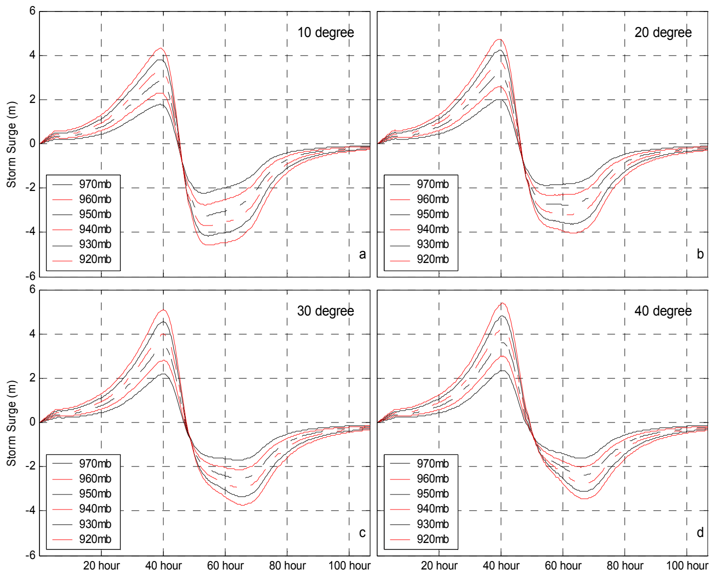

Fig. 6 The effect of hurricane's inflow angle on the asymmetry of the surge and fall.

As, shown in Fig. 6, consideration of inflow angle fundamentally changes the symmetry of wind fields, and provides the surge model an asymmetrical (with respect to its center) exterior force as in real cases. In the Northern Hemisphere, if a hurricane moves northward with land on its left, inflow angle consideration is expected to generate larger surge and smaller fall, or, moderate the asymmetry of surge and fall that would otherwise be overestimated.

HISTORIC HURRICANE CASES

Any mistake of parameterization in the wind model may lead to mistakes in surge simulation. The misrepresentation as indicated previously is more apparent in the negative phase of the sea level movement. As hurricane's inflow angle is not intentionally measured and documented as other parameters, it is singled out in the following hindcast studies to investigate its effects on storm surge asymmetry. Hurricane Charley (2004) and Isabel (2003) are the two historic hurricanes that are studied.

Hurricane Charley

Hurricane Charley passed over the mid-eastern coast of the U.S. on Aug 14, 2004, as shown in Fig. 7. Only wind inflow angle is considered as the variable in the experiments while others, such as track, central pressure,

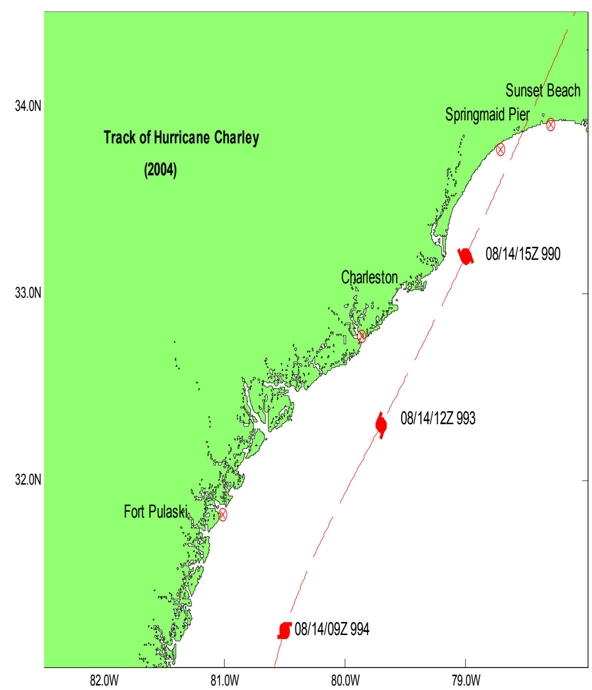

Fig. 7 Track of Hurricane Charley and locations of sea level stations

translation speed, and RMW, take their interpolated values from observations at each time. Sea level data are available at 4 stations before, during, and after landfall, and the locations of the stations are illustrated in Fig. 7.

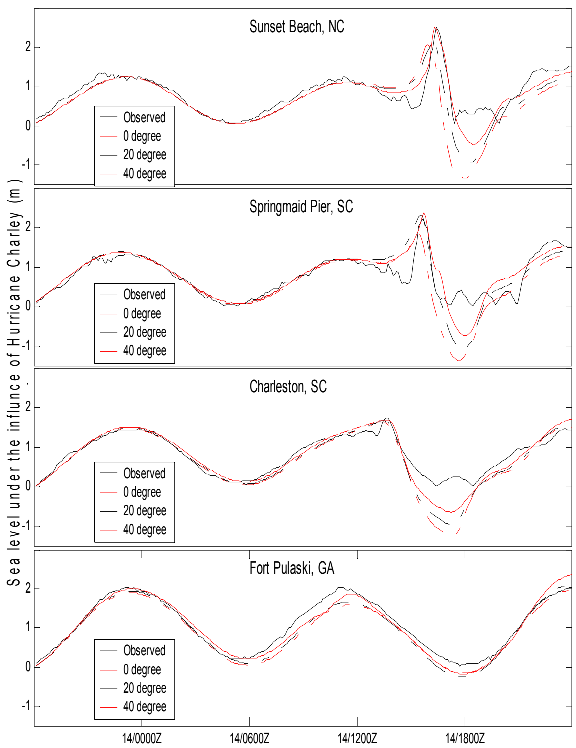

Fig. 8 Sea level time series taking 0°, 20° and 40° as the wind inflow angle are compared with the observation for Hurricane Charley.

The results indicate the maximum sea level fall will be largely reduced as inflow angle is considered in the parametric wind model. As a result, the asymmetry of the maximum sea level fall and surge is moderated.

Hurricane Isabel

The track of Hurricane Isabel has been shown in Fig. 1. As mentioned previously, the parametric wind fields with no inflow angle correction lead to an apparent sea level distortion in the fall phase, though the overall maximum sea level surge at most stations agreed well with the observations. Different inflow angles are fed into the model to see how much difference they can make with regard to sea level surge and fall and their asymmetry. The influence of the inflow angle on the surge and fall is illustrated in Fig. 9

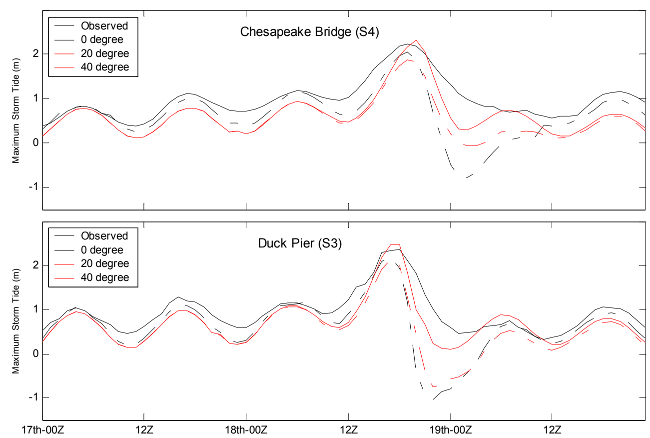

Fig. 9 Sea level time series taking 0°, 20° and 40° as the wind inflow angle are compared with the observation for Hurricane Isabel

With inflow angle consideration, the pseudo negative surge is largely moderated. The discrepancy still existing in negative water phase may due to the contribution of precipitation and runoffs that is not considered in the model.

CONCLUSION

It is found that offshore winds are more effective in suppressing coastal sea level than the corresponding onshore winds in inducing surge. As a result, the response of sea level in the hurricane's offshore wind quadrant is more sensitive to wind force than in the onshore wind quadrant. Any mistakes of the model specified parameters, such as translation speed, RMW, and inflow angle may lead to inaccurate sea level results, and this is more apparent in the hurricane's offshore wind quadrant. This asymmetry implies that an accurate sea level forecast is more difficult to achieve in negative than in positive phase.

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