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Effect of ocean surface waves on storm surge and coastal flooding

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Abstract

The effects of wave-current interaction on the storm surge and inundation induced by Hurricane Hugo in and around the Charleston Harbor and its adjacent shelf are examined by using a three-dimensional (3-D) wave-current coupled modeling system. The 3-D storm surge and inundation modeling component of the coupled system is based on the Princeton Ocean Model (POM), whereas the wave modeling component is based on the third generation wave model Simulating WAves Nearshore (SWAN). The results indicate that it is important to introduce wave-current effects into any storm surge and inundation prediction modeling system. Consideration of wave-induced wind stress, bottom shear stress, and 3-D radiation stress in storm surge and inundation modeling can lead to significantly improvement in inundation prediction.

1. Introduction

Wind waves, storm surges and ocean circulation are important, mutually interacting physical processes in coastal waters. Over the past two decades, there have been a number of studies focusing on wave-current interactions [Tolman, 1990, Zhang and Li 1996, Xie et al. 2001, 2003]. It is believed that wind waves can indirectly affect the coastal ocean circulation by enhancing the wind stress [Mastenbroek et al., 1993] and by influencing the bed friction coefficients [Signell et al., 1990, Davies and Lawrence, 1995]. Xie et al. [2001, 2003] studied wave-current interactions through surface and bottom stresses and found that wind waves can play a significant role in the overall circulation in coastal regions.

The key questions here must address how these processes affect one another and how these processes can be properly coupled in numerical models. In general, these processes influence one another in several ways: (1) wind stress, which is changed by incorporating the wave effect [Donelan et al., 1993]; (2) radiation stress, which is considered to be an additional mechanical force in storm surge models [Xie et al., 2001, Mellor, 2003, Xia et al., 2004] and can be incorporated into wave models by invoking wave-action conservation [Komen et al., 1994, Lin and Huang, 1996]; (3) bottom stress, which is a function of wave-current interaction in the near bottom layer when the water depth is sufficiently shallow for wave effects to penetrate to the bottom [Signell et al., 1990]; (4) the depth variation and current conditions, which are inputted into wave models [Tolman, 1991].

Flooding caused by coastal storms is an occasional threat to people living in coastal regions. The focus of this study is on investigating the effect of wave-current interaction on coastal atmospheric storm induced storm surge and inundation via the inclusions of wave-dependent surface wind stress and wave-current-dependent bottom shear stress, time-dependent water depth

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in the wave model and the three-dimensional radiation stress. An inundation scheme, developed in Xie et al [2004], is included in the more complete system.

2. Coupled wave-current system model description

The coupled wave-current system is based on the well known POM [Mellor, 1996] and third generation wave model (SWAN) [Booij et al. 1999]. POM is a three-dimensional, primitive-equation model that uses a sigma coordinate in the vertical, a curvilinear orthogonal coordinate and an "Arakawa C" grid scheme in the horizontal with previous applications described in Xie et al. [2001]. SWAN is a third generation wave model developed by Booij et al. [1999] in the spirit of the WAM [WAMDI Group, 1988]. The model is based on an Eulerian formulation of the discrete spectral balance of action density that accounts for refractive propagation over arbitrary bathymetry and current fields. Moreover the surface elevation can be added to the water depth in SWAN, so that the effect of storm surge on waves can be included.

The coupling procedure

As mentioned above, in this study, there are three types of wave effects incorporated into the POM model: (1) through surface wind stress; (2) through bottom stress; and (3) via the 3-D radiation stress. This is illustrated in Figure 1.

3. Model settings and experiments

Model domain and nesting windows set

In this study, the wave-current coupling system is configured for Charleston Harbor, its coastline and its adjacent shelf. In order to resolve the hydrodynamics of the relatively small harbor and periphery, three nested domains (Figure 2) with the smallest imbedded into a central sized domain, in turn imbedded into a larger one, are employed for the study. The outermost domain is 78.0-82.5°W, 31.0-34.5°N with 1 minute as the spatial grid size for both latitude and longitude. The mid domain is 79.7-80.1°W, 32.5-33.0°N, with 12 seconds as the spatial grid size. The innermost domain, providing detailed information in and around Charleston Harbor, covers 79.75 -80.00°W, 32.70-32.90°N, with 3 seconds as the spatial grid size. As we are principally interested in investigating the coupled effects of waves and currents on storm surge, inundation and retreat, the coupled model system was only used in the innermost domain.

Experiments

Hurricane Hugo is chosen as the actual event around which to focus the numerical experiment to examine the effect of wave-current interaction on storm surge and inundation. The Hugo wind field is calculated from the theoretical hurricane wind model of Holland [1980]. In order to investigate the effects of interactively coupled vs. non-coupled wave-current interactions on storm surge and inundations, five experiments (Table 1) are conducted in this paper. Storm surge and inundation model runs without including any wave-current effects are in case NN. Case YN, NY and NNR assume wave-current coupling only through changing surface stress, bottom stress and radiation stress respectively. The fully coupling system is conducted in case YYR. In all the cases the vertically integrated current and the surface elevation, as calculated from the storm surge model are inputted into the wave model.

4. Results of experiments

Case NN

In this study, we focus on examining the effect of wave-current interaction on storm surge and inundation. First we will simulate the storm surge, inundation and current fields generated by Hugo without considering wave-current interaction effects. The Charleston areas flooded during the passage of Hurricane Hugo are shown in Figure 3

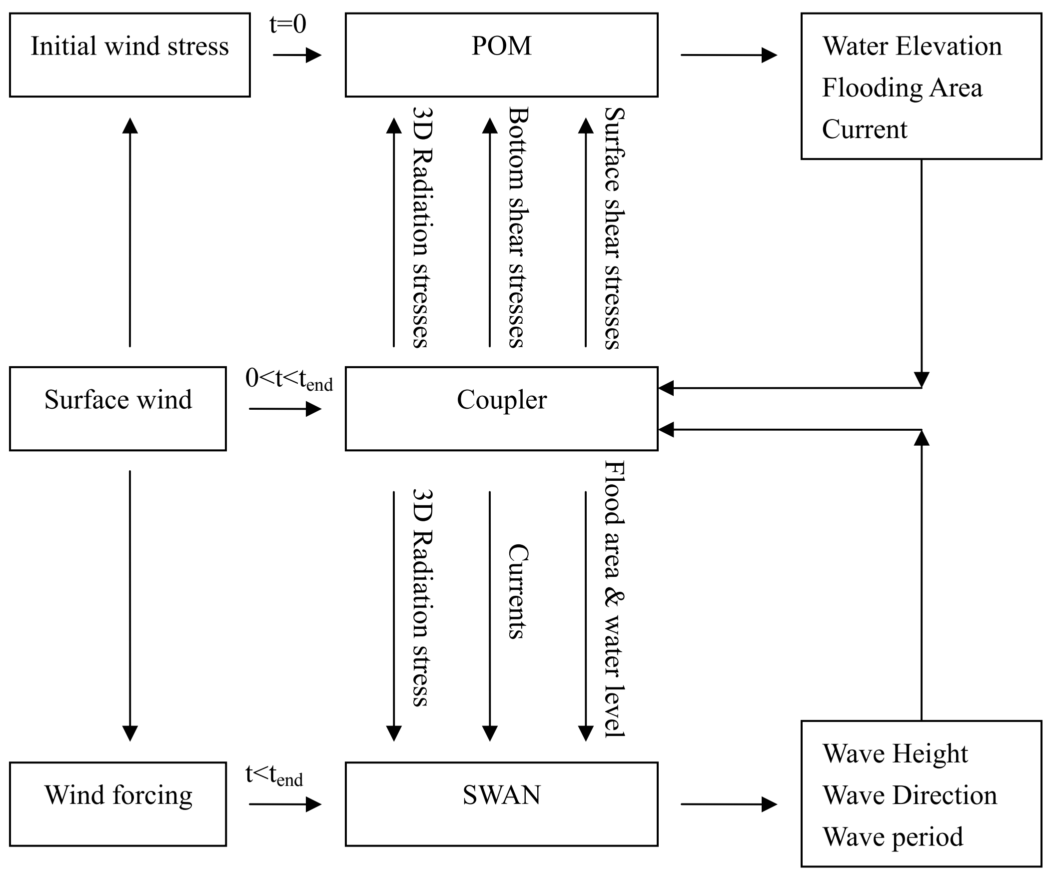


Figure 1 Flow diagram illustrating the coupling process between the wave and current model.

Experiments	Cases	Wave induced surface Stress	Wave induced bottom Stress	Radiation Stress
1	NN	no	no	no
2	YN	yes	no	no
3	NY	no	yes	no
4	NNR	no	no	yes
5	YYR	yes	yes	yes

Table 1. List of Experiments

There are two main inundation locations in our domain of study. One is located in the northeast domain and the other is located in the west domain.

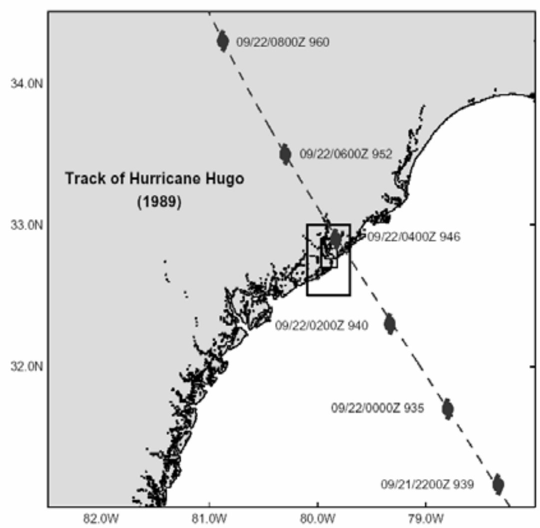


Figure 2 The setup of nesting domain and the best track of hurricane Hugo.

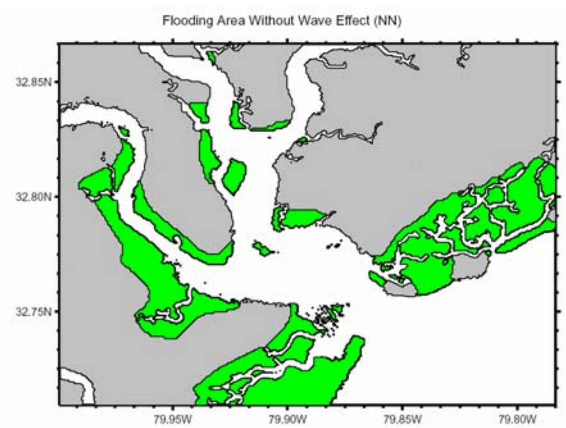
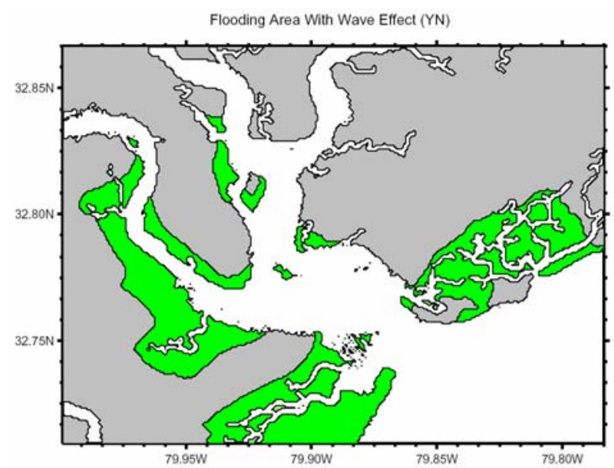


Figure 3 Simulated maximum flooding areas induced by Hugo of case NN

Case YN

In Figure 4a, the maximum flooded area with wave effects incorporated into the wind stress is presented. The difference of the flooded area between case YN and case NN is presented by YN minus NN, shown in Figure 4b and demonstrates that the effect of wave induced surface stress on subsequent inundation is significant. There are two obvious impacts on the flooded areas, one is in the northeast region, where the flooding area is reduced, and the other is in the west region, where the area flooded is increased significantly.

a



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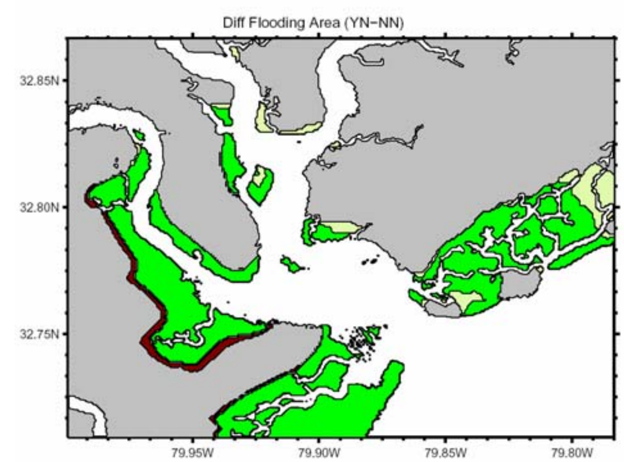
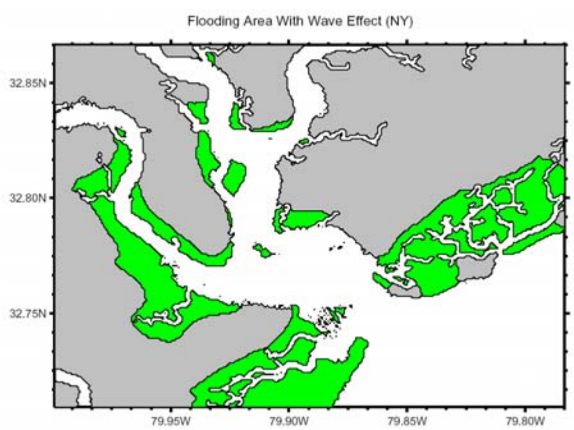


Figure 4 (a) Simulated maximum flooding areas induced by Hugo of case YN and (b) the different maximum flooding areas between case YN and NN (case YN – case NN). The dark red color represents the shoreward increase flooding areas and the light green color represents the reduced flooding areas.

Case NY

Figure 5a shows the area flooded area, for which the effect of wave-current interaction on bottom stress is considered. Figure 5b depicts the difference of the areas flooded between cases YN and NN, presented as YN minus NN. Clearly the wave-current interaction through the bottom stress does not affect inundation as much as it does through the surface stress. The only obvious difference lies in the northeast region, in which the maximum flooding area is increased in case NY (Figure 5b). In other words, the effect of wave-current interaction through bottom stress on inundation is significant only in the northeast region and its effect on inundation in other regions is negligible. Compared to Figure 5b, the effect of wave-current interaction, through the bottom stress, on inundation in the northeast region is exactly the reverse.

a



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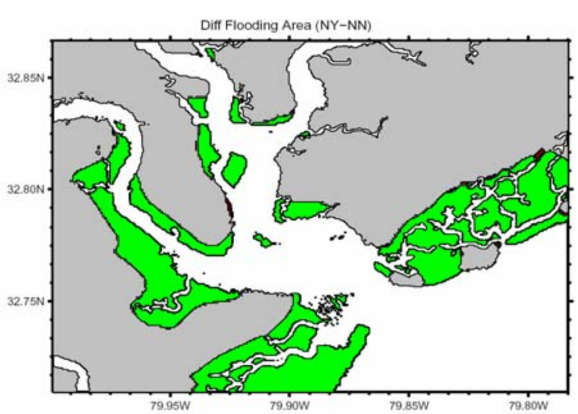

Figure 5 Same as Figure 4 but for case NY

Case NNR

The radiation stress was first introduced by Longuet-Higgins and Stewart [1962], and they used this concept to analyze wave set-up and set-down. Following this publication, the issue on how to incorporate the radiation stress caused by waves into a current model became topical. Recently the concept of a 3-D radiation stress was defined by Mellor [2003]. Also, Xia et al. [2004] extended the traditional 2-D concept of radiation stress via the introduction of vertical dependence using a new technique.

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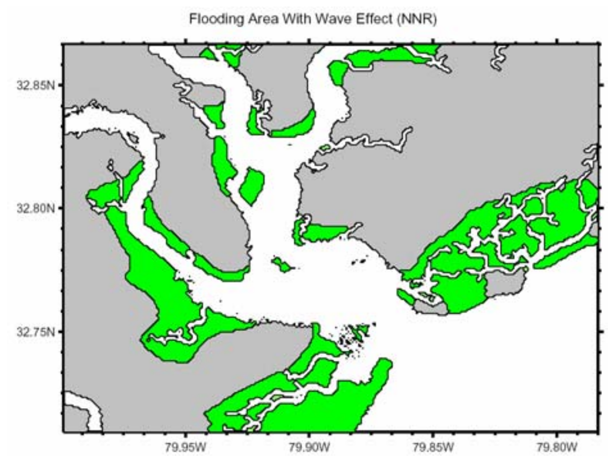

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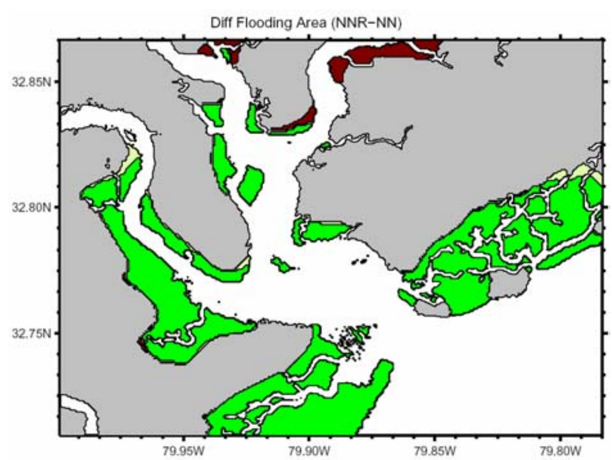

Figure 6 Same as Figure 4 but for case NNR

The flooded area of case NNR is shown in Figure 6a and Figure 6b displays the difference of the area flooded between cases NNR and NN (case NNR minus case NN). It shows that the effect of radiation stress on inundation is not as significant as wave-induced surface stress does. However there are three small regions are impacted, one locates at north region, in which the maximum flooding area is increased in case NNR (Figure 6b), and the other two locate at northwest and northeast regions respectively, in which the maximum flooding area is decreased in case NNR (Figure 6b).

Case YYR

The maximum area flooded for case YYR is presented in Figure 7a. Figure 7b shows the difference of the area flooded between cases YYR and NN (case YYR minus case NN). Figure 7a shows a similar inundation trend to the case YN (Figure 4a). It appears that the wave-induced wind stress played the most important role in determining the inundation during the period when the hurricane reached the coast. However, there is still a little difference between cases YYR and YN, which locates in the northeast, northwest and north regions, as seen by comparing Figure 7b and Figure 4b. One additional increased flooding area in north region is added into case YYR. The reduced flooding areas in the northeast region are lager in case YYR than in case YN; There is one more reduced flooding area (northwest region) in case YYR than in case YN. That means that the wave-induced bottom stress and the radiation stress also play roles (relatively important) in determining the inundation areas.

5. Discussions and conclusions

Previous studies have shown that wave-current interactions can significantly influence currents, both near surface and near bottom, and water elevation. These prior studies suggested that the inclusion of wave-current effects in coastal current modeling and in particular storm surge and inundation prediction systems was desirable to increase the applicability of the model predictions, especially during impending storms [Xie et al., 2001, 2003]. The results from the study presented within show that the combined effects of wave and currents on the inundation caused by a tropical storm (a Category 4 Hurricane, Hugo in 1989) are significant and furthermore the effects are not the same across the model domain. A major effect occurs via the surface current field which can have its direction altered significantly and thus the extent of lateral flooding is either diminished or greatly enhanced as a function of the direction of the surface current, either more landward or less landward and/or more seaward.

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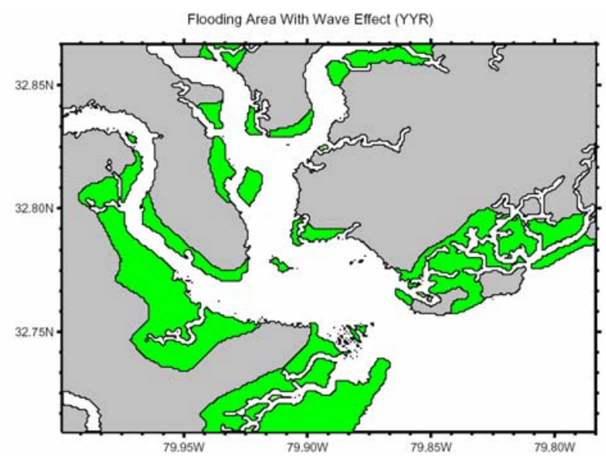

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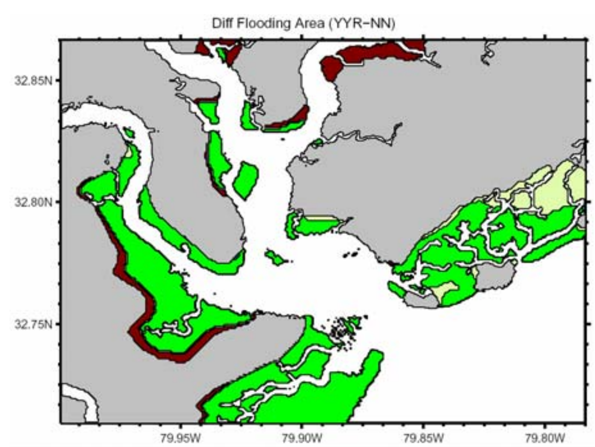

Figure 7 Same as Figure 4 but for case YYR

Comparing the three effects induced by the wave-current interaction (case YN, case NY and case NNR), the wave-induced wind stress played the most significant role in determining the inundation changes than either of the other two effects. To the contrary, the effects of the wave-induced bottom stress and the surface radiation stress were not nearly as significant as was the wave-induced wind surface stress in affecting greater inundation (the maximum flooded area). By examining the bottom shear stress induced inundation difference (Figure 6b) we note that the differences are principally evident in the relatively confined northeast region of the model domain. And the 3-D radiation stress induced inundation differences (Figure 8b) locate in three small regions not as large as the surface wind stress induced inundation differences. However, since these dynamically processes are a part of the physics of the system and because different atmospheric-ocean coupled events, whether they be tropical or extra-tropical, will occur in different regions with varying sizes, translation speeds, asymmetries and so on, none of the processes should be arbitrarily neglected in the more fully coupled system.

The experiment results and discussions presented in the above sections indicate that wave-current interaction effects should be taken into account not only in storm induced current and surge simulations but also, and very importantly, in inundation simulations. As shown within, the consideration of wave-induced wind stress in storm surge and inundation models can significantly improve inundation predictions. Incorporating wave-induced bottom stress and surface radiation stress will further improve inundation predictions, as well.

Acknowledgements

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