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A numerical study of wave-current interaction through surface and bottom stresses: Coastal ocean response to Hurricane Fran of 1996

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[1] A three-dimensional wave-current coupled modeling system is used to examine the influence of waves on coastal currents and sea level. This coupled modeling system consists of the wave model-WAM (Cycle 4) and the Princeton Ocean Model (POM). The results from this study show that it is important to incorporate surface wave effects into coastal storm surge and circulation models. Specifically, we find that (1) storm surge models without coupled surface waves generally under estimate not only the peak surge but also the coastal water level drop which can also cause substantial impact on the coastal environment, (2) introducing wave-induced surface stress effect into storm surge models can significantly improve storm surge prediction, (3) incorporating wave-induced bottom stress into the coupled wave-current model further improves storm surge prediction, and (4) calibration of the wave module according to minimum error in significant wave height does not necessarily result in an optimum wave module in a wave-current coupled system for current and storm surge prediction. *INDEX TERMS:* 4560 Oceanography: Physical: Surface waves and tides (1255); 4255 Oceanography: General: Numerical modeling; 4512 Oceanography: Physical: Currents; 4219 Oceanography: General: Continental shelf processes; 4504 Oceanography: Physical: Air/sea interactions (0312); *KEYWORDS:* surface waves, storm surge, wave-current interaction

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1. Introduction

[2] It has long been recognized that wind-driven surface waves can significantly influence ocean currents [*Phillips*, 1997]. In the past decade, modeling studies on this issue range from how the process of wave-current interaction influences the bed friction coefficient [*Signell et al.*, 1990; *Davies and Lawrence*, 1995] to how waves can affect the current field by enhancing the wind stress [*Mastenbroek et al.*, 1993]. Recently, coastal scientists have become increasingly interested in establishing regional environment predicting systems which would contain physical, chemical, geological, and biological processes. However, in moving end to end, through a hierarchy of physical to biological models, one key problem is the treatment of wave-current interaction. The aim of this paper is to focus on establishing a better understanding of wave influence on currents, from the perspective of the wave-current response to a hurricane before, during, and after the hurricane passes through a continental margin and subsequently makes landfall.

[3] Generally speaking, ocean currents are influenced by ocean surface waves primarily by way of (1) wind stress, which not only depends on wind speeds but also on wave state [*Donelan et al.*, 1993], (2) radiation stress, which can be either considered to be an additional mechanical force for driving currents [*Longuet-Higgins and Stewart*, 1962] or incorporated into the wave model 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) Stokes' drift currents induced by the non-linearity of surface waves [*Huang*, 1979].

[4] Attempts to incorporate surface wave effects into ocean current models have taken on community interest in the recent past. *Signell et al.* [1990] studied the influence of wave-current interactions on wind-driven circulation in a narrow, shallow embayment. The numerical hydrodynamic model employed by *Signell et al.* [1990] was two-dimensional (2-D), did not resolve the variation of flow within the water column, and the wave field was assumed to be constant. While this effort made a significant advance in our basic understanding of the effects of waves on currents, the 2-D flow and constant wave assumptions limited the application of the solutions. When winds blow over the water surface, both surface waves and water currents are generated contemporaneously. The surface currents and waves vary both spatially and temporally. Moreover, wave feedback effects on the wind stress, which could have direct

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effects on the current field, were not considered by *Signell et al.* [1990]. *Davies and Lawrence* [1995] examined the effect of wave-current interaction on three-dimensional (3-D) wind-driven circulation, and their results showed that surface waves could play an important role in determining both near surface and near bottom currents as well as on water level variation over a coastal region. However, in their study, surface waves were considered to be a constant external input into the current model. By prescribing the wave field, the feedback effect of currents on waves could not be addressed. Furthermore, the effect of waves on surface wind stress was not included in their model. *Mastenbroek et al.* [1993] investigated the dynamic coupling between wind, waves, and storm surge. In this study the effect of a wave-dependent drag coefficient on the generation of storm surge was found to be significant. However, their storm surge model was limited to two spatial dimensions, and the effects of coupled wave-current interaction on bottom stress were not included. Moreover, analysis of current fields was not presented, except for the detailed discussion of storm surge elevations, albeit, the study demonstrated the importance of considering wave-current coupling.

[5] Current and wave data are in general difficult to obtain during any hurricane passage to validate a model. Still, hurricane induced ocean surface current velocities were observed to be of the order of 60–120 cm/s. The National Hurricane Center (NHC) (hurricane preliminary report available via internet at http://www.nhc.noaa.gov/1996text.html) reported that there were giant surface waves of the order of 14 m during the passage of Hurricane Floyd in the South Atlantic Bight in September 1999. However, these estimates may vary because of sampling discontinuities in space. Recently, *Walsh et al.* [2000] reported 10–11 m waves in the same area during the passage of Hurricane Bonnie in August 1998. So the state of knowledge, both in observations and with modeling, in observing and predicting the wave and current fields present during hurricane passage is certainly not well established. Albeit, to accurately simulate the superposed fields of currents and waves, especially how surface waves influence currents, it is desirable to pursue the development of a wave-current coupled model. This coupled model should contain state of the art wave and current models, and wave-current interactions should also be taken into account. The purpose of this paper is to extend the study from constant, uniform wind forcing [*Xie et al.*, 2001] to hurricane forcing and examine surface wave effects on currents over the coastal area of North and South Carolinas during the passage of Hurricane Fran in September 1996 by using a two-way coupled wave-current model.

[6] The focus of this study will be on the evolution of the fields of currents, waves, and water level, by inclusion of both wave-dependent wind and bottom stresses in the process of Hurricane Fran's traverse across the NC continental ocean margin. The wave model employed in the coupling is the basic WAM model (cycle 4) [*Komen et al.*, 1994; *WAMDI Group*, 1988], which was extended in this study by adding the term of radiation stress into the spectral transport equation, as the method of incorporating the wave-current interactions. The current model adopted for this study is the Princeton Ocean Model (POM) [*Mellor*, 1996]. POM is also extended by incorporating the concepts of *Donelan et al.* [1993], which consider wave effects on the surface drag coefficient and hence on wind stress, and by introducing the effect of wave-current interaction on the bed friction coefficient via the model of *Grant and Madsen* [1979], in the form applied by *Signell et al.* [1990] and *Davies and Lawrence* [1995]. The coupling architecture follows that developed by *Xie et al.* [2001].

[7] Section 2 describes the model settings and the model-derived wind fields of Hurricane Fran. Detailed analysis of currents and water level variation in response to Hurricane Fran is given in section 3. The results are summarized in section 4.

2. Model Setting and Wind Fields of Hurricane Fran of 1996

2.1. Study Area and Model Domain

[8] The model domain and study area are shown in Figure 1 with Hurricane Fran with her track superimposed. The study area covers the northern South Atlantic Bight and southern Middle Atlantic Bight. The horizontal grid size for both the current and wave models is uniformly set to 5 km in both x and y directions which are rotated 37° counterclockwise from the zonal and meridional direction, respectively, to align the coast approximately with the y axis. The bottom topography is derived from the ETOPO5 bathymetry database (available from NOAA/NGDC internet site at http://www.ngdc.noaa.gov/mgg/global/soltop.html) (Figure 2).

[9] The time steps for integration of source function and propagation in the WAM model are set at 240 s. The time steps in the POM model are set, for external mode, at 360 s, and for the internal model, at 180 s. More information about the coupled wave-current model is given by *Xie et al.* [2001].

2.2. Wind Fields of Hurricane Fran of 1996

[10] Hurricane Fran lasted from 23 August to 10 September 1996. Figure 1 shows the storm track from 1800 UTC on 3 September to 0000 UTC on 9 September. On 5 September 1996, Hurricane Fran, a Category 3 hurricane at that time, took a path towards North Carolina's southern coast with sustained winds of approximately 185 km/h (115 mph), and gusts as high as 200 km/h (125 mph). Subsequent storm-related flooding, both coastal and inland, was a severe problem in North Carolina, Virginia, West Virginia, and Maryland. Fran produced copious amounts of rainfall, over 25–33 cm (10–13 inches) in some parts of eastern North Carolina and western Virginia. Total insured and uninsured costs incurred for North Carolina alone exceeded \$6 billion, making Fran the third most costly hurricane in U.S. history (NCDC/NOAA). As shown in Figure 1, Fran crossed the Charleston trough [*Pietrafesa*, 1983] and then made landfall on the North Carolina coast south of Wilmington.

[11] In the present paper, the wind field of Fran is calculated from the theoretical hurricane wind model of *Holland* [1980]. Holland's hurricane wind model also provides a distribution of sea level pressure and the gradient

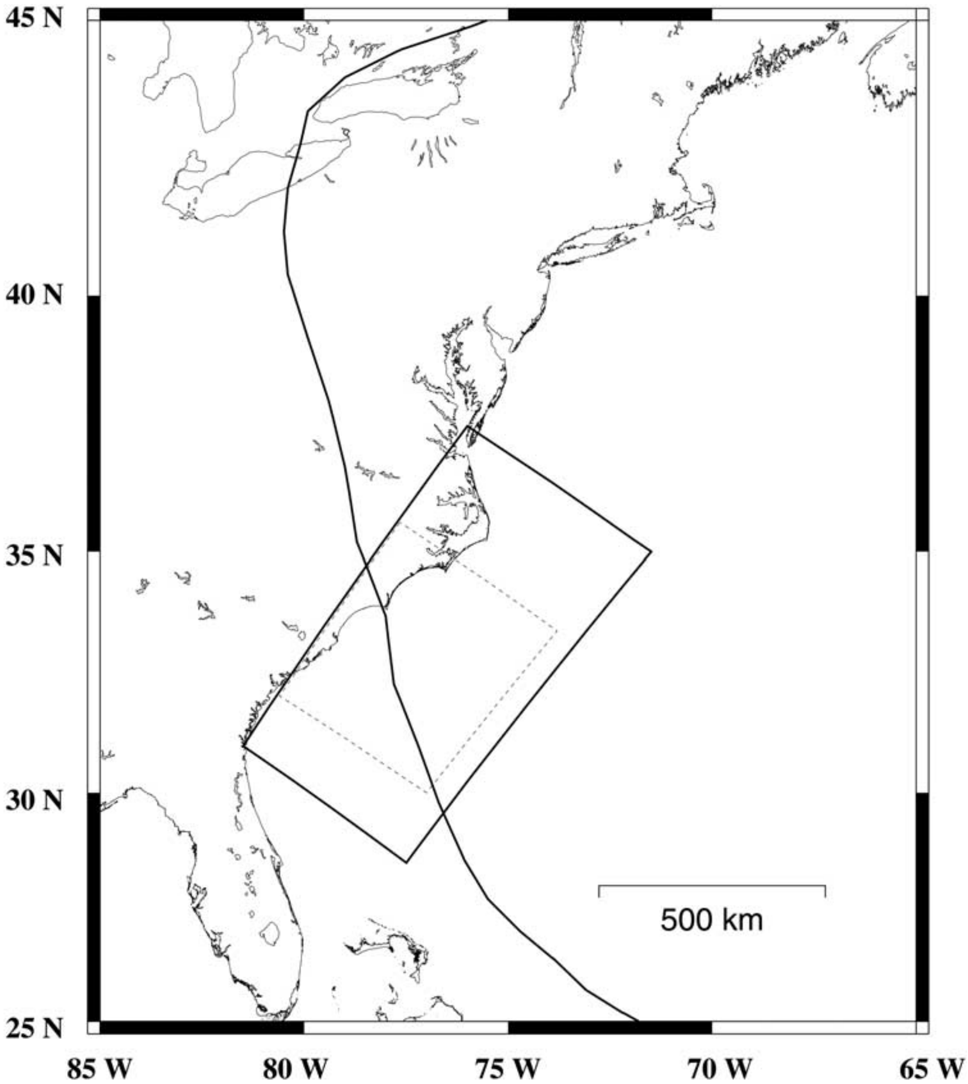

Figure 1. Study area and model domain. The ''best track'' of Hurricane Fran is depicted by the solid curve.

wind within a tropical storm. The differences between Holland's model and other theoretical hurricane wind models for barotropic ocean applications has been discussed by *Ginis and Sutyrin* [1995] and for storm surge modeling was discussed by *Chen* [1997]. In general, the differences in ocean response to different theoretical hurricane wind models were found to be small. In this study, we choose to use Holland's hurricane wind model which was applied to the POM model to simulate the coastal ocean response to hurricanes [*Xie et al.*, 1998, 1999]. The wind speed as a function of radial distance from the center of the storm is described as

$$V_a = \left[AB(P_n - P_c)\exp\left(-A/r^B\right)/\rho_a r^B\right]^{1/2} \qquad (1)$$

where V_a is wind speed at radius r, P_c is the central pressure, P_n the ambient pressure, and A and B are scaling parameters. The following set of parameters associated with Holland's model are used: $P_c = 9.5 \times 10^4$ Pa, $P_n = 10^5$ Pa, $\rho_a = 1.2$ kg/m^3, $A = (R_{max})^B$, $R_{max} = 6 \times 10^4$ m and $B = 1.9$.

[12] Again, the storm track of Hurricane Fran is shown in Figure 1 and the wind field parameters used in equation (1) were obtained from the National Hurricane Center. The procedure used to determine the surface and bottom drag coefficients and the computation of surface wind stress and bottom shear stress are described in detail by *Xie et al.* [2001].

3. Simulated Results

[13] To investigate surface wave influences on currents, four cases of numerical simulations are considered in this study. Case 1 assumes no wave-current interactions between the POM and WAM models (NN). In this case the current model and wave model run essentially independently, with the only relationship being that the POM model provides average currents for the WAM model, with no feedback to

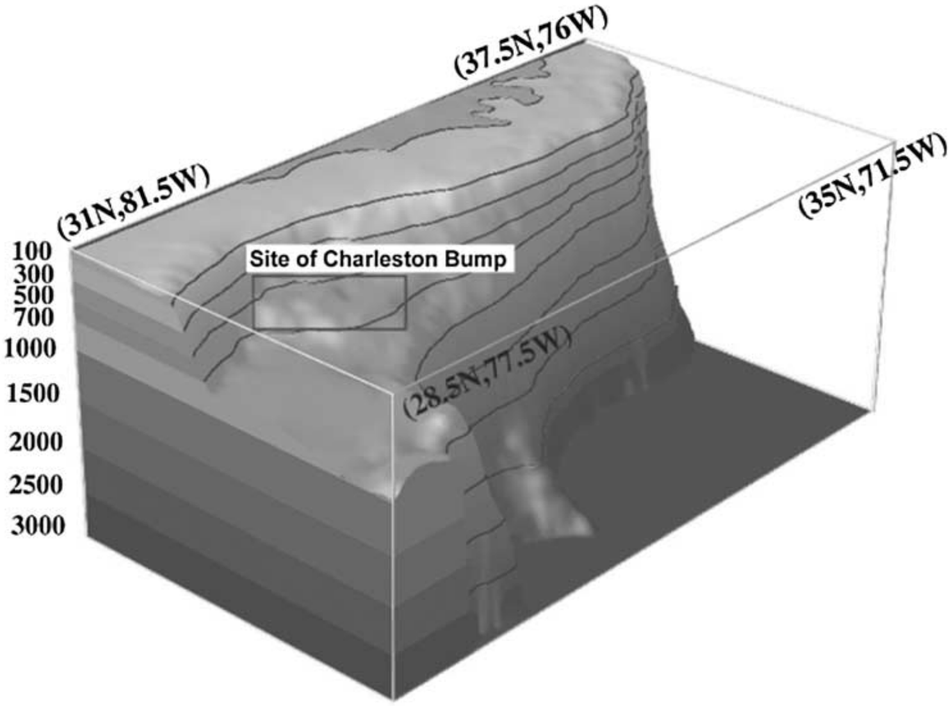

Figure 2. Bathymetry in the model domain.

the POM model. Case 2 assumes surface wave effects on the wind stress but no wave effects on bottom stress (YN). Case 3 assumes surface wave effects on bottom stress but not on wind stress (NY). Case 4 assumes full coupling with wave influences on both wind and bottom stresses (YY). This case illustrates how the surface wave field could have affected the current field as Hurricane Fran moves across the model domain. With the POM and WAM models running contemporaneously, the data relating to currents and waves can be exchanged automatically within the coupled model. In all cases, the model is run for 48 hours and storm follows its track from the southeast (outside the model domain) to the northwest (upper-left domain) (Figure 1). The simulated results of surface and bottom currents, water level, and surface wave characteristic parameters at = 36, 42, and 48 hours are presented for each of the cases.

3.1. Case NN

[14] We first consider the case of wind-generated currents induced by Hurricane Fran, without considering surface wave influences on the currents. Figures 3a–3c depict the surface current distributions at t = 36, 42, and 48 hours, respectively. At t = 36 hours the storm center just entered the model domain. As the storm center moved across the model domain, the magnitude of the surface current near the coast gradually increased until the storm made landfall at approximately t = 48 hours. Meanwhile, the coastal currents evolved from being southward when the storm was still far offshore (Figure 3a) to a circular pattern when the storm was near the coast (Figure 3b), and to northward flow after the storm made landfall (Figure 3c). This sequence of results reflects the ocean response to the increase in wind magnitude and the change in wind pattern, i.e., the translation of the storm vortex, as it moves towards the coast.

[15] Near bottom currents at 36, 42, and 48 hours are shown in Figures 3e–3f. At t = 18 and 24 hours, the magnitude of near-bed currents ranged from 0.04–0.08 m/s (not shown), as the storm center was far away from the model domain and the winds over the model domain were not strong. As the storm moved into the model domain at t = 36 hours, the magnitude of the bottom currents increased to 0.10–0.4m/s (Figure 3d). Like the surface currents, the maximum magnitude of the bottom currents (1.4 m/s) occurred when the storm was near the coast (Figure 3e). Following landfall, the magnitude of bottom currents decreased to 0.2–0.6m/s (Figure 3f). Notice that near the coast, the near-bottom currents are generally in the same direction of the surface currents, indicating equivalent barotropic response.

[16] The water levels for Case 1 are shown in Figures 4a–4c. Slight water level increases in shallow water occurred at t = 18 and 24 hours (not shown) prior to the storm center moving into the model domain. At t = 36 hours, the winds become stronger and maximum water level near the coast increased to approximately 0.4 m (Figure 4a). Notice at this stage, because of the linear wind pattern, water level rose along the entire coast within the model domain. At t = 42 hours, as the wind pattern near the coast changed to a circular pattern, the water level pattern became distinctively different (Figure 4b). Water level rose in the coastal region to the front-right of the storm center (i.e., the Onslow Bay) but dropped in the region to the left of the storm. For example, the water level increased to about 2.3 m near Wrightsville Beach, N.C. and dropped to −0.40 m near

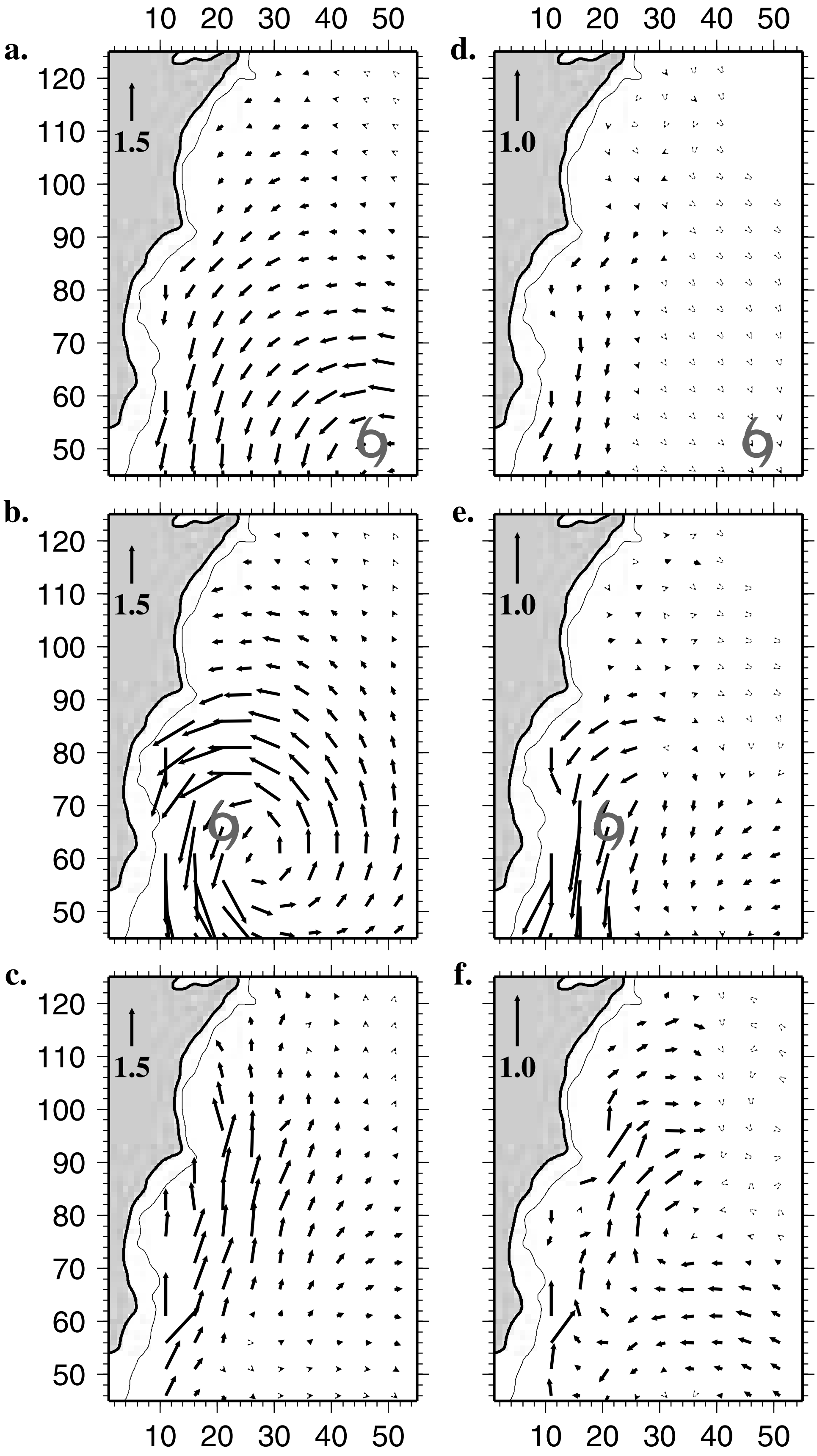

Figure 3. (a–c) Simulated surface currents (NN) at t = 36, 42, and 48 hours. (d–f) As in Figures 3a–3c but for bed currents (NN).

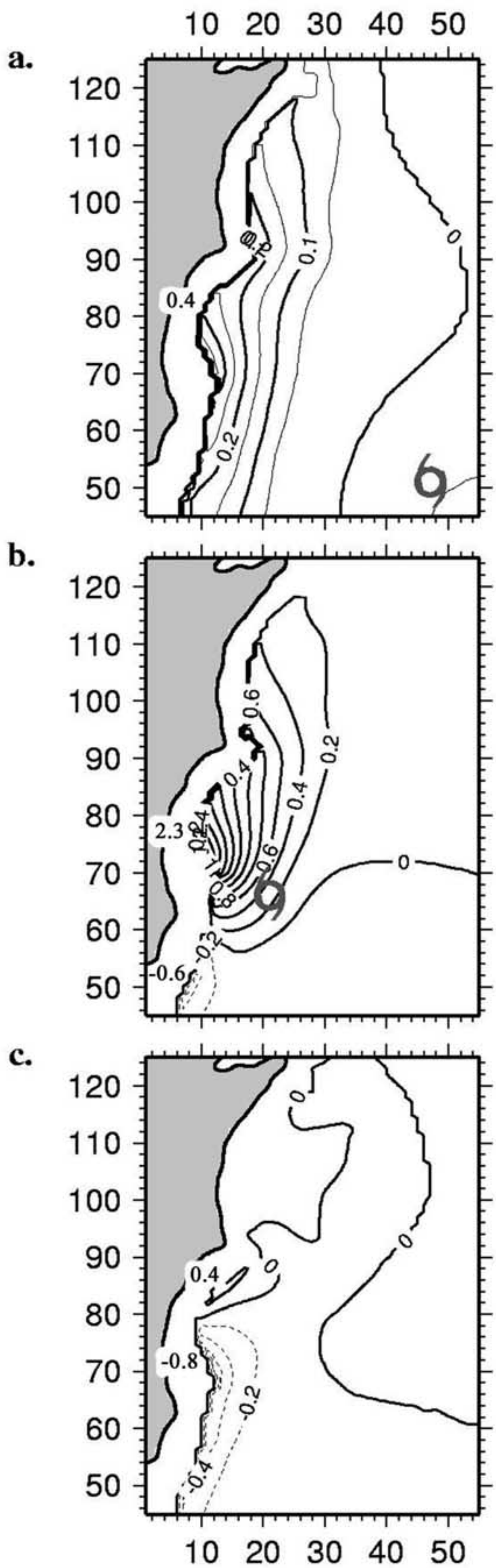

Figure 4. Simulated sea level (NN) at t = 36, 42, and 48 hours.

Charleston, S.C. The reason for such a water level difference is related to the direct, mechanical forcing of the wind. The wind direction was onshore on the right (north) side of the hurricane and offshore on the left (south) side. After the hurricane made landfall (t = 48 hours), the increased and decreased water levels were distinctively different over different parts of the coastline. Notice that the high water level in Onslow Bay relaxed with a maximum at around 0.4 m, but the water level to the south continued to be depressed (Figure 4c). This is because after the storm made landfall, the winds over the entire coastal water within the model domain became northerly or offshore, which would drive offshore flowing surface currents and depress coastal sea level.

3.2. Case YN

[17] In this subsection we will examine how surface waves affect currents via wave-induced modification of the wind stress, which is the primary mechanism for driving the currents. Then we compare currents and water level elevations between cases NN and YN. Before doing this, we first give a brief discussion of the wave spectral peak frequency that plays an important role in determining the wind stress.

[18] The wind stress vector is functionally dependent not only on the wind vector but also on the surface wave field [*Donelan et al.*, 1993]. Thus a more complete simulation of the current field should incorporate the effects of surface wave characteristics. *Donelan et al.* [1993] found that among the surface wave characteristics related to the wind drag coefficient C_D, wave age, which describes the wave development stages, is found to be the most important parameter in the representation of C_D. Wave age can be expressed as V_{w10}/ω_0, where V_{w10} is the wind velocity at 10 m above the sea surface and ω_0 is the spectral peak frequency of the wind wave spectrum. So for a given wind speed, ω_0 can be used to describe surface wave development stages.

[19] In Figures 5a–5c, the contours of the spectral peak frequency f_0 ($=\omega_0/2\pi$) in Hz, and in Figures 5d–5f, the significant wave height field H_s (in meters), are presented for Case YN, as the hurricane moved across the domain. At t = 18 hours, the spectral peak frequency f_0 is nearly a constant 0.18 Hz (not shown) and the significant wave height ranges from 1.2 m in the deep sea to 0.3 m near the coast. The wave states over the entire domain are the same. At t = 24 and 30 hours, with the storm eye still outside of the domain, f_0 changes gradually from lower deep sea values to higher shallow water values. At t = 36 hours (Figure 5a) f_0 varies from 0.08 Hz to 0.12–0.16Hz, indicating that waves near the storm center are much more mature than are those farther away from the storm center. Figures 5b and 5c are contours of f_0 after the storm eye moved to the center of the model domain and then made landfall. The distributions of f_0 in these two figures appear to be more complicated than that in Figure 5a. However, consistency in the f_0 distribution can still be found. In general, waves near the coast show higher spectral peak frequency than waves near the storm further offshore. Higher waves appear to the right of the storm and further offshore with maximum significant wave height exceeding 14 m at t = 42 hours (Figure 5e).

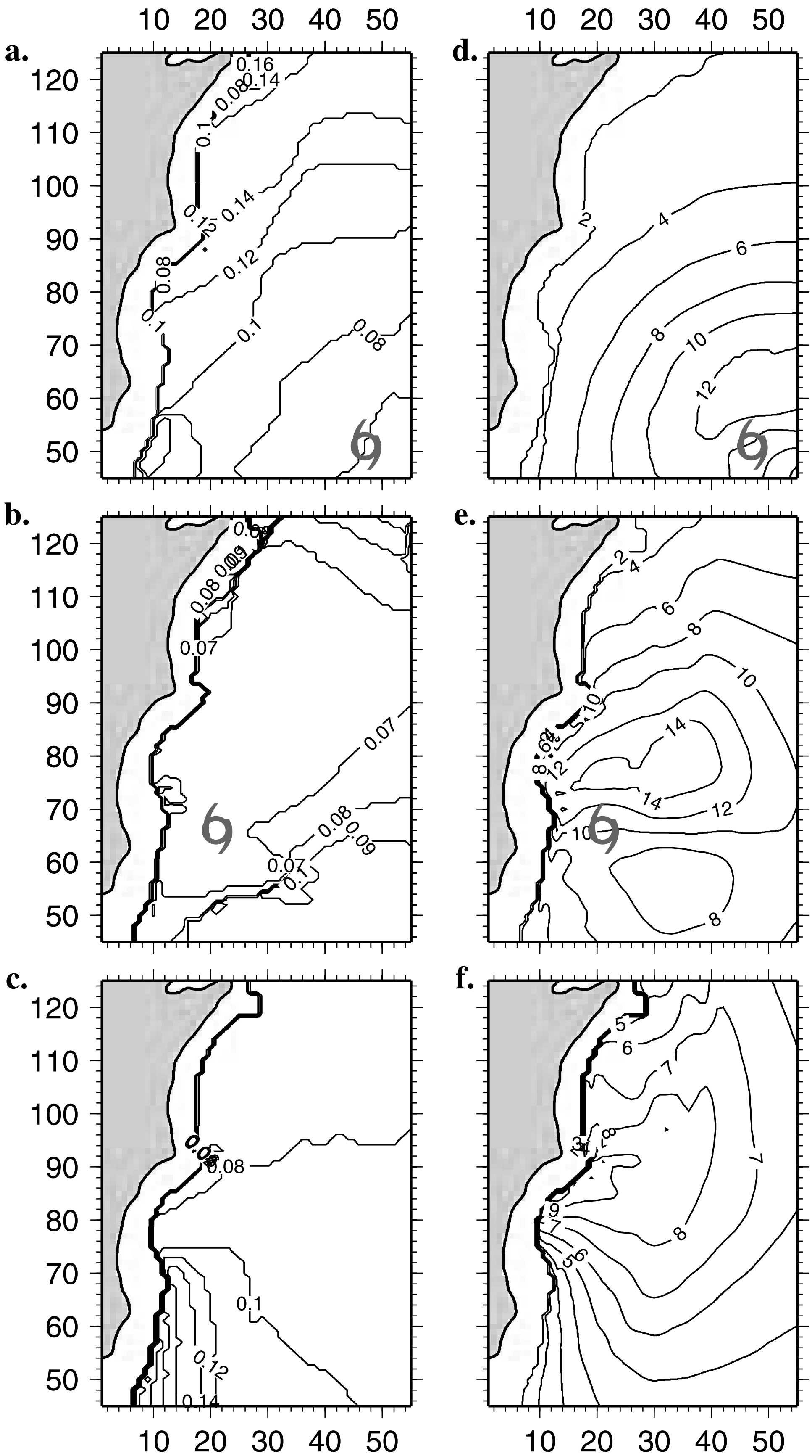

Figure 5. (a–c) Wave spectral peak frequency (Hz) for Case NN at t = 36, 42, and 48 hours. (d–f) As in Figures 5a–5c but for significant wave height (m).

[20] The surface current fields with wave effects incorporated into the wind stress are shown in Figures 6a–6c. The current patterns appear to be similar to the non-wave affected case (NN) (see Figures 3a–3c). The differences of the surface current field in case YN minus that of case NN indicate a strengthening of surface currents due to surface wave influences (Figures 6d–6f). During the time when the storm eye is still outside the model domain, wind speeds over the model domain are weak and wind-generated wave heights are small. Under such conditions, surface waves will not significantly affect the wind stress and the surface currents (not shown). As the storm entered the boundary of our model domain area, the winds near the coast became stronger and were accompanied by augmented surface waves. By 36 hours, wave influence on the wind stress increased the magnitude of surface currents by about 0.20 m/s (Figure 6d). Once the hurricane eye moved inside the model domain (Figure 6e) the influence of the wave field on the current field became more significant with the magnitude of the enhanced surface currents reaching as high as 0.45 m/s (Figure 6e). After the hurricane made landfall but still near the coast, wave effects on surface currents remained significant, of the order of 0.40 m/s (Figure 6f). Notice that the largest increase of surface currents occurred near the coast whereas the largest significant wave height occurred offshore, which indicates that the effect of wave-induced wind stress has a strong influence on coastal currents even though the wave heights there are much lower than those offshore. The reason for the above result is simple. In the wave-induced surface stress parameterization [*Xie et al.*, 2001], we used the empirical model of *Donelan et al.* [1993] in which the surface roughness length is a function of wave age determined by wind speed and peak spectral frequency.

[21] The bottom current field for the YN case is shown in Figures 7a–7c and the difference of bottom currents between case YN and case NN is shown in Figures 7d–7f. The flow pattern in case YN was similar to that in case NN before the storm entered the model domain. After the storm center entered the model domain, currents for the YN case increased by 0.08–0.01 m/s over the NN case (Figures 7d–7f). Albeit, it is only after the storm eye has moved inside the model domain that the effects of surface waves on bottom currents became significant. Again, the largest difference occurred near the coast, not correlated with significant wave height as in the case of surface currents.

[22] The pattern of storm surge in case YN (Figures 8a–8c) is similar to that in case NN (Figure 4). Figures 8d–8f show the water level differences between case YN and case NN (Case YN-Case NN). At t = 18, 24, and 30 hours, the increase of water levels were negligible (not shown). At t = 36 hours, wave-induced increases in storm surge near the coast reached 0.08–0.10 m (Figure 8d). At t = 42 hours, the peak storm surge reached 2.7 m on the right side of the storm track where winds are blowing onshore, indicating a 0.4 m or 17% increase due to wave-induced wind stress. On the left side of the storm where winds are blowing offshore, the water level decreased by as much as 0.2 m more than in case NN. Following landfall, the storm surge increased by 0.1–0.15 m near the coast to the north of the storm track and lowered by an additional 0.1–0.25 m to the south of the storm track (Figure 8c).

3.3. Case NY

[23] Surface wave effects on the bottom stress are the primary consideration in this subsection. This issue has been discussed by many authors such as *Davies and Lawrence* [1995] and *Signell et al.* [1990]. In these prior studies, constant wave fields were employed to examine the fundamental effects of waves on currents.

[24] According to the wave-current interaction model of *Grant and Madsen* [1979], which was revisited by *Signell et al.* [1990], variations in the wave friction coefficient f_c depend mainly on wave height and period. Here we will only discuss the distribution of wave periods as the hurricane moves, since the distribution of wave height can be found in section 3.2 and is shown in Figures 5d–5f. Figures 9a–9c present the plots of wave period. The periods are nonhomogeneously distributed and gradually decrease from offshore to onshore areas before the hurricane entered the model domain (not shown). However, once the hurricane was inside the model domain (Figures 9a and 9b) or just made landfall (Figure 9c), wave periods were greater near the storm center and decrease away from the center. Once the wave heights and periods are computed, the bed friction coefficient f_c depending on them can be obtained and used to compute the currents.

[25] Figures 10a–10c depict the surface currents in case NY. The wave effect on currents is most pronounced near the coast and is very well illustrated as the storm center moved inside the model domain (Figures 10a and 10b) and just made landfall (Figure 10c). Figures 10d–10f present the difference between the surface currents in case NN and those in case NY. In deep offshore waters the surface wave field did not affect the surface current field via the bottom stress, no matter where the storm center was. This is because the wind wave orbital velocity decreases exponentially with depth away from the sea surface. Wave orbital velocities approach zero at water depths well above the sea bed. So, in deep water, the bed stress is not affected by wave effects, no matter what the wave heights and periods are. However, in shallower coastal waters, due to bed stress enhancement via wave-current interactions, the near-bed currents are decreased and, accordingly, the surface currents also show a decrease (Figures 10d–10f). A large decrease in current magnitude occurred during and after the passage of the storm (Figures 10e–10f).

[26] For t = 36, 42, and 48 hours, the bottom layer current field is shown in Figures 11a–11c and the differences of this bottom layer current field minus that without wave-current interaction effects on the bed friction coefficient, f_c, are shown in Figures 11d–11f. We see that the wave effects on the bottom stress caused a decrease in currents in shallower coastal waters. When the storm center was well outside the model domain there was essentially no effect (results not shown). As the storm center moved close to the model boundary, wave influence became stronger and heights as well as the periods were large enough to enhance the bed stress, which decreased bottom currents by about 0.20 m/s (Figure 11d). The maximum effect of the decrease in current magnitude occurred on the left side of the storm

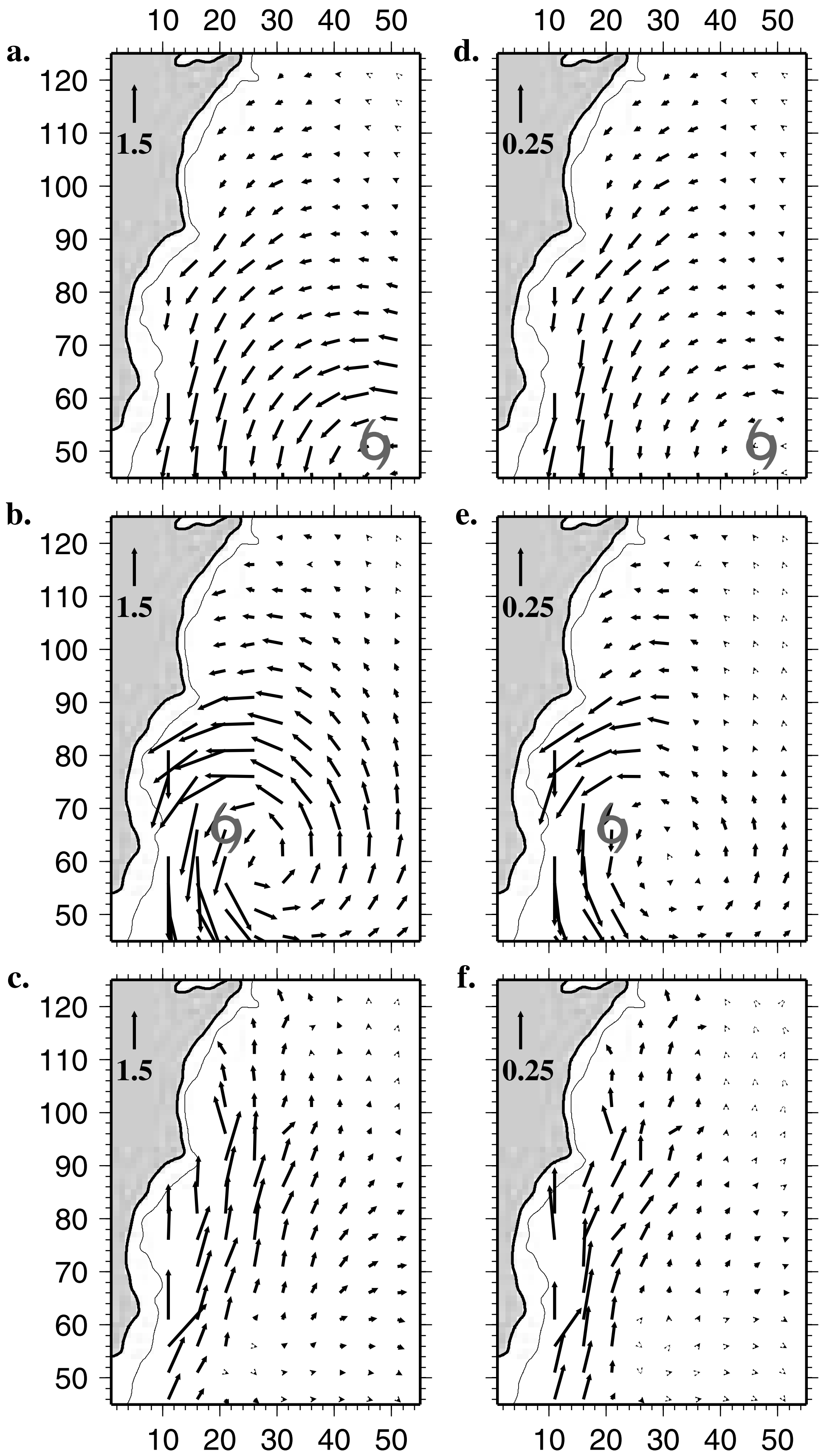

Figure 6. (a–c) Simulated surface currents with wave effects (YN) at t = 36, 42, and 48 hours. (d–f) Differences of simulated surface currents between (YN) and (NN) at t = 36, 42, and 48 hours.

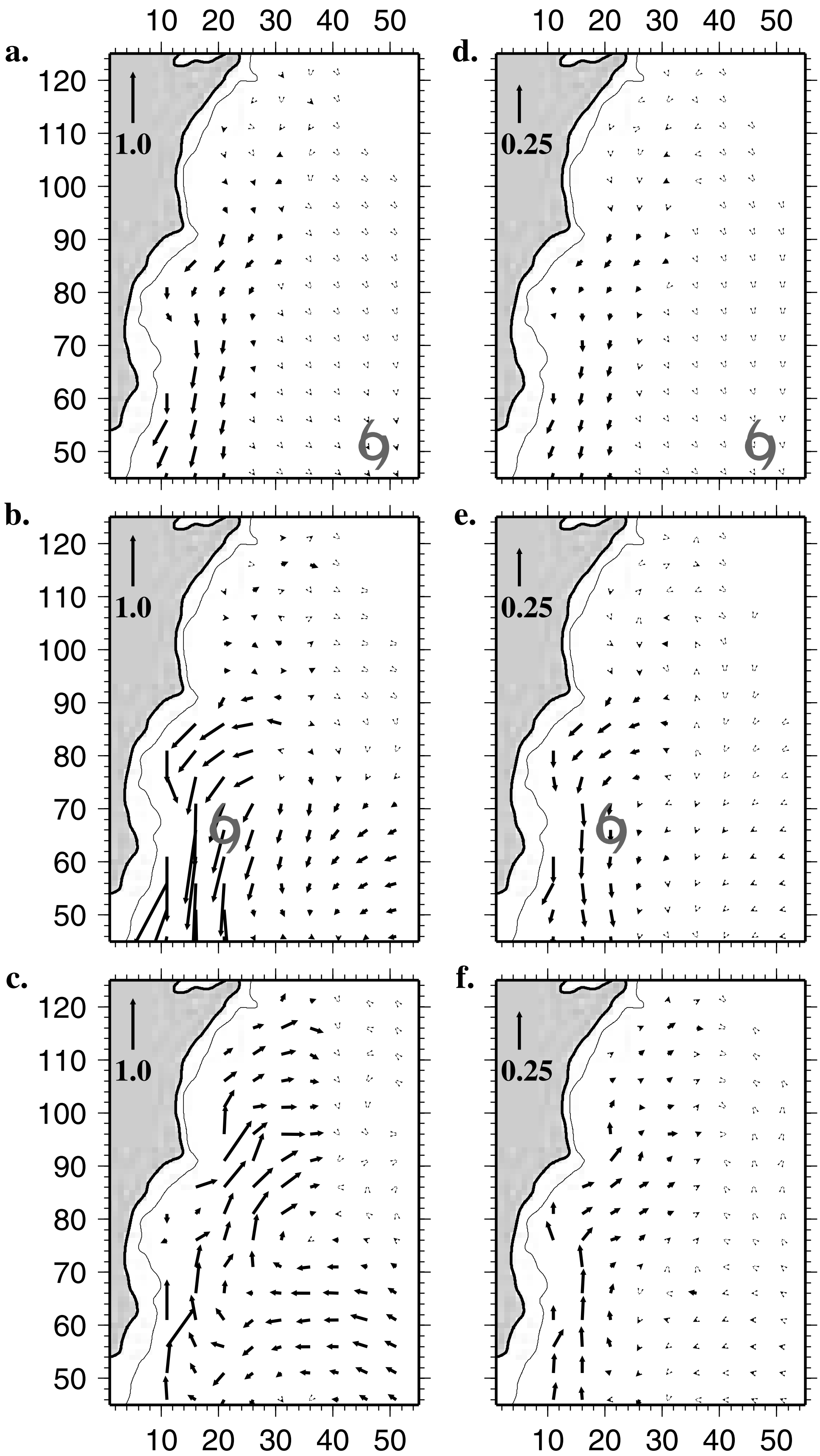

Figure 7. (a–c) As in Figures 6a–6c but for bed currents (YN). (d–f) As in Figures 6d–6f but for bed current difference.

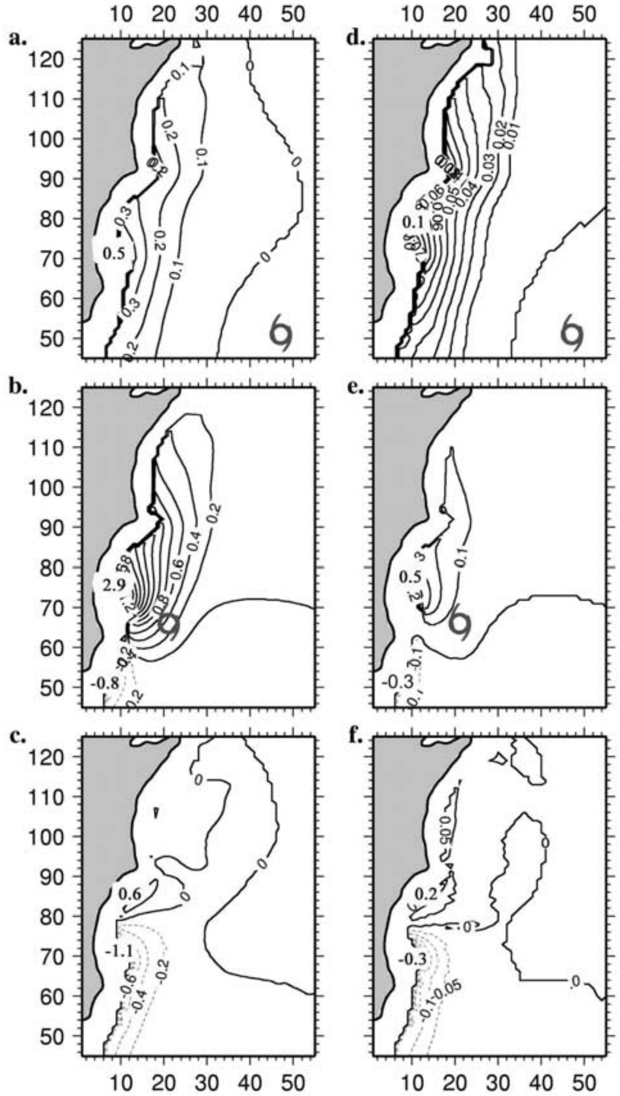

Figure 8. (a–c) As in Figures 6a–6c but for water level. (d–f) As in Figures 7d–7f but for water level difference.

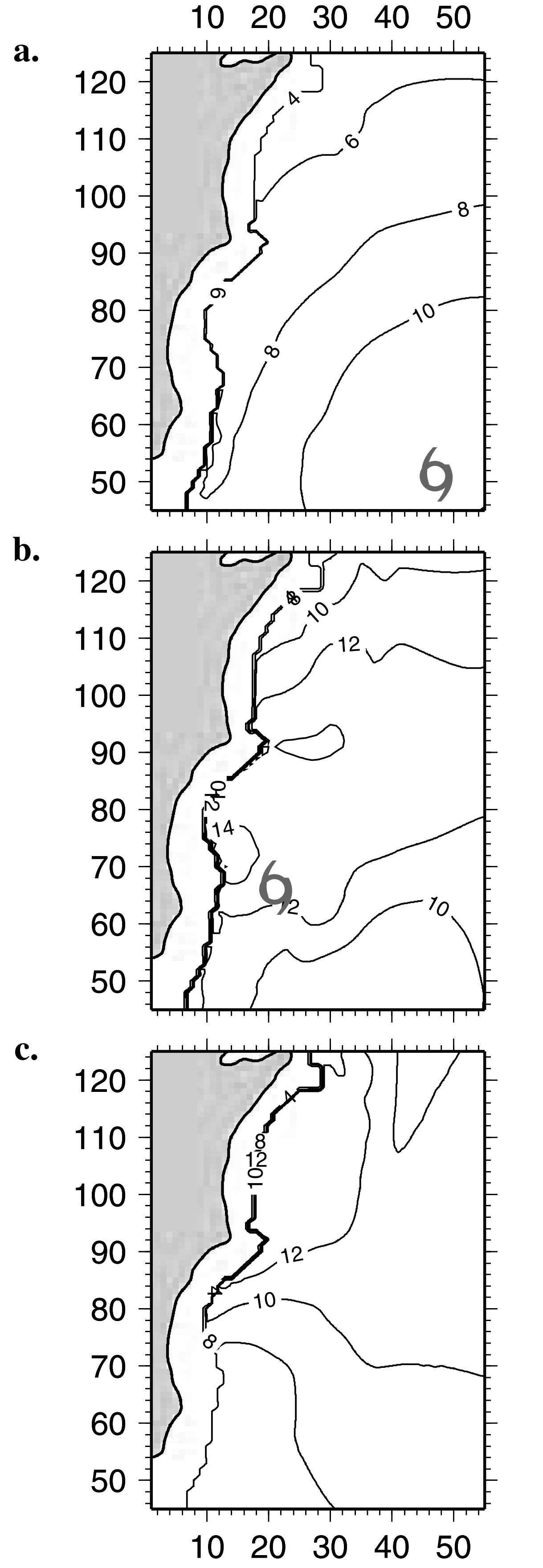

Figure 9. (a–c) Same as in Figures 5a–5c but for Case YN.

center near the coast and was 0.6–0.8 m/s (Figure 11e). Just after the hurricane made landfall, wave influence was still strong on the bottom stress, and bottom currents were decreased by 0.2–0.4 m/s (Figure 11f).

[27] Water level changes induced by wave-current interaction on the bottom stress can be seen for t = 36, 42, and 48 hours for case NY (Figures 12a–12c) and for the differences of water level for case NN minus that of case NY (Figures 12d–12f). No significant water level changes were found for t = 18, 24, 30 (not shown), and 36 hours (Figure 12d). Only when the storm center moved inside the model domain (t = 42 hours) could the water level be found to change significantly (Figure 12e). The water level at this time was decreased by the order of 0.20–0.30 m near the coast. After the hurricane made landfall, water level changes were distinctively different over the two areas divided along the storm track (Figure 12f). Water level decreased over the left side area of the storm track, whereas it increased over the right side area of the storm track, indicating that for this

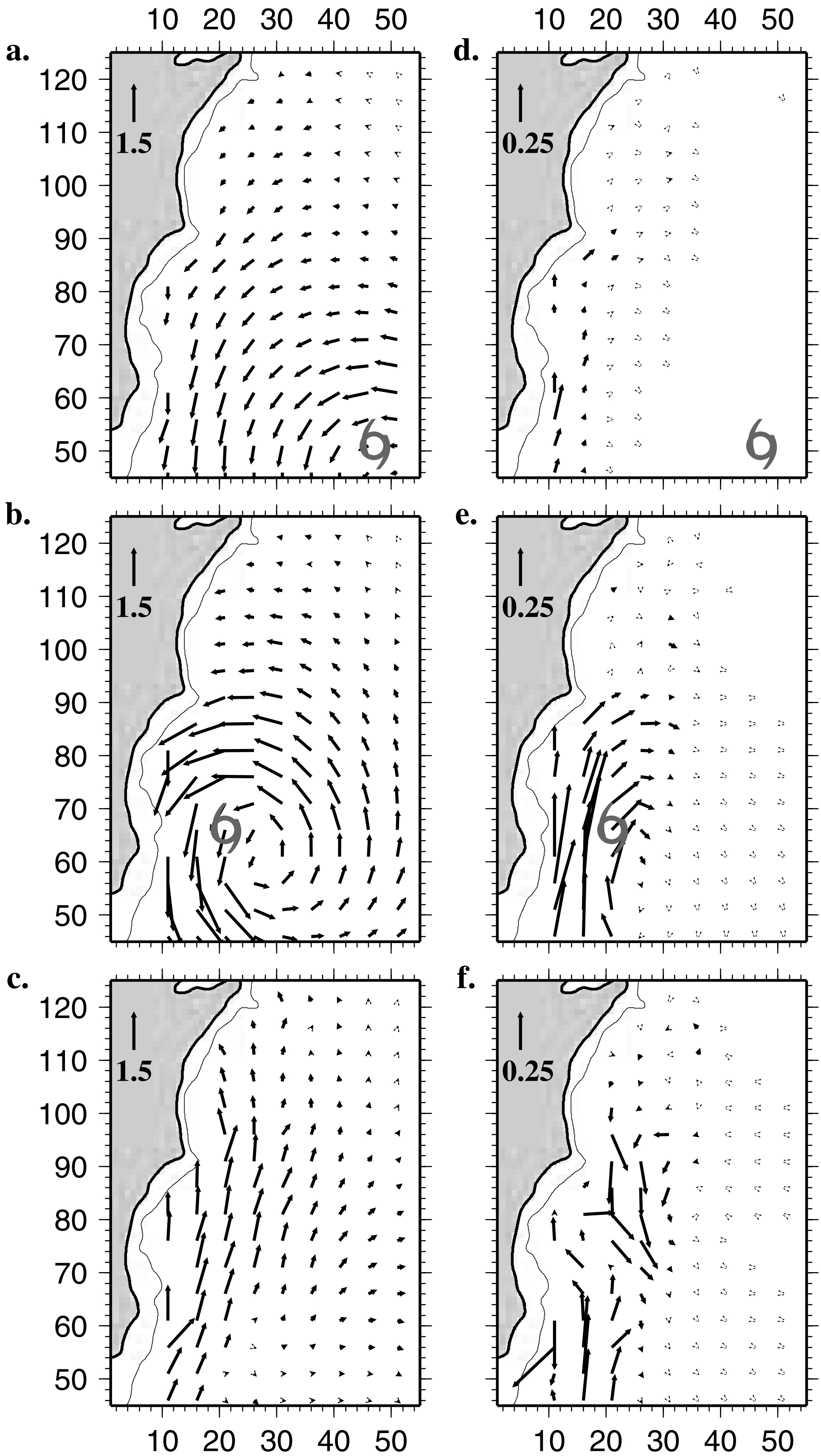

Figure 10. (a–c) Simulated surface currents with wave effects on bottom stress (NY). (d–f) Differences of simulated surface currents between (NY) and (NN) at t = 36, 42, and 48 hours.

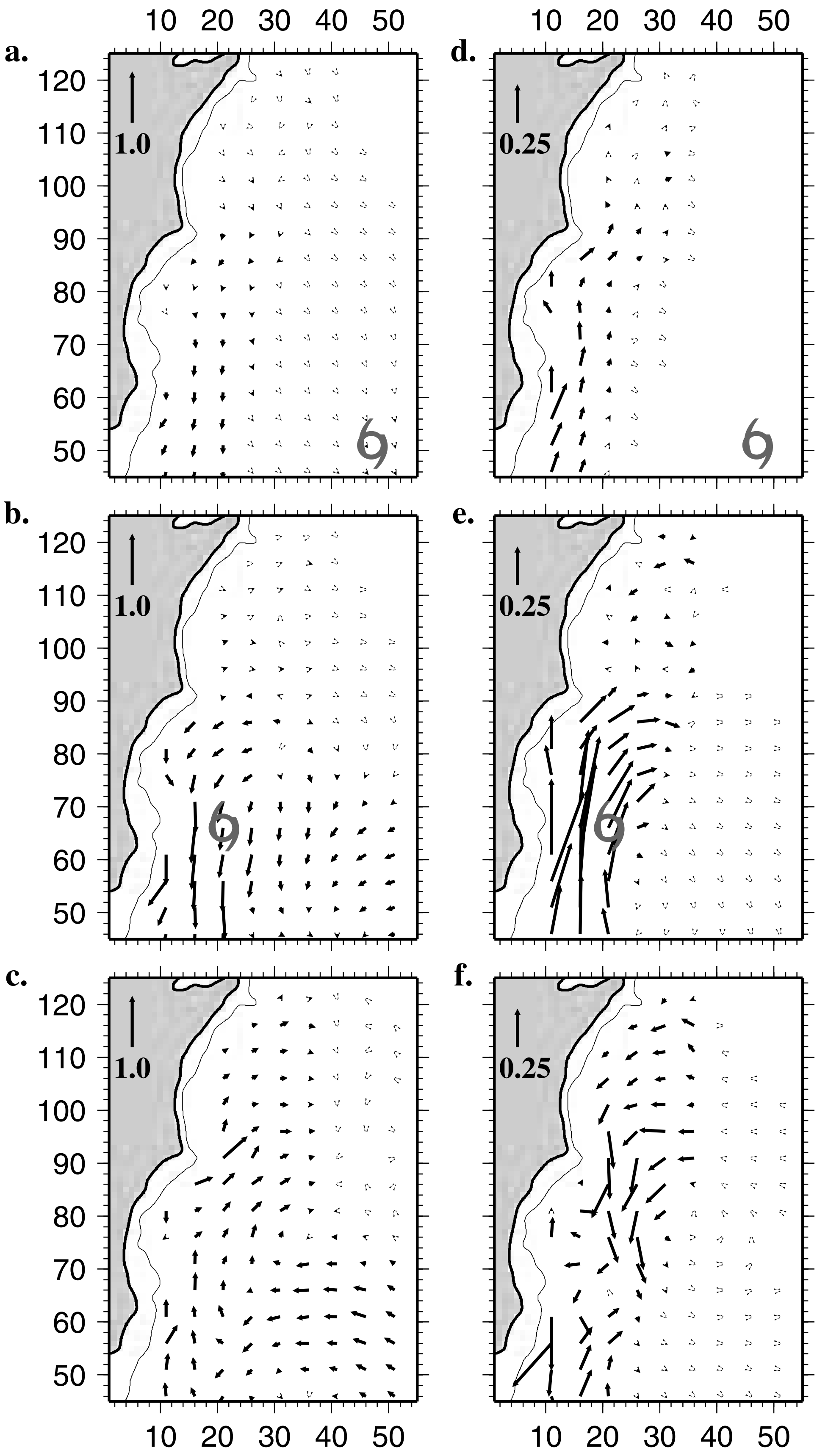

Figure 11. (a–c) As in Figures 10a–10c but for bed currents (**NY**). (d–f) As in Figures 10d–10f but for bed current differences.

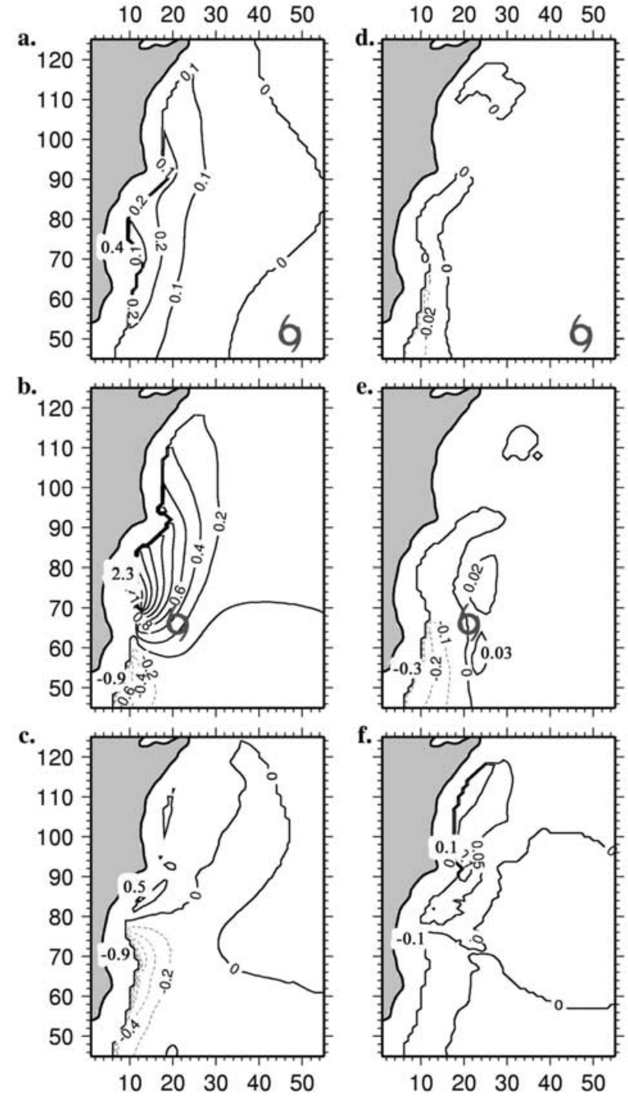

Figure 12. (a–c) Simulated sea level (NY). (d–f) As in Figures 10d–10f but for water level difference.

case, wave effects caused a water level decrease when wind blew offshore and a water level increase when the wind blew onshore. Still, the water level changes were essentially negligible as suggested by Figure 12f.

3.4. Case YY

[28] We now discuss the effect of wave-induced wind and bottom stresses (case YY). First, consider the evolution of significant wave height near wave station FPSN7. FPSN7 is the only station with recorded wave height data in the vicinity of Hurricane Fran's track. The simulated and observed significant wave heights at FPSN7 (figure omitted) showed that the simulation results generally agree with the observations, including the trend, the value, and timing of peak wave height. However, it should be noted that the model simulated wave height is generally less than the observations until the storm moved well into the center of the model domain (at t = 38 hours). This discrepancy existed at initialization. The model assumed a motionless initial state, while the real ocean is well set up by wind long before the storm arrived. Thus, the hypothesis is that the underestimation of wave height by the model prior to t = 38 hours is due to the lack of realistic initialization. This underscores the importance of data assimilation in wave prediction.

[29] Surface currents at t = 36, 42, and 48 hours for this case are presented in Figures 13a–13c, and the difference of surface currents between case YY and case NN are shown in Figures 13d–13f. When the storm center is still well outside the model domain (at t = 18 and 24 hours), the surface wave field has no tangible influence on the current fields. At t = 36 hours the wave influences caused an increase in the surface currents by 0.10–0.15 m/s (Figure 13d). However, when the storm center moved closer to the coast, the combined effects of waves on currents changed. At t = 42 hours there was a net decrease (by as much as 0.30–0.40 m/s) in surface currents to the left of storm and a net increase to the right (Figure 13e). After the hurricane made landfall, the wave effects on C_D and f_c reversed and the wave-induced wind stress again played a more important role than wave-induced bottom stress, in determining the near-surface current changes, as depicted by the 0.20–0.40m/s increase in surface currents near the coast (Figure 13f).

[30] Bottom layer currents for t = 36, 42, and 48 hours are shown in Figures 14a–14c. For a comparison of case YY results with those of case NN, Figures 14d–14f provide the differences of the near bottom current field in case YY minus that of case NN. The waves began to influence the bottom currents at t = 30 hours when the storm center was still outside but near the model boundary. As the storm center moved inside the model boundary, at t = 36 hours and moved to the center of the model domain at t = 42 hours, wave effects on currents became very significant (Figures 14d and 14e). When the eye of the storm made landfall, at t = 48 hours, the near bottom current field became far more complicated than the previous three cases discussed. Figures 14c and 14f show the complexity of the near bottom current field with an increase to the left and decrease to the right side of the storm track. The increase of bottom currents on the left side of the storm track indicates that there the effect of wave-induced wind stress is more important than the effect of wave-induced bottom stress. On the other hand, on the right side of the storm, it is the opposite.

[31] Finally, we will present the results of water level changes in case YY. The water levels in case YY and water level differences between case YY and case NN are depicted in Figures 15a–15c and Figures 15d–15f, respectively, for t = 36, 42, and 48 hours. The simulated storm surge maximum at t = 36 hours was about 0.5 m (Figure 15a). This represents an increase of about 0.10 m compared with case NN. The rise of coastal surge occurred along a large section of the coast from southern N.C. to northern S.C. The peak storm tide (surge and tide) records along the coast of SC ranged from 0.32 m (1.1 foot) at the Charleston City Office to about 1 m (3.6 feet) at Myrtle Beach Pier during the passage of Hurricane Fran (Preliminary report on Hurricane Fran of 1996 available at http://www.nhc.noaa.gov). The simulated storm surge maximum falls within the range of observations. At t = 42 hours the peak surge reached 2.8 m and occurred in Onslow Bay (Figure 15b). This represents an increase of about 0.5 m or 21% over the

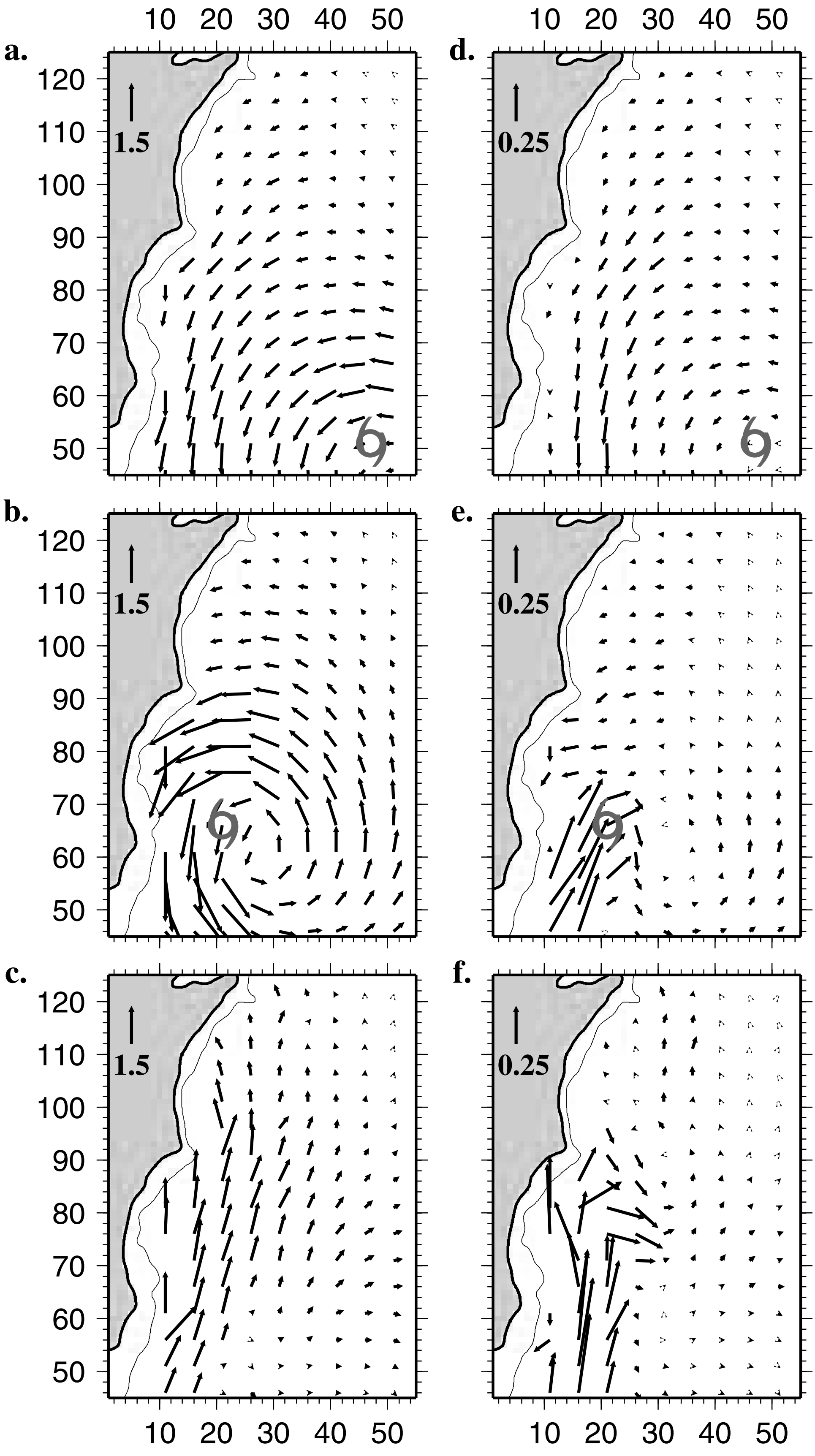

Figure 13. (a–c) Simulated surface currents with wave effects (YY). (d–f) Differences of simulated surface currents between (YY) and (NN).

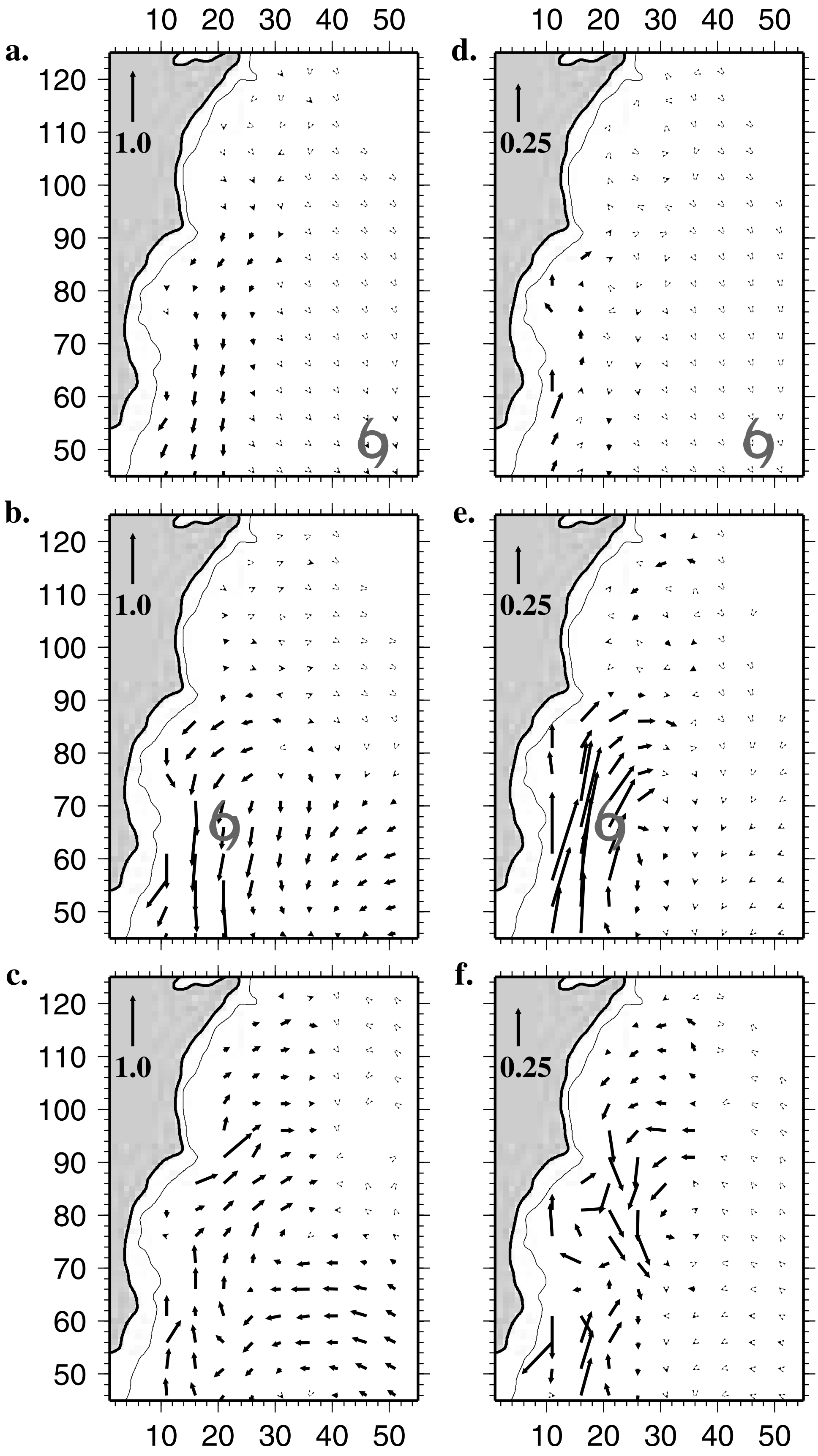

Figure 14. (a–c) As in Figures 13a–13c but for bed currents (YY). (d–f) As in Figures 13d–13f but for bed current difference.

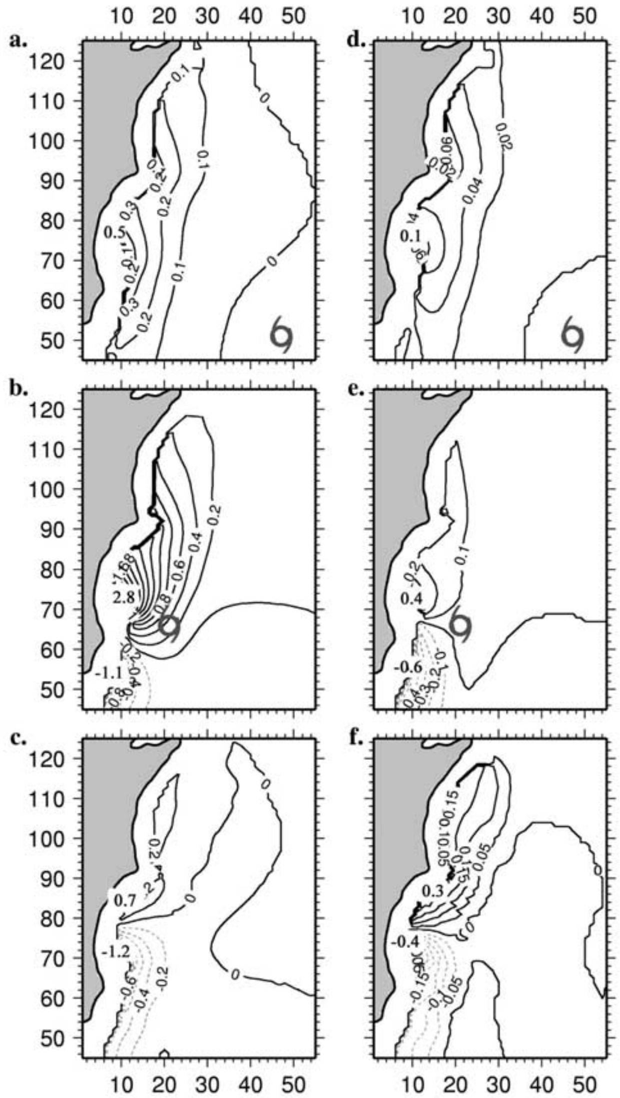

Figure 15. (a–c) Simulated sea level (YY). (d–f) As in Figures 13d–13f but for water level difference.

peak surge in case NN (Figure 15e). The peak storm tide in Onslow Bay ranged from 2.5–3.5m (8–9 feet in North topsail Beach, 10–11 feet in Wrightsville Beach) (Preliminary report on Hurricane Fran of 1996 available at http://www.nhc.noaa. gov). Although an accurate assessment of the model accuracy requires more dedicated analysis and additional observations, the results from the model indicated that the observed water level was in general higher than the simulated surge in case NN and more in line with the results from the wave-current coupled model. Notice that at this time, the water level actually lowered and lowered more than in case NN along the S.C. coast on the left side of the storm track (Figure 15e). At t = 48 hours, the peak surge relaxed to about 0.7 m and occurred along the northern coast of Onslow Bay (Figure 15c), still about 0.3 m above the peak value in case NN (Figure 15f). The primary reason for the increases in water levels was the wave-induced wind stress, since no significant water level changes were found when only wave effects on the bottom stress were considered in isolation. At t = 42 and 48 hours, water levels rose where the wind was onshore, and fell where the wind was offshore.

4. Summary and Discussions

[32] *Xie et al.* [2001] investigated the combined effects of wave-induced surface and bottom stresses on coastal ocean currents and storm surges under constant, uniform winds. The main results were that while wave-induced surface stress increases the currents throughout the water column in shallow coastal waters, this increase is partially balanced by a decrease due to wave-induced bottom stress. The relative importance of current acceleration by wave-induced surface stress and damping by wave-induced bottom stress depends on the direction of wind. This raises an issue, i.e., how would the ocean respond to spatially and temporally changing winds, such as in the case of a hurricane? Wave-current coupled models that only consider the effect of wave-induced surface stress generally lead to stronger surface currents and higher storm surge [*Komen et al.*, 1994]. Will it still be the case when wave-induced bottom stress is also incorporated into the coupled model? To address these questions, the coupled wave-current model described by *Xie et al.* [2001] has been applied to investigate the effect of waves on currents and storm surge over the region of South Atlantic Bight during the passage of Hurricane Fran in September 1996.

[33] The results from this study indicate that although the conclusions from the uniform wind cases [*Xie et al.*, 2001], in general, can be extended to temporally and spatially varying wind cases associated with moving hurricanes, a number of specific differences exist between uniform and nonuniform wind cases. For example, in both cases, wave-induced surface (bottom) stress was found to increase (decrease) wind-driven currents throughout the water column. However, the effect of waves on coastal storm surge is quite different between the two cases. For the uniform northerly wind case studied by *Xie et al.* [2001], the coastal sea level response was relatively simple, i.e., wave-induced surface stress increased the coastal sea level, whereas wave-induced bottom stress decreased it. In the case of the moving hurricane examined here, the change of coastal sea level (storm surge) is more complex. Wave-induced surface stress was found to increase the storm surge in the region of rising coastal water level but decrease the coastal water level where the water level was depressed. However, the effect of wave-induced bottom stress did not cause any significant change in peak storm surge while the storm was over the coastal water. It did depress the water level along the coast to the left of storm track during this period. This water level drop, combined with that caused by wave-induced surface stress, resulted in a large drop of water level on the left side of the storm track in the coupled case (case YY). Another important difference between the uniform and the nonuniform wind (hurricane) cases occurred after the storm made landfall. In the uniform northerly wind case, wave-induced bottom stress depresses the coastal water level along the coast. However, in the hurricane wind case, wave-induced bottom stress increased the peak coastal storm surge after the storm made landfall (t = 48 hours). By examining the surface (Figure 10f) and bottom currents (Figure 11f) induced by wave-induced bottom stress at this time, the higher storm surge at t = 48 hours can be attributed to the reduced seaward

flowing surface and, particularly, bottom currents in response to the predominantly southerly winds (Figure 11f). The wave-enhanced damping of offshore-flowing currents allowed the coastal storm surge to maintain at a relatively higher level than that in the uncoupled case.

5. Conclusions and Remarks

[34] The modeling results presented above indicate the importance of surface wave effects on the currents in coastal waters and storm surge in general and under hurricane forced conditions in particular. Surface wind and bottom stresses are functionally related to surface waves, and both of them should be taken into account simultaneously in current simulations under normal [*Xie et al.*, 2001] and hurricane conditions.

[35] Main conclusions of this study are

1. Accurate predictions of storm surge, coastal currents, and waves require a coupled wave-current prediction system. Storm surge models without coupled surface waves generally will under estimate not only the peak surge but also the coastal water level drop which can also cause substantial impact on the coastal environment.

2. Introducing wave-induced surface stress effect into storm surge models can significantly improve storm surge prediction. In the case of Hurricane Fran examined in this study, wave-induced surface stress resulted in a peak surge which is approximately 17% higher than that in the stand-alone storm surge model.

3. Incorporating wave-induced bottom stress into the coupled wave-current model further improves storm surge prediction. Wave-induced bottom stress not only delays the retreat of storm surge after the landfall but also increases the sea level drop during the landfall of the storm. However, in the hurricane Fran case studied here, wave-induced bottom stress did not significantly alter the maximum storm surge which occurred near the storm's landfall and to the right of the storm track.

4. Since the effect of wave-induced surface stress is parameterized as a function of wave age, the location of peak significant wave height does not appear to be related to the locations of maximum current velocity and sea level change. The largest significant wave height occurred in offshore waters, whereas the most significant modification of currents and sea level by waves occurred near the coast. Thus calibration of the wave module according to minimum error in peak significant wave height does not necessarily result in an optimum wave module in the coupled wave-current model if the purpose of the coupled system is for current and storm surge prediction. In a wave-current coupled storm surge prediction system, all components of the coupled system should be calibrated according to minimum error in currents and storm surge.

[36] Finally, it should be noted that there are several limitations in the present study. First, the POM model utilizes second order turbulent kinetic energy (TKE) closure scheme to determine the vertical turbulent mixing coefficients. Apart from the surface stress effect, surface waves can also modify the upper ocean energetic processes, which should be considered in the TKE parameterization. This is beyond the scope of the present study. Another limitation comes from the uncertainty in the drag coefficient, or air-sea fluxes in general, under high wind situations. This is an active research area and a commonly accepted formula for determining the drag coefficient at high wind speeds is not yet available. Thus the issue of wave-current coupled modeling should be revisited with improvements in above areas.

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