The influence of wave drag and sea spray on storm waves

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1. Introduction

Under high wind conditions, rapidly varying winds continuously generate young waves and enhanced surface stress. Sea spray from breaking waves is ejected into lower level of the atmosphere, enhancing the air-sea enthalpy exchange (Andreas and Emanuel, 2001). Emanuel (1995) suggested that if estimated values of the exchange coefficients at 20 ms^{-1} are applied at higher wind speeds, maintaining a storm of much greater than marginal hurricane intensity would be impossible. Thus, sea spray is a possible mechanism to enhance the air-sea enthalpy exchange at high winds (Andreas and Emanuel 2001) and maintain the boundary layer.

Although studies of the impact of wave-induced drag and sea spray processes, as separate air-sea flux processes have made recent progress, their collective impact has received less attention. Storm-induced waves are complex and rapidly varying in time and space. The effective fetch of wave growth is modulated by the storm's motion. Waves that propagate in the direction of storm's motion remain under the influence of aligned winds for longer effective time and distance. Bowyer and MacAffee (2005) showed that enhanced fetch can give notably high waves even for rather modest storms, because there is more time to pump energy into the waves from the winds. Thus, storm translation speed is an important factor determining the height and spatial distribution of wave fields. Moon et al. (2003) suggest that rapid storm translation tends to cause the peak storm waves to lag behind the peak winds. They also found that the hurricane-generated wave fields are mostly determined by the distance from the hurricane center, the maximum wind radius and the storm translation speed.

We present a coupled atmosphere-wave-spray model in section 2, a storm in section 3, the impact of spray and roughness drag on waves in section 4, and conclusions, section 5.

2 Model description and experiments

The MC2 (Mesoscale Compressible Community) atmospheric model is used in all numerical simulations. MC2 is coupled to WAVEWATCH III (hereafter WW3; Tolman and Chalikov, 1996) wave model and a bulk algorithm for turbulent air-sea fluxes with a high-wind sea spray formulation. MC2 is implemented on a latitude-longitude projection, on the domain 40°W to 80°W and 25°N to 58°N, with 30 vertical layers, 0.25° horizontal resolution, and 600 s integration time steps. Lateral boundary conditions use CMC (Canadian Meteorlogical Centre) data. WW3 was implemented on the same domain as MC2 with 0.25° resolution. Over the sea, MC2's interfacial momentum and heat fluxes use Monin-Obukhov theory. Total momentum τ_T latent $H_{L,T}$ and sensible $H_{S,T}$ heat fluxes, are obtained by adding the bulk interfacial (τ, H_L, H_S) and spray fluxes (τ_{SP}, $Q_{L,SP}$, $Q_{S,SP}$) following Andreas (2003)

$$\tau_T = \tau + \tau_{sp} \quad (1)$$

$$H_{L,T} = H_L + Q_{L,SP} \quad (2)$$

$$H_{s,T} = H_s + Q_{S,SP} \qquad (3)$$

At every coupling time step, data are exchanged between atmosphere and waves: wind speed and direction computed by MC2 are sent to the wave model WW3, and new roughness Z_{0m} from WW3 is sent back to MC2. Spray-mediated heat fluxes are sent back to MC2. We also conducted two partially-coupled studies of wave drag and spray: (a) coupled MC2-wave simulations with no spray-modified fluxes, and (b) coupled MC2-spray runs with no wave-drag effects.

3. Storm Case

Superbomb developed off Cape Hatteras in 2000, and deepened explosively from 995 mb at 1200 UTC 20 January to 951 mb by 1200 UTC on 21 January. At mid-levels, CMC analysis suggests that a short wave traveled quickly around the base of a deepening larger-scale trough over Hudson Bay. Propagating northeastward, Superbomb's peak U_{10} winds reached 45 ms^{-1} near Nova Scotia. It made landfall at 0000 UTC 22 January and continued weakening.

4. Results

a. Baseline simulation of wind and wave fields

Walsh et al. (2002) suggest that the wave field in the vicinity of a hurricane may be sometimes modeled by a few parameters such as the maximum wind speed, the radii of the maximum gale force winds, and the recent movement of the storm. Figures 1-2 show the simulated winds and SWH swath isolines for Superbomb, respectively. Swath maps give the maximum value at every grid point during the passage of the storm; all appear in the right forward quadrant along the storm track. Maximum winds (36 ms^{-1}) occur at 06 UTC 21 Jan., while 17 m waves appear several hours later, at 18 UTC 21 Jan. (Figs. 1a and 2a).

The lag in the peak waves behind the peak storm winds occurs because the storm translation speed exceeds the propagation speed of the dominant waves (Bowyer and MacAfee, 2005; Moon et al., 2003). For example, there are two instances, at 06 UTC and 18 UTC on 21 Jan., when Superbomb's translation speed are comparable to each other (Fig. 3), but the SWH during the latter stage, when storm's movement is decelerating and tends to the dominant wave speed, SWH grows dramatically and is ~ 4 meters higher than that during the accelerating stage with the strongest wind, as shown in Fig. 2a.

b. Effects of spray and wave drag

The mechanisms of sea spray and wave-drag have differing influences on storm development (Zhang et al., 2006). These processes affect the winds that drive the waves and also the wave feedbacks on the winds and the storm. Wave drag effects roughen the sea surface and dissipate momentum; spray tends to increase storm intensity by evaporation. Thus, compared to SWH observations, wave-drag simulations (MC2-wave) tend to reduce SWH values compared to control (MC2-only) runs, whereas spray (MC2-spray) tends to increase SWH. Swath plots of wind speed and SWH from the MC2-wave and MC2-spray runs show these features (1b-1c, 2b-2c).

The maximum reductions / increases in wind speed due to wave/spray are -3/+6 ms^{-1} for Superbomb. For SWH, the maximum effects are -3/+2 m. The effects on waves lag the corresponding effects on winds by about 6-12 hr, because of the dependence of wave development on storm translation speed and the wind forcing history (Moon et al., 2004). The corresponding spatial distributions of wind and SWH from the control simulation and the difference fields, between MC2-wave, MC2-spray, fully-coupled and control simulations are shown in Fig. 4. These plots correspond to the instance when the maxima influences of wave-drag/spray on SWH occur. The highest waves coincide with the maximum winds and appear in the rear right quadrant relative to the storm center (Fig. 4a). Thus, the storm centre is relatively distant from the regions where the maximum winds and waves occur, compared with the distances occurring at the storm peak, for example, 06 UTC 21 Jan. for Superbomb.

High waves occur near the storm centers as well as in extended spiral bands in the storm's right forward quadrants, dominated by the curvature of the wind fields. As a result of the rapid variation in winds in these regions, the sea is rough, young waves are continuously being generated, wave-drag is high and sea spray is being ejected into the lower atmosphere. The influence of wave-drag / spray on wind speed in these spiral regions is at least as significant as in the maximum wind regions close to the storm centers (Figs. 4b and 4c). The MC2-wave runs suggest that the youngest ocean waves have maximum Charnock parameter (not shown) in excess of 0.035 in the extended right and forward quadrants; this is consistent with the growth of high waves in spiral bands shown in Fig. 4. It is notable that the effect of wave-drag and spray on SWH (Figs. 4b and 4c) is more significant in the high wind region, regardless of the sea state complexity in high wind curvature regions. Corresponding maximum reductions/ increases are respectively 2.8m / 2.4m or ~15.3% / 14.6% for Superbomb.

5. Conclusions

In this study, a coupled atmosphere – wave – sea spray model system is used to investigate the impacts of sea spray and wave drag on storm-generated waves, with respect to the storm location and translation speed. A rapidly moving intense winter storm is studied. Results show that the decrease or increase of significant wave heights due to wave-drag and spray effects is most significant in high wind regions to the right of the storm track. This occurs in spite of the complexity of the sea state. Because the storm translation speed exceeds the propagation speed of the dominant waves, maximum wave heights tend to appear several hours after the peak wind events.

Because the combined influences of spray and wave are competitive with each other, the final significant wave heights (SWH) can be close to the SWH results from the uncoupled MC2-only runs. This result is obtained in Superbomb; the increase in SWH due to spray is comparable with the decrease due to wave-drag, and the combination of both processes is close to observed SWH values.

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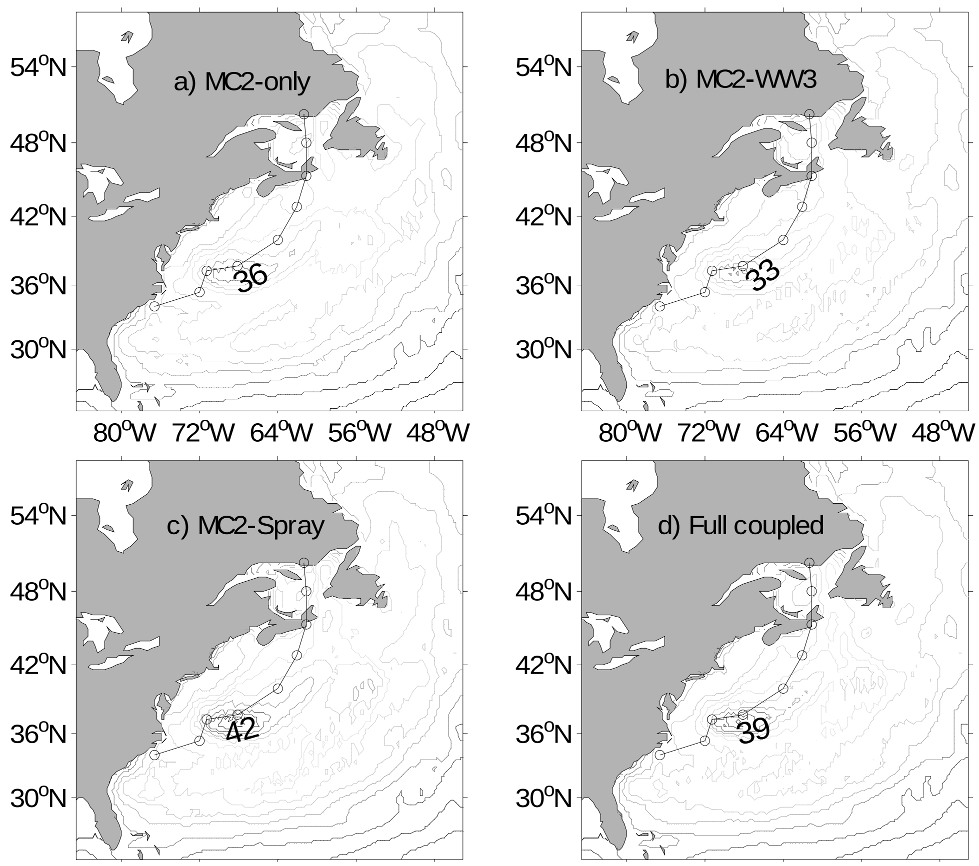

Figure 1. Swath maps of wind speed (ms^{-1}) from the passage of Superbomb at 3 ms^{-1} intervals. In each panel the 6 hourly storm track is superposed, starting at 12 UTC 20 Jan 2000.

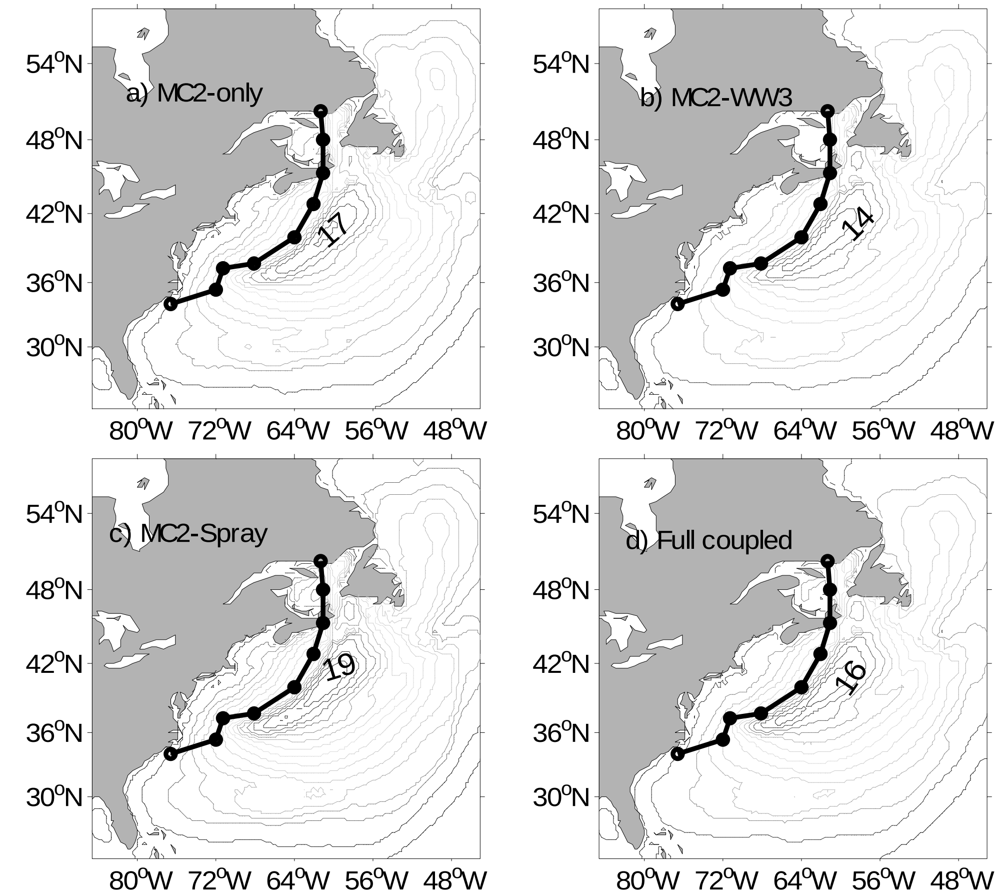

Figure 2. Swath maps of SWH (m) with the passage of Superbomb at 1 m intervals.

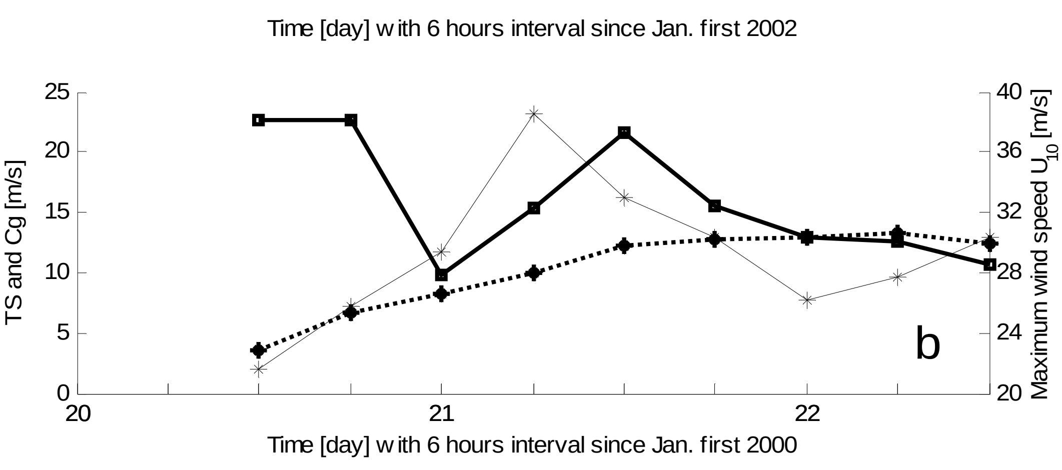

Figure 3. Time series of translation speed (▬▬), mean group velocity (▪▪▪) of the dominant wave, and maximum wind speed (—) from the uncoupled MC2-only simulation for Superbomb in 2000.

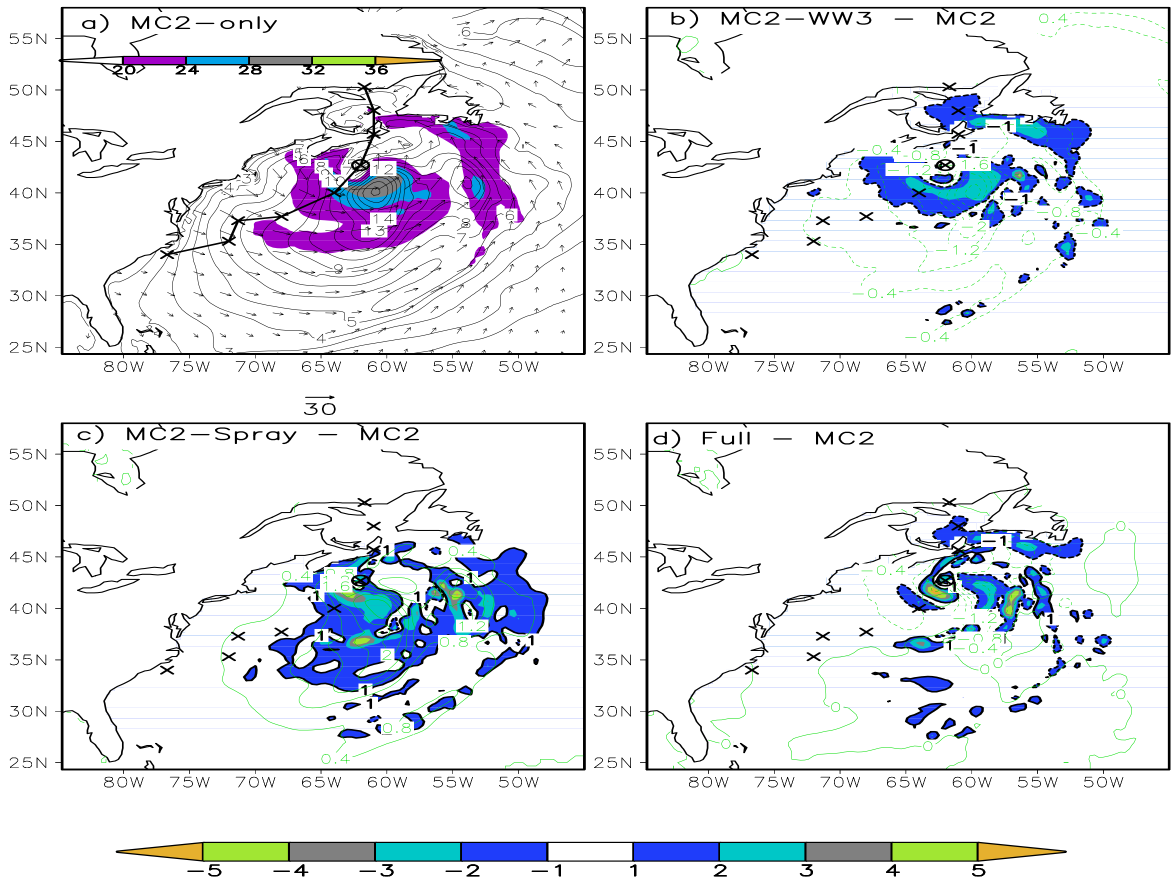

Figure 4. SWH (contour), wind vector (arrow), and wind speed (shaded) from MC2-only simulation for Superbomb at 18 UTC 21 Jan. 2000: (a). Differences in wind speed (shaded) and SWH (contour) are shown, between: (b) MC2-wave and MC2-only, (c) MC2-Spray and MC2-only, and (d) fully coupled and MC2-only. Storm centers are marked by ⊗.