P4.4 INFLUENCE of SEA SPRAY and WAVE DRAG on MIDLATITUDE STORM STRUCTURE and INTENSITY

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1. Introduction

The intensity of tropical storms is sensitive to the rates at which enthalpy and momentum are transferred between the sea and the air, particularly in the high-wind core of the storm. Emanuel (1995, 1999) showed that if estimated values of the exchange coefficients at 20 m s^{-1} are applied at higher wind speeds, maintaining a storm of much greater than marginal hurricane intensity would be impossible. Andreas and Emanuel (2001) suggest that some mechanism must enhance the air-sea enthalpy exchange at high wind speeds, and that sea spray is a plausible candidate to do this. Strong winds above the sea surface eject large amounts of spray into the lower atmospheric boundary layer. Heat fluxes can be significantly modified through the evaporation of spray droplets, which can ultimately affect cyclone dynamics. A competing mechanism is the impact of wind-waves on air-sea momentum fluxes, as shown by Janssen (1997), Chalikov and Makin (1991), Smith et al. (1992), Donelan et al. (1993). Waves can impact on the surface stress, contributing to cyclone decay (Lionello et al. 1998; Bao et al. 2000; Doyle et. al. 2002).

Although studies of the impact of wave-induced drag and sea spray as separate factors on air-sea fluxes have made progress in recent years, their collective impact has received less attention (Makin, 1998). In this study, we construct a composite atmosphere-wave-spray model, consisting of a mesoscale weather model, and models for waves and sea spray. Case studies are extratropical Hurricane Earl (1998) and two intense winter storms: the Bomb of 12-15 January 2002, and the Superbomb of 20-22 January 2000. Our focus is to evaluate the combined impacts of spray and waves on midlatitude storm intensity and the structure of the lower atmosphere.

2. Model description and experimental design

The Mesoscale Compressible Community (MC2) atmospheric model, version 4.9.3 is used in all numerical simulations, coupled to the WaveWatch3 (WW3) ocean wave model (Tolman, 2002) and a bulk algorithm for turbulent air-sea fluxes, with a high-wind sea spray formulation (Andreas and DeCosmo, 2002).

The MC2 model (Benoit et al., 1997) is implemented on a latitude-longitude domain 40°W to 80°W and 25°N to 58°N, with 30 vertical layers and a horizontal resolution of 0.25°. The integration time step is 600 s. Lateral boundary and initial conditions are taken from CMC (Canadian Meteorlogical Centre) analysis data. WW3 wave model was implemented on the same resolution as MC2, to simulate wave spectra field in terms of wavenumber – direction bands.

Each simulation begins with the integration of MC2, for 3 model time-steps (1800 s), with fixed Charnock parameter β. Wind speed and direction, are transferred to WW3 and the spray model. WW3 is then integrated for 2 model time-steps (900s). A new Z_0 field, as produced by C_P (peak phase speed from WW3) computed within WW3, is then passed to MC2, which is integrated for an additional 3 model time-steps. Spray-mediated heat fluxes are passed from the spray model to MC2 at each model time-step.

Four experiments were performed: (1) a control simulation uses MC2 atmospheric model winds to drive the WW3 waves, assuming the conventional Charnock roughness, with no feedback, and no spray, (2) a fully-coupled MC2-wave-spray simulation, with spray-enhanced heat and momentum fluxes, and wave-modified stress feedbacks to MC2, (3) two partly-coupled runs are: (a) the coupled MC2-wave simulation, with wave-

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modified β passed to MC2, but no spray, and (b) the coupled MC2-spray run, driving WW3, with no wave-modified β passed to MC2.

3. Storm cases

Tropical Storm Earl became extratropical, as it crossed the Carolinas, exited continental USA near Cape Hatteras, followed a northeastward trajectory and intensified over the Maritime Provinces of Eastern Canada. On September 6, it crossed the Avalon Peninsula of Newfoundland and continued northeastward.

The 2002 January Bomb originated off the coast of North Carolina on 12 UTC 13 January 2002, rapidly intensified, and deepening over the next 12 hours, it moved northeastward. Nearing Nova Scotia on 00 UTC January 14, maximum sustained winds were 60 knots. It then attenuated and crossed eastern Nova Scotia.

Superbomb developed off Cape Hatteras, deepening explosively from 995 mb at 12 UTC 20 January to 951 mb by 12 UTC on 21 January. The system propagated to the northeast at 11 ms^{-1}, reached peak winds of 45 ms^{-1} at 250 km of Nova Scotia, and made landfall on Cape Breton at 00 UTC 22 January.

4. Surface fluxes, storm tracks and intensity

Sea spray enhances heat fluxes, tending to deepen ultimate storm intensity. Ocean waves are continuously generated and driven by winds, enhancing surface roughness, and decrease the storm intensity (Doyle et al. 2002).

4.1 Storm tracks

By comparison, the modeled storm tracks of Earl, Bomb and Superbomb (Fig. 1a-1c), using the MC2 (with and without spray and waves) capture the basic evolution of the storms' tracks, and moreover, show little sensitivity to spray or waves.

4.2 Storm intensity

Figures 2a-2c show the time series of central SLP from simulations with and without sea spray and waves, during the developments of Earl, Bomb and Superbomb, along their respective storm tracks.

Inclusion of spray results in intensification of the three storms: SLP deepening is about 1.2, 2.8 and 5.0 hPa, compared to the control simulations, at the peak of the respective storms. By comparison, the combined impact of spray and waves in the fully-coupled MC2-waves-spray simulation lessens Earl's peak intensity by 1.5 hPa, but deepens Bomb's and Superbomb's peak intensity by 1.3 and 2.5 hPa, respectively, relative to the MC2 control simulation. Therefore, wave drag slightly dominates over spray in Earl, whereas for the other two storm cases, spray effects are slightly dominant.

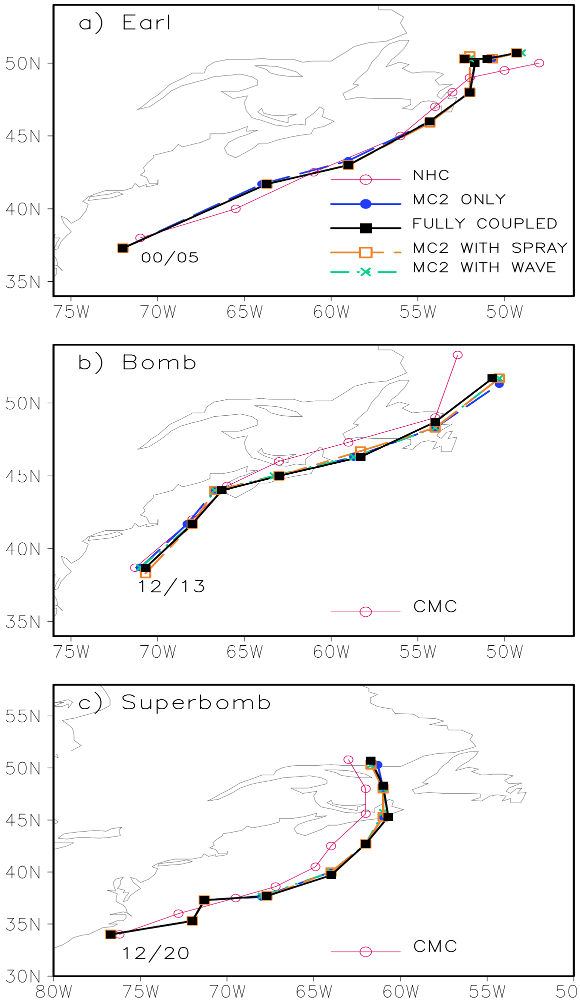

Figure 1. Storm tracks of (a) Earl (b) Bomb and (c) Superbomb, using MC2 with and without spray and waves, as well as NHC and CMC analyses. Storm centers are plotted every 6-h.

Maximum winds U_{10} are given in Figs. 2d-2f, with and without sea spray and waves, following each storm's trajectory. These are area-averaged on 200 km^2 over each storm's high-wind regions. For the three storms, the maximum sea spray (positive) impacts on winds are 2, 7 and 10 knots, and corresponding wave (negative) impacts are 5, 6 and 7 knots, respectively, compared to the control simulations. In the fully-coupled simulation, the maximum combined impact of spray and waves on Earl is a reduction of 3 knots in U_{10}, relative to the control run (at 00 UTC 6 September), showing that the wave impacts exceed spray impacts. In Bomb, which is stronger than Earl, the maximum U_{10} change is a 4 knot increase, relative to the control (18 UTC 13 January): spray dominates wave impacts. In Superbomb, the strongest of the three storms, the maximum U_{10} change is a 6 knot increase (06 UTC 21 January) relative to the control: showing once more that spray exceeds the wave impacts. In each case, both waves' maximum de-intensifying impact and sprays' maximum intensifying impact tends to become significant at or near (about 6-18 h prior) the storms' minimum SLPs, during the storm's rapid intensification phase when rough young waves abound and spray droplets are ejected from the sea surface. This is illustrated in the presentation by the time series of the corresponding Charnock parameter β, as estimated by the fully-coupled run. Thereafter, as storms begin to attenuate, spray and wave impacts begin to decrease and tend to balance, as control and fully coupled simulations tend to converge.

4.3 Surface flux effects

The direct impact of sea spray and wave drag is to modify the heat fluxes and momentum flux across the air-sea interface (Andreas and Emanuel, 2001 Andreas, 2004). Figures 3a-3c give the time series of area-averaged (200^2 km^2) latent and sensible heat fluxes following the maximum heat flux centers for Earl, Bomb, and Superbomb. In each case, the impact of wave drag on heat fluxes is quite small. While storm intensity is reduced due to the wave-induced drag. Consequently, heat fluxes from MC2-spray and the fully coupled runs are very similar.

Our presentation will show that the dynamic compensation downdraft and entrainment associated with wave-drag result in a cooler drier boundary layer. This is partially due to the fixed SST fields used in simulations of this study. Fixed SSTs in addition to cooler and drier boundary layers will increase the difference of temperature and moisture (ΔT and Δq) between air and sea. Thus, wave-drag's combined effects, namely reduced wind speed (Figs. 2d-2f) and increased ΔT and Δq, tend to give small changes in heat fluxes. This is a thermal-dynamic effect resulting from the bulk formulations, where the roughness lengths for thermal fluxes are held constant. Thus, Figs. 3a-3c show that the latent heat fluxes from MC2-wave simulations tend to be larger than those from MC2-only. This occurs because wave-drag results in a slightly dryer boundary structure, and is particularly evident when the difference in latent heat flux between those two simulations is maximal as shown in Figs. 3d-3f.

Compared to wave drag, spray impacts are variable depending on storm conditions, such as the sea surface temperature, moisture, and wind speed. For example, Earl moves quickly during the initial phase of its extratropical intensification (Fig. 1a), as it passes over relatively warm Gulf Stream and midlatitude waters, which are potential heat and moisture sources. Thereafter, Earl decelerates markedly over cold waters north of Newfoundland. Thus, spray's peak impact on latent heat is only about 30 W m^{-2} (5%) compared to the MC2-control run (Fig. 3a). By comparison, spray produces a peak latent heat enhancement of about 16% (Fig. 3b) for Bomb, and about 30% (Fig. 3c) for Superbomb, reflecting their slow propagation over warm midlatitude waters, during the intensification phase of their developments.

For sensible heat flux, maximum impacts of spray are about 2%, 12% and 25% in Earl, Bomb and Superbomb, compared to the MC2-control runs respectively. This enhancement to sensible heat flux is due to the spray-mediated increase in air-sea temperature difference ΔT, and related cooler boundary layers due to spray evaporation.

It is important to investigate the linkage between surface-flux distributions and storm development and intensity. The significant spray impacts on heat fluxes that occur *during* the intensifying periods for Bomb (00UT on January 14 to 12 UTC on January 14) and Superbomb (00 UTC on January 21 to 18 UT on January 21) are notable. This is a positive feedback, by which winds are high and more spray droplets are ejected into the lower part of the atmosphere, during the storm's intensifying period, providing more energy for storm development.

5. Summary and Conclusions

A coupled atmosphere –wave – sea spray model system is used to evaluate the combined impacts of spray evaporation and wave drag on midlatitude storms. Our focus is on the role of air-sea fluxes on storm intensity and development, and related impacts on the structure of the atmospheric boundary layer. The composite model system consists of the Canadian Mesoscale

Compressible Community (MC2) atmospheric model coupled to the operational wave model WaveWatch**III** (WW3), and a recent bulk parameterization for heat fluxes due to sea spray. Case studies are extratropical hurricane Earl (1998) and two intense winter storms from 2000 and 2002, Superbomb and Bomb, respectively. Results show that sea spray tends to intensify storms, whereas wave-related drag tends to de-intensify. The mechanisms by which spray and wave-related drag can influence storm intensity are quite different. When wind speeds are high and sea surface temperatures (SSTs) warm, spray can significantly increase the surface heat fluxes. By comparison, momentum fluxes related to wave-drag are important over regions of the storm where young, newly generated waves are prevalent, for example during the rapid-development phase of the storm, and decreases in areas where the storm waves reach maturity. We show that the collective influence of spray and waves on storm intensity depends on their occurrence in the early stages of a storm's rapid intensification phase, and their spatial distribution and the storm center, and improves the simulation skill in modeling a given storm.

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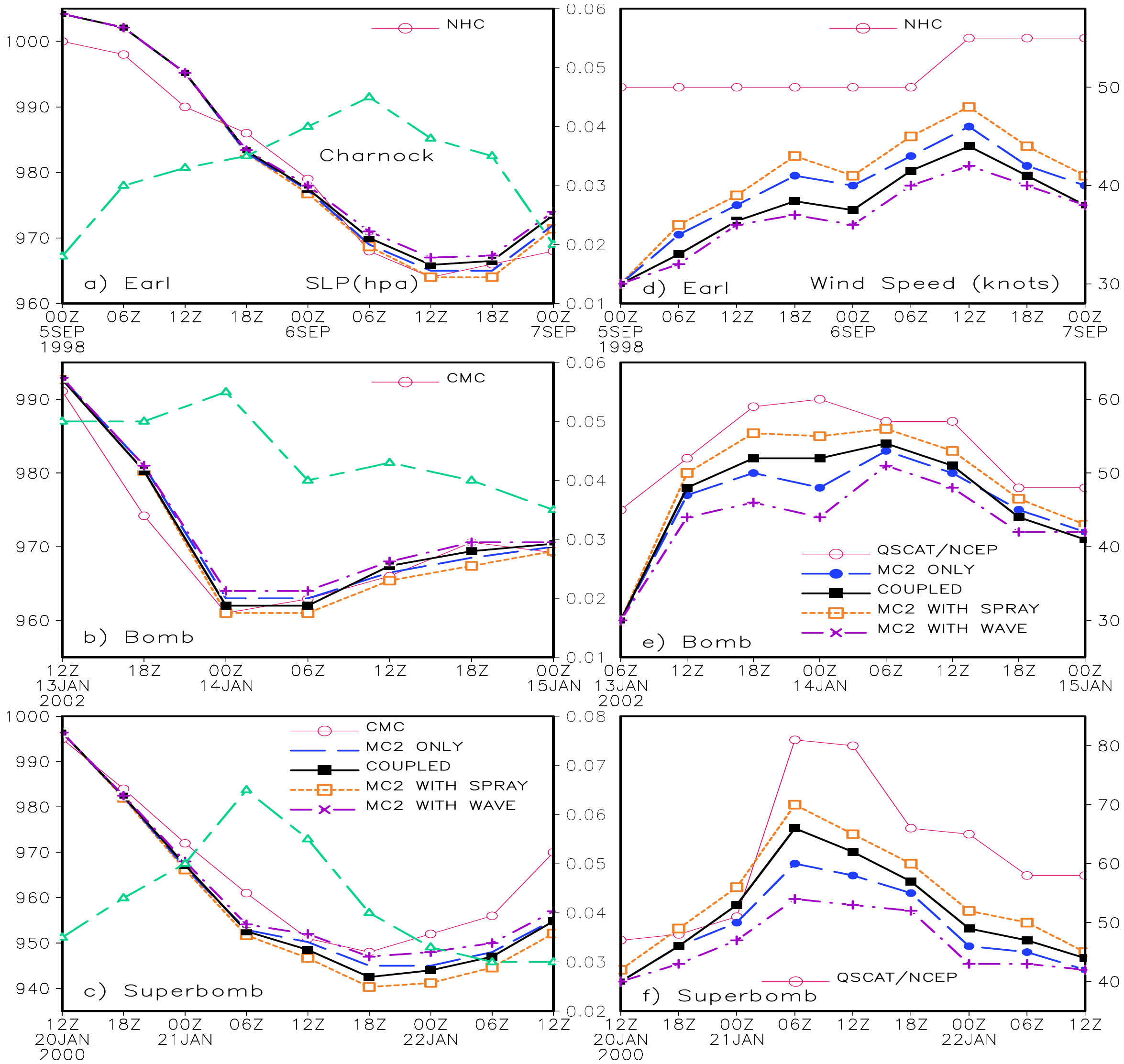

Figure 2. Minimum sea level pressure (SLP), and winds U_{10} time series for Earl (2a, 2d), Bomb (2b, 2e) and Superbomb (2c, 2f), following the storm tracks. Charnock parameter is indicated △— in (a)-(c).

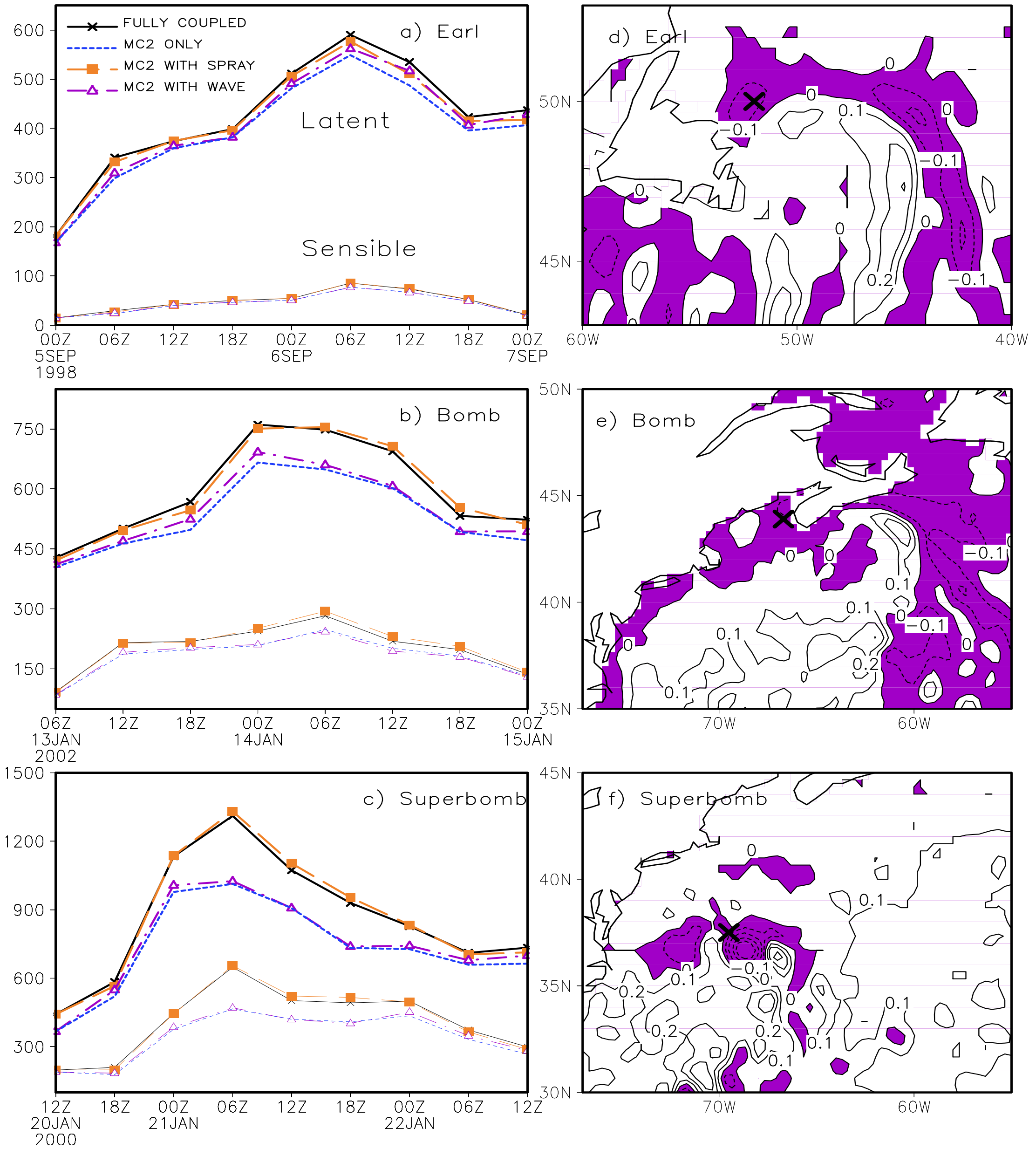

Figure 3. Time series for 200×200 km^2 area-averaged sensible (lower 4 time series) and latent (upper 4 time series) following maximal flux center storm with and without spray and waves, for (a) Earl, (b) Bomb, (c) Superbomb. The difference of specific humidity q between MC2-wave and MC2 runs are given in (d) for Earl on 06UTC 06 Sept., (e) Bomb on 00UTC 14 Jan., and (f) Superbomb on 00UTC 21 Jan