2.5 **IMPACT OF SEA SPRAY ON NUMERICAL SIMULATION OF EXTRATROPICAL HURRICANES**

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1. INTRODUCTION

Although the question as to whether or how sea spray affects the evolution of hurricanes has been around a long time, the answer has been remained elusive. Over 50 years ago, Riehl (1954) suggested that the sea spray provides a significant amount of the heat needed to generate and maintain a tropical storm. Since the 1970s, a new wave of scientists rediscovered the sea spray problem (Wu, 1973, 1974; Bortkovskii, 1973; Ling and Kao 1976). With the more resent Humidity Exchange over the Sea (HEXOS) program, new ideas, better instruments, and more powerful analytical tools were brought to bear on the study of sea spray (Katsaros et al., 1987; Smith, 1988; Rouault et al., 1991). However, despite the huge HEXOS effort, parameterization of sea spray and its contribution to heat fluxes at high wind speeds remains a challenging task, because the data are still quite scanty.

Andreas (1992) developed a simple model for the contribution of sea spray to sensible and latent heat fluxes. Fairall et al. (1994) then developed a parameterization scheme for use in numerical atmosphere models to study the effect of sea spray during hurricane development. Andreas (1998) later modified his simple model for application to high wind conditions. This led to the development of the Andreas and DeCosmo (1999) parameterization of sea spray suitable for high winds. These parameterization schemes make it possible to study the impact of sea spray on hurricanes with a coupled atmosphere /ocean modeling system. In many recent studies, the effects of sea spray mainly focus on tropical storms, not only because of the extreme wind speeds involved, but also because of high sea surface temperatures over the tropical ocean. In fact, Fairall et al. (1994) claimed that without taking into account evaporating spray droplets, the boundary layer of a modeled tropical cyclone evolves in an unrealistic manner. Kepert et al. (1999) and Bao et al. (2000) investigated the impact of spray on the development of a simulated hurricane using a coupled atmosphere-ocean-wave model. They found that the hurricane intensity is able to substantially increase. Wang et al. (2001) reported a moderate enhancement of the final intensity of a modeled tropical cyclone, because of spray.

By comparison, the effects of sea spray on extratropical storms seem to have received less attention in the literature. Quite recently, Meirink and Makin (2001) suggested that sea spray has significant impact on mid-latitude storms. More extensive studies in different model frameworks will help clarify the potential effects of sea spray on extratropical hurricanes. In this paper, two extratropical storms, ex-hurricane Earl (1998) and ex-hurricane Danielle (1998), are simulated using a coupled atmosphere-sea-spray modeling system. Our objective is to investigate how the sea spray affects simulations of extratropical hurricanes over the North Atlantic. In Section 2, the setup for the numerical simulations is outlined. This includes a description of the Canadian MC2 (mesoscale compressible community) model and the inclusion of a sea spray parameterization in it. The results of case studies using this modeling system are presented in Section 3. Concluding remarks are given in Section 4.

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2. MODEL DESCRIPTION

All numerical simulations for this study are performed using a coupled atmosphere-sea-spray model, constructed from a well tested mesoscale model, namely the Canadian MC2 model, and a bulk algorithm for turbulent air-sea fluxes with a parameterization scheme for sea spray in high winds. This section describes the MC2 model and the sea spray parameterization scheme.

2.1 The MC2 model

Our atmospheric model is the MC2 (version 4.9.3) model from the Meteorological Service of Canada (MSC) described in http://www.cmc.ec.gc.ca/rpn/modcom/index2.html. MC2 originates from of a limited-area model developed by Robert et al. (1985). It is a state-of-the-art fully-elastic nonhydrostatic model solving the full Euler equations on a limited-area Cartesian domain with time-dependent nesting of lateral boundary conditions, which are given by the large-scale model. It uses semi-Lagranigan advection and a semi-implicit time differencing dynamical scheme. Mainly due to its semi-implicit semi-Lagrangian scheme, the MC2 model is accurate and efficient. It has proven to be quite versatile as a modeling tool, allowing excellent simulations over a wide spectrum of scales (Benoit et al. 1997). It has also been well-tested for simulations related to hurricanes (Mctaggart-Cowan et al. 2001).

We run MC2 with a horizontal resolution of 30km and with 30 layers in the vertical. The lowest model level is located approximately 18m above the surface. The integration time step is 600-s. All simulations are initialized using the analysis data generated by the regional data assimilation system at CMC (Chouinard et al. 1994). A force-restore scheme, as described by Benoit et al. (1997), is used to calculate surface heat and moisture fluxes over land. Deep cumulus convection is parameterized using the Kain-Fritsch scheme.

2.2 Air-sea fluxes and sea spray parameterization

In MC2, the surface fluxes above the sea are calculated using Monin-Obukhov similarity theory. The resulting bulk formulations for the turbulent fluxes of momentum Ã, sensible heat Hs, latent heat H_L are

$$\Gamma = r_a C_D U_{zl}^2 \qquad (1)$$

$$H_s = r_a C_{pa} C_H U_{zl} (q_0 - q_{zl}) \qquad (2)$$

$$H_L = r_a L_n C_E U_{zl} (q_0 - q_{zl}) \qquad (3)$$

Here U_{zl} is the mean horizontal wind speed, q the potential temperature, q the specific humidity, r_a the density of air, C_{pa} the specific heat of moist air at constant pressure, and L_n the latent heat of evaporation of water. The heat fluxes are defined positive in the upward direction. The subscript z_l denotes the lowest model level, while 0 refers to the water surface. The exchange coefficients C_i(i = D, H, E) are determined from their neutral counterparts C_{iN} :

$$C_{DN} = \frac{k^2}{\ln^2(z_l / z_{0m})} \qquad (4)$$

$$C_{HN} = \frac{k^2}{\ln(z_l / z_{0m}) \ln(z_l / z_{0t})} \qquad (5)$$

$$C_{EN} = \frac{k^2}{\ln(z_l / z_{0m}) \ln(z_l / z_{0q})} \qquad (6)$$

where k is the von Kármán constant, and z_{0m}, z_{0t}, and z_{0q} are the roughness lengths for momentum, temperature, and humidity, respectively.

Our concern is microphysical modelling of air-sea processes, namely sea spray, related to heat and moisture transfer during severe storm conditions. Sea spray droplets in the range 1 to 500
the transfers of latent and sensible heat related to these droplets are essentially de-coupled – the sensible heat exchange occurs about three orders of magnitude faster than the latent heat

transfer. The ambient humidity has very little effect on the temperature scale and the sea surface temperature T_S has very little effect on the radius time scale because the droplet is at its equilibrium temperature T_{EQ} during most of its evaporation. These facts and related arguments of Andreas and Emanuel (2001) imply that sea spray can accomplish a net air-sea enthalpy transfer. Following Andreas and DeCosmo (2002), total air-sea latent and sensible heat fluxes are represented,

$$\Gamma_{sp} = 0.062 U_*^4 \quad (7)$$

$$H_{L,T} = H_L + Q_{L,sp} \quad (8)$$

$$H_{s,T} = H_s + Q_{S,sp} \quad (9)$$

where

$$Q_{L,sp} = \alpha \overline{Q}_L \quad (10)$$

$$Q_{S,sp} = \beta \overline{Q}_S - (\alpha - \gamma)\overline{Q}_L \quad (11)$$

are the spray fluxes. Γ_{sp} is the spray momentum flux. U_* the friction velocity. H_s and H_L, the turbulent or interfacial sensible and latent heat fluxes respectively, are the bulk aerodynamic estimates, $\overline{Q}_S$ and $\overline{Q}_L$ are 'nominal' values for spray sensible and latent heat fluxes, and α, β and γ are constants tuned with HEXOS data. Details of the computation of $Q_{S,sp}$ and $Q_{L,sp}$ are given in Andreas and DeCosmo (2002). Following Andreas and Emanuel (2001), the sea spray contributions to Equations (7)-(9) are given bulk formulae representations. Andreas (2003) provides more details of the bulk spray algorithm.

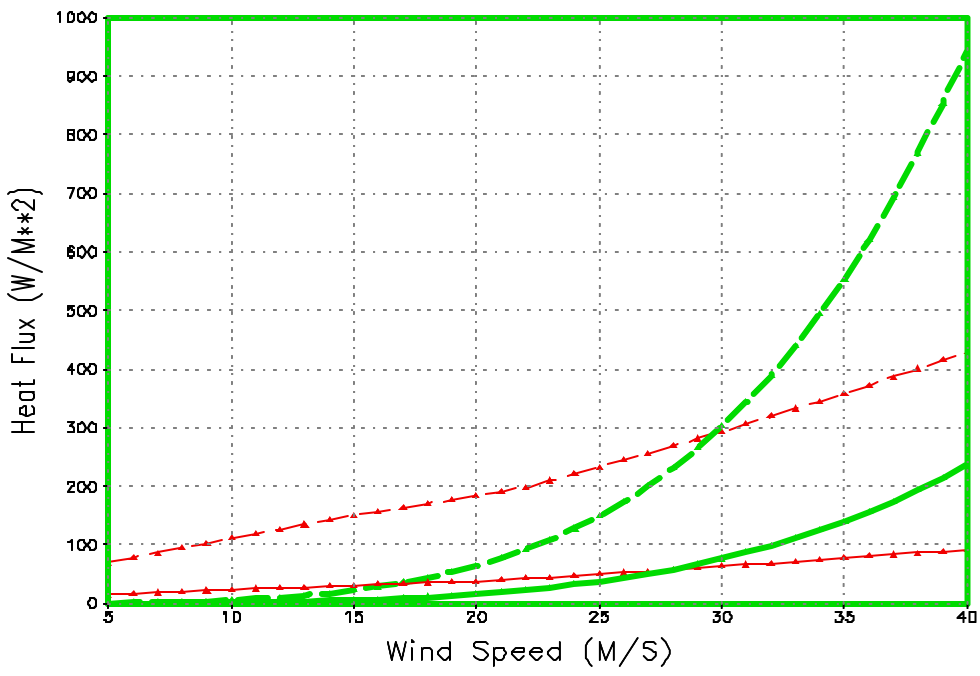


Fig. 1 Typical magnitude of the interfacial and spray-mediated sensible and latent heat flux over an extratropical area as a function of wind speed. The fluxes have been calculated for: RH= 80%, S=35psu, Ps=980hpa, Ta=15°C, SST=17°C. Thick dashed line is: $Q_{L,sp}$; Thin dashed line: H_L ; Thick solid line: $Q_{S,sp}$; Thin solid line: H_s

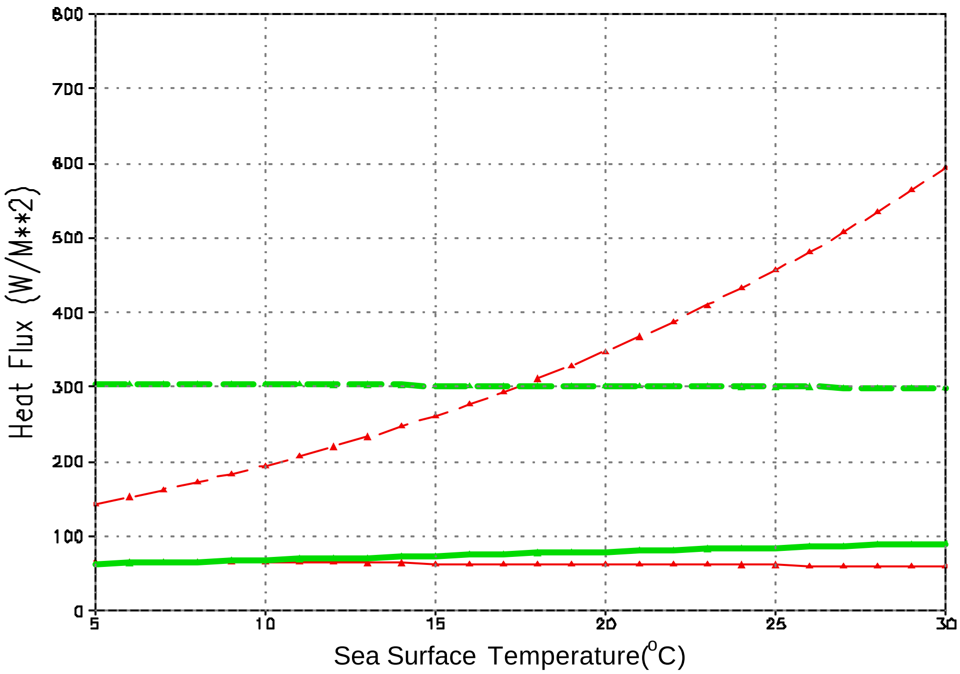


Fig. 2 Typical magnitude of the interfacial and spray-mediated sensible and latent heat flux as a function of sea surface temperature. The fluxes have been calculated for: U=30m/s, RH=80%, S=35psu, Ps=980hpa, Ta=SST-2°C. Thick dashed line: $Q_{L,sp}$; Thin dashed line: H_L ; Thick solid line: $Q_{S,sp}$; Thin solid line: H_s

To get an indication of the magnitude of the spray-mediated fluxes, the estimates H_s, H_L, $Q_{S,sp}$, and $Q_{L,sp}$ are plotted as a function of wind speed at 18m (the lowest model level in this study) in Fig. 1, and sea surface temperature (SST) Fig. 2. The conditions for the calculation of Fig. 1 are more or less typical for the hurricane seasons over the extratropical Atlantic. Figure 1 shows that spray-mediated latent heat fluxes increase much more rapidly with wind speed than the interfacial fluxes. It suggests that latent heat flux rather than sensible heat flux is the key factor in the influences of sea spray on hurricanes. The stronger the hurricane is, the more important the sea spray could be. It is interesting to note from Fig. 2 that the spray-mediated fluxes over a high SST area (tropical) have almost the same magnitudes as those over a relatively low SST area (extratropical). This implies that sea spray may play an important role in the evolution of either tropical or extratropical storms.

3. NUMERICAL RESULTS

In this section, two case studies using the coupled atmosphere-sea-spray modeling system are presented: ex-hurricane Earl (1998) and ex-hurricane Danielle (1998).

Hurricane Earl originated on 17 August from a tropical wave off the west coast of Africa. This evolved into a weak surface cyclonic circulation as the system passed through the Lesser Antilles on August 23. The large Hurricane Bonnie, at that time located over the southwest North Atlantic, inhibited the upper-level outflow of Earl, continuing through the Gulf of Mexico, the tropical wave became a tropical depression between Merida and Tampico, Mexico, on

August 31. This developed into Tropical Storm Earl about 930 km south-southwest of New Orleans and reached hurricane status on September 2. At that time, it was 230 km south-southwest of New Orleans. Maximum winds reached 189 km/hr and a minimum pressure of 850 mb was measured. Earl made landfall as a Category 1 hurricane near Panama City, Florida on September 3. While moving towards Georgia, the storm weakened quickly and became extra-tropical on September 3. It continued, crossing the Carolinas and intensifying over Atlantic Canada. By September 6, Earl crossed Newfoundland and by September 8 it was absorbed by a larger extra-tropical cyclone resulting from Hurricane Danielle.

Danielle had a long track across the Atlantic. It originated from a tropical wave on 21 August and became a hurricane by 1200 UTC 25 August over the middle tropical Atlantic. Danielle began to lose its tropical characteristics on 3 September, as its center passed about 200 nautical miles south of Cape Race, Newfoundland. It is estimated that Danielle became an extratropical storm with 65 knots wind speed by 0000 UTC 4 September. The storm moved eastward to east-northeastward across the north Atlantic for the next couple of days, and weakened only slowly. Danielle became indistinct when it merged with Earl on 8 September.

For both case studies, we run the model for two days from 0000 UTC 5 September 1998, with a 6-h nesting interval, producing forecasts up to 48-h.

3.1 Effects on surface fluxes

The evaporation of sea spray is expected to modify the heat fluxes across the air-sea interface at high wind speeds by perturbing the logarithmic profiles of temperature and humidity. One can see this estimated maxima of surface latent heat fluxes between simulations of our model 'with-sea-spray' and 'without-sea-spray (not shown here). The sea spray can increase latent heat fluxes from the ocean by about 20% in Earl, and by about 70% in Danielle. Since Danielle is stronger than Earl, it is suggested that sea spray is more important in a strong hurricane than in a relatively weak one.

3.2 Effects on the hurricane evolution: Storm track and intensity

In both storm cases, the 48-h simulations using the MC2-sea-spray model capture reasonably well the evolutions of the storm track and intensity. Figure 3 shows the comparison of

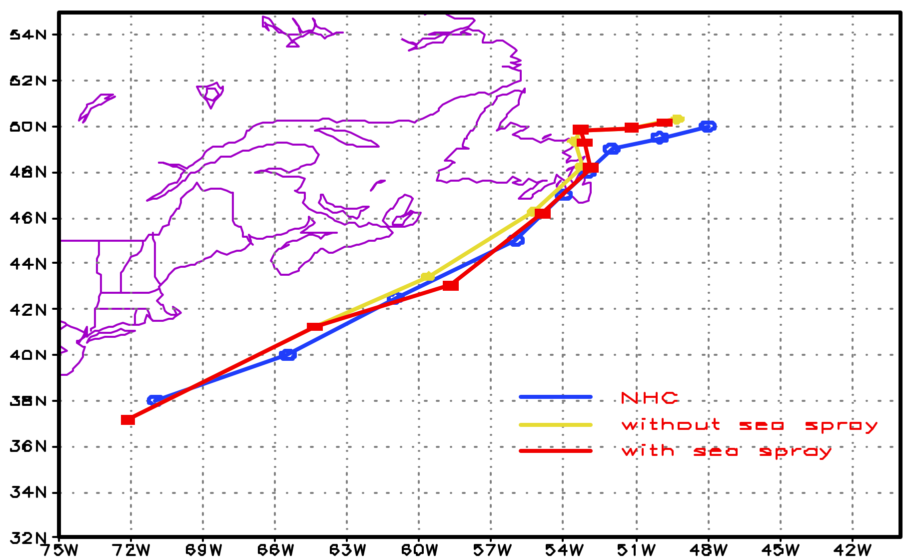
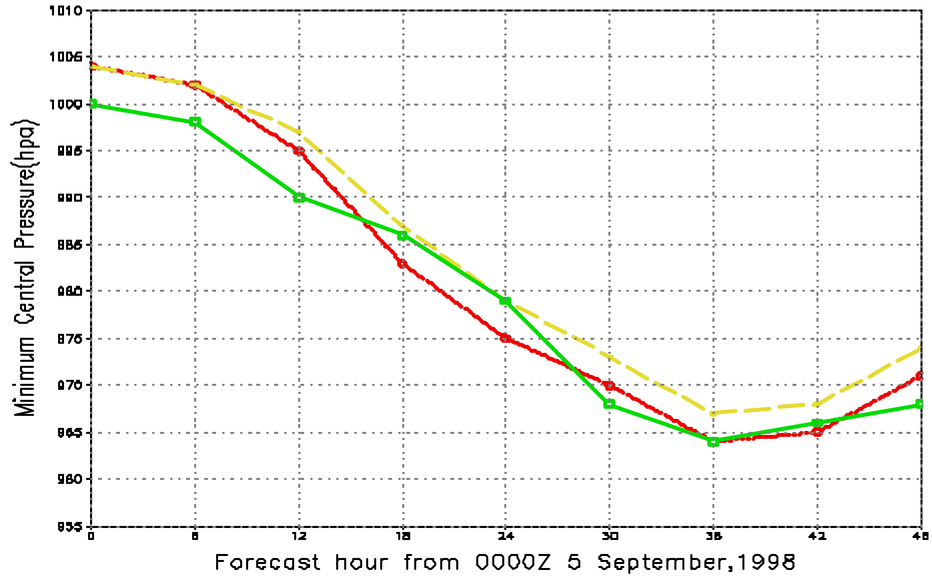
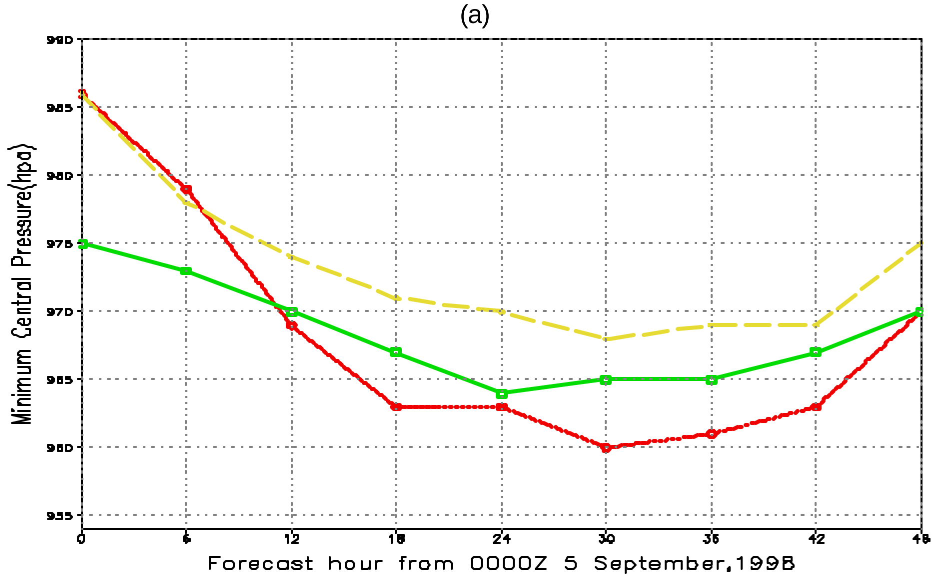


Fig. 3 Comparison of storm tracks of hurricane Earl: with and without sea spray simulations, as well as NHC analyses. Storm center locations are plotted every 6-h, beginning with 0000 UTC 5 Sept. 1998.



(a)

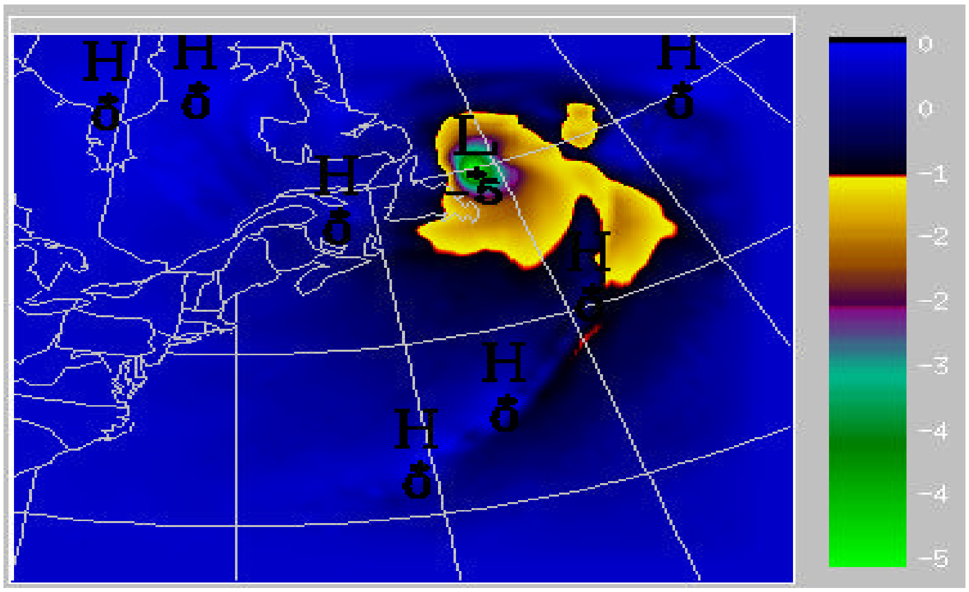


(b)

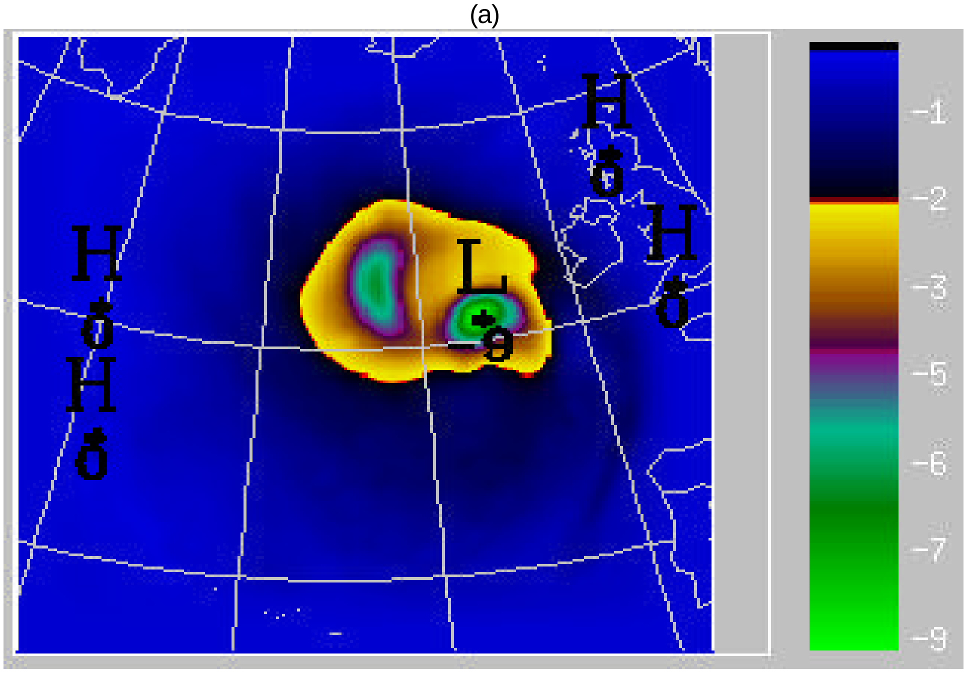
Fig. 4 Minimum sea level pressure time series for Earl (a) and Danielle (b). Solid green line is NHC analysis; dashed line is model simulation with no sea spray; solid red line is with sea spray.

the storm tracks of Earl, using the coupled and uncoupled sea-spray simulations, as well as the NHC (American National Hurricane Center) analyses. It is seen that, in both the coupled and uncoupled sea spray cases, the simulated tracks are quite close to the NHC analysis although it seems the modeled hurricane tracks move a little faster in the first 24 model hours and a little slower in the second 24 model hours. The simulated storm tracks of hurricane Danielle (not shown here) are also very close to those of the NHC analysis. It is interesting to note that, In our case studies, sea spray seems to have biased the storm track to the high-wind side of the hurricane.

In Figure 4 we give the minimum sea level pressure (SLP) over the hurricane center from coupled and uncoupled MC2/sea spray model simulations for Earl and Danielle. These are compared with NHC analysis. Figure 4(a) shows that the maximum impact of sea spray on SLP is about 5-mb near the peak of the Earl's intensity during its extra-tropical phase. Corresponding maximum 10-m wind speed increases are about 20% (8 knots) (not shown here). With Danielle, a relatively strong extratropical storm, the effects of sea spray are more significant. The maximum impact of sea spray on the SLP of Danielle is up to 9-mb, and a corresponding maximum increase in 10-m wind speed is about 30% (16 knots) (not shown here).



(a)



(b)

Fig. 5 Difference in SLP (hpa) between the simulations, with and without sea spray, at 30 model hours for (a) Earl; (b) Danielle

3.3 Effects on hurricane spatial structure: winds and sea level pressure

Both Earl and Danielle have very asymmetric wind fields. Before 1800 UTC 5 September 1998, the strongest winds of Earl remained well to the east and southeast of the center, while moving to Newfoundland, the strong winds were located to the north and northeast of the center. The wind field of hurricane Danielle is even more asymmetric than that of Earl, with its strongest winds mainly on the southern part of the hurricane. In section 2, we emphasized that spray-mediated-fluxes are highly dependant on wind speed, which suggests that the maximum effects of sea spray will occur in the strong wind zone of the hurricanes.

Figure 5 shows the SLP difference between the simulations with and without sea spray, after 30 model hours. It is noted that sea spray deepens the sea level pressure over the whole hurricane region. The maximum deepening of SLP, due to sea spray, is located on the high-wind side near the hurricane center, with a 5-mb decrease for Earl and a 9-mb decrease for Danielle. The comparisons of 10-m wind speeds between sea-spray simulations, compared to without-sea-spray simulations (not shown here) also indicate that the maximum enhancement of surface wind field is located on the high-wind side near the hurricane center.

4. CONCLUSIONS

In this study, the impact of sea spray on mesoscale numerical simulations of extratropical Atlantic hurricanes is investigated using a coupled atmosphere/ sea spray modeling system. Two case studies of extratropical hurricanes, Earl and Danielle from 1998, are analyzed. We found that: 1) sea spray can cause a significant latent heat flux increase of up to 20% of the interfacial fluxes in Earl, and up to 70% of the interfacial fluxes in Danielle; 2)Taking into account the effects of sea spray, the intensity of a modeled extratropical hurricane can be increased by 20% in 10-m wind speed in Earl, and 30% in Danielle; 3) the maximum deepening of SLP and the maximum enhancement of surface winds due to sea spray occurs on the high wind side near the hurricane center. Overall, sea spray has a notable impact on extratropical hurricane evolution. In both storms, the inclusion of sea spray parameterization improved estimates of storm maximum intensity, as indicated by NHC analysis. Moreover, it is recognized that these analysis fields often underpredict storm intensities (Mctaggart-Cowan et al. 2001).

Bearing in mind the complications of hurricane mechanisms, and the uncertainties in the spray parameterizations, we acknowledge that our study is very preliminary, and that we need to do further studies, with more extratropical hurricane case studies to identify the effects of sea spray.

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