The Effect of Sea Spray on Tropical Cyclone Intensity

Jeffrey S. Gall, Young Kwon, and William Frank*
The Pennsylvania State University
University Park, Pennsylvania 16802

1. Introduction

Under high-wind conditions, breaking waves and whitecaps eject sea spray droplets into the atmosphere. The spray droplets are of the same temperature and salinity as the ocean surface and thus increase the effective surface area of the ocean in contact with the atmosphere. This modification of the air-sea interface may play an important role in the transfer of latent and sensible heat, as well as in the transfer of momentum. The presence of high concentrations of liquid water in the lower boundary layer (BL) could have a substantial effect on tropical cyclone intensity because these disturbances are strongly dependent on the exchange of energy at the ocean surface.

The resulting sensible and latent heat fluxes from the spray are considered separately, which is a reasonable assumption since the time scale of latent heat transfer is much larger than the sensible heat transfer time scale. The thermodynamic feedbacks between a drop and the environment are also included because the latent and sensible heat fluxes from the drop modify the ambient temperature and humidity profile. This modification, in turn, affects the interfacial fluxes because these fluxes are dependent upon the ambient conditions. Sea spray is also a small, yet significant, momentum sink. When spray is ejected into the near-surface layer, it is accelerated to the environmental wind speed. The spray droplets then fall back to the sea and serve to transfer momentum from the atmosphere to the ocean.

Wang et al. (2001) evaluated the effect of parameterized sea spray on tropical cyclone BL structure and intensity using a high resolution tropical cyclone model (TCM3) developed by Wang (1999). The authors tested two spray droplet parameterizations - the Fairall et al. (1995) scheme and the Andreas and DeCosmo (1999) scheme. When the Fairall et al. (1995) parameterization is used in the simulation, the total enthalpy flux increases by approximately 20%, and the maximum wind speed of the model tropical cyclone increases by 8%. Results from the Andreas and DeCosmo parameterization, however, unrealistically enhance the maximum wind speeds by 25%. Andreas and Emanuel (2001) demonstrated that spray is important in both the transfer of enthalpy and momentum between the air and sea in high wind conditions. The authors found that including both enthalpy and momentum effects due to spray produces model results similar to simulations with no spray and no drag effects. Bao et al. (2000) employed a coupled atmosphere-ocean modeling system to simulate air-sea interaction under high wind conditions. Results from model simulations with and without sea spray demonstrate that the inclusion of sea spray evaporation can significantly increase hurricane intensity when the part of the spray that evaporates is only a small fraction of the total spray mass.

Sensitivity tests were performed on an idealized, axisymmetric hurricane as described by Kwon and Frank (2005) by altering the spray source function to increase or decrease the amount of spray generated. Simulations were also conducted with and without a simple horizontal spray momentum parameterization. Results indicate that the inclusion of sea spray has non-linear effects on the net sensible and latent heat fluxes. The near-surface wind speed is also modified by spray. The intensity of the idealized hurricane varied significantly depending upon both the amount of sea spray and horizontal spray drag effects.

*jsg229@psu.edu

2. Flux Equations

The total sensible heat flux $H_{s,tot}$ realized at the top of the droplet evaporation layer is

$$H_{s,tot} = H_s + H_{s,feed} + Q_s + H_{se} - Q_l \quad (1)$$

where H_s is the bulk interfacial surface sensible heat flux, Q_s is spray-to-air sensible heat flux, $H_{s,feed}$ is the change in the interfacial sensible heat flux owing to the modification of the ambient environment from spray effects, H_{se} is the frictional heating in the near-surface layer owing to sea spray effects, and Q_l is the spray-to-air latent heat flux. This last term is included in equation (1) because a spray droplet must extract as much sensible heat from the near-surface layer as it gives up in latent heat (Andreas 1995).

The total latent heat flux realized at the top of the droplet evaporation layer is

$$H_{l,tot} = H_l + H_{l,feed} + Q_l \quad (2)$$

where H_l is the bulk interfacial surface latent heat flux, $H_{l,feed}$ is the change in the interfacial latent heat flux owing to the modification of the ambient environment from spray efforts, and Q_l is the spray-to-air latent heat flux. It should be noted that H_s and H_l are calculated in the model boundary layer scheme. All other terms on the right hand side of(1) and (2) are calculated from the Fairall et al. (1995) spray parameterization.

3. Spray Momentum Parameterization

The simple spray momentum parameterization is based on the conservation of momentum. It was assumed that sea spray only has a direct impact on the lowest level wind field, with the higher levels modified through vertical diffusion of momentum. Before the injection of spray into the atmosphere, the momentum in the lowest level (M_i) is given by,

$$M_i = m_{a,i} V_i, \quad (3)$$

where $m_{a,i}$ is the initial mass of air in a grid box and V_i is the initial wind speed of the lowest layer. After injecting sea spray into the atmosphere, some of the momentum in the lowest model layer is transferred to the sea spray before the spray falls back to the sea. The momentum in the lowest level (M_f) is now,

$$M_f = m_{a,f} V_f + m_s V_f, \quad (4)$$

where $m_{a,f}$ is the final mass of air in a grid box, m_s is the total spray mass in a grid box, and V_f is the final wind speed of the lowest layer after adjusting to the injected spray. Equating (3) and (4) and solving for V_f gives

$$V_f = \frac{m_{a,i}}{m_s + m_{a,f}} V_i. \quad (5)$$

A reasonable assumption to invoke is that $m_{a,f} = m_{a,i}$ because the total spray volume in a grid box is too small to modify the density of air. Thus, (5) can be rewritten as

$$V_f = \frac{m_{a,i}}{m_s + m_{a,i}} V_i. \quad (6)$$

The variables V_i and $m_{a,i}$ can be computed from standard variables used in the model. The spray mass (m_s), however, is estimated from the spray mass flux, which is calculated by the Fairall et al. (1995) spray parameterization.

4. Experimental Design

An axisymmetric control hurricane was created from the output of a real-data simulation of Hurricane Floyd (1999) as described in Kwon and Frank (2005) using the Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) nonhydrostatic fifth-generation Mesoscale Model version 3.4 (MM5V3.4).

Table 1: Summary of the MM5 simulations used in this study.

Experiment	Spray Source Strength (ζ)	Spray Drag
1	0	No
2	0.3	No
3	0.3	Yes
4	1.5	No
5	1.5	Yes

The model was run in a one-way nested fashion with a coarse grid domain of 162-km horizontal resolution covering most of the Atlantic Ocean, North America, and South America; a nested 54-km grid covering the eastern half of the United states and most of the Atlantic basin; a nested 18-km grid covering most of the Atlantic ocean; and a nested, high-resolution 6-km grid in the western Atlantic centered on 17°N latitude. The model implements the full-physics Blackadar boundary-layer scheme (Blackadar 1976, 1979; Zhang and Anthes 1982) and employs the simple ice (Dudhia) explicit moisture scheme for grid-scale precipitation. The Kain-Fritsch convective scheme (Kain and Fritsch 1995) was implemented for all grids except the 6-km domain. At this domain size, convection is assumed to be resolved explicitly, and no cumulus parameterization is needed. The cloud radiation scheme was implemented for all domains. Twenty-four hours of output were averaged, and the axisymmetric storm is then placed in a zero-flow environment on an f-plane. The sea surface temperature is kept constant at a value of $29°C$.

Several model simulations were conducted in order to explore the sensitivity of the results to variations in the employed parameterization, as listed in Table 1. The sensitivity tests are performed by altering the source function strength (ζ) variable in the spray parameterization, which is essentially the amount of spray generated for a specific surface wind speed. The effects of sea spray drag are also explored through the drag parameterization described in the previous section. All model simulations were integrated for a 48-hour period. The control simulation (EXP1) was run with no spray parameterization. Experiments two (EXP2) and three (EXP3) employed the modified Fairall et al. (1995) spray parameterization, but neglected spray momentum drag effects. EXP2 used the suggested spray source function strength of Fairall. EXP3 is the same as EXP2 except that the spray source function strength is five times as large in order to account for the uncertainty in the magnitude of the spray source function. Experiments four (EXP4) and five (EXP5) are the same as EXP2 and EXP3 except that the simulations also incorporate the spray drag parameterization.

5. Results and Conclusions

As small amounts of spray are ejected into the atmosphere, sea spray has little net effect on the total sensible heat flux, but increases the total latent heat flux. The effects of small spray amounts result in a net increase in the enthalpy flux which, in turn produces a stronger simulated hurricane as shown in Fig. 1. Sea spray serves to warm the near-surface layer through net spray-to-air sensible heat transfer. The feedback effect of BL cooling from spray evaporation is small in comparison to the warming from the spray-to-air sensible heat flux. Introducing spray drag effects reduces the surface winds by 2-3 m s^{-1}. Spray drag effects have significant effects on storm intensity for moderate amounts of spray after *t* = 24hr. Since the spray heat fluxes are strongly dependent on wind speed, a slight decrease in wind speed by *t* = 30hr results in a decrease in the magnitude of the spray fluxes. This decrease in the magnitude of spray fluxes causes a net decrease in the enthalpy flux and ultimately a decrease in hurricane intensity.

As more spray is added into the near-surface layer, the non-linearity effects of spray become apparent. The total latent heat flux further increases because of the increase in the spray-to-air latent heat flux. The total sensible heat flux, however, decreases for heavier spray amounts because the spray-to-air latent heat flux is subtracted from the total sensible heat flux budget.

The large increase in the spray-air latent heat flux for the heavy spray mass flux (EXP4 and EXP5) implies that the ambient feedback effects on the evaporation of spray are relatively small. The BL remains subsaturated and large amounts of spray continue to evaporate. The surface net enthalpy flux increases and the modeled hurricane strengthens further. For even larger amounts of spray, there must be a point at which the BL becomes saturated and feedback effects become large. At this point, the spray-air latent heat flux would reach an upper limit and prevent the net enthalpy flux from further increasing. The small decrease in wind speed (2-3 m s^{-1}) owing to drag effects for large amounts of spray has no effect on the net enthalpy flux. For large amounts of spray, a decrease in the total latent heat flux is counteracted by an increase of similar magnitude in the total sensible heat flux.

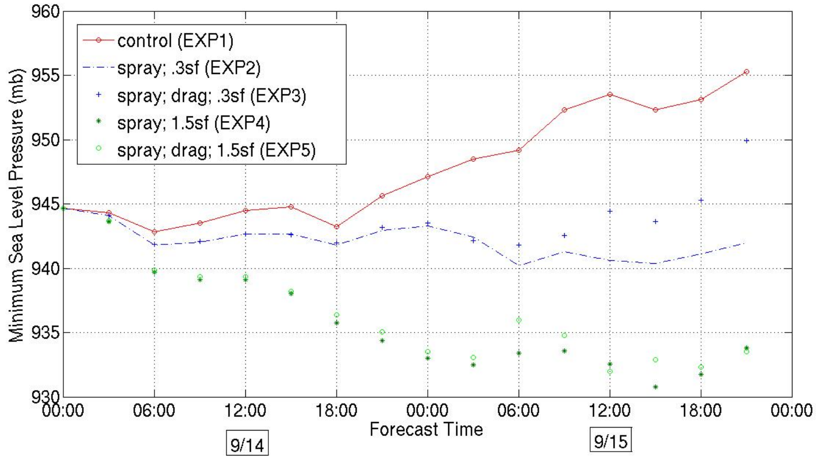

Figure 1: Time series of the minimum sea level pressure for EXP1 and EXP2.

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