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Modelling Air-Sea Fluxes during a Western Pacific Typhoon: Role of Sea Spray

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ABSTRACT

It has long been recognized that the evolution of marine storms may be strongly affected by the flux transfer processes over the ocean. High winds in a storm can generate large amounts of spray, which can modify the transfer of momentum, heat, and moisture across the air-sea interface. However, the role of sea spray and air-sea processes in western Pacific typhoons has remained elusive. In this study, the impact of sea spray on air-sea fluxes and the evolution of a typhoon over the western Pacific is investigated using a coupled atmosphere-sea-spray modeling system. Through the case study of the recent Typhoon Fengshen from 2002, we found that: (1) Sea spray can cause a significant latent heat flux increase of up to 40% of the interfacial fluxes in the typhoon; (2) Taking into account the effects of sea spray, the intensity of the modeled typhoon can be increased by 30% in the 10-m wind speed, which may greatly improve estimates of storm maximum intensity and, to some extent, improve the simulations of overall storm structure in the atmospheric model; (3) The effects of sea spray are mainly focused over the high wind regions around the storm center and are mainly felt in the lower part of the troposphere.

Key words: air-sea flux, sea spray, typhoon

1. Introduction

China is one of the countries that is most vulnerable to typhoons. Millions of people live along the coastline and are exposed to the threat from wind, rain, storm surges, and severe weather caused by western Pacific typhoons. During the last two decades, the theory of typhoon evolution has been investigated extensively. In particular, large efforts were focused on the effects of large-scale circulation, typhoon structure, and terrain, etc on the evolution of the typhoon (see the review in Meng et al., 2002). By comparison, the role of air-sea exchange processes in western Pacific typhoons seems to have received less attention in the earlier studies.

Indeed, typhoons are known as powerful 'engines' that convert energy extracted from the ocean into the air. Momentum and heat flux transfer at the air-sea interface has long been recognized as an important element to generate and maintain a typhoon (Riehl, 1954). Flux transfer processes over the ocean are commonly parameterized using Monin-Obhukov similarity theory. However, during high wind conditions in a typhoon, a complicating factor is present because large amounts of sea spray are produced by both bursting air bubbles in whitecaps and whipping spume from the tips of waves. Through the evaporation of spray droplets, the fluxes might be significantly modified, which can, in turn, affect the evolution process of the typhoon. 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 recent 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 large HEXOS effort, the 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 param-

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eterization 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 cyclones or hurricanes over the Atlantic. 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. Quite recently, modeling results (e.g., Meirink and Makin, 2001; Li et al., 2003) even suggest that sea spray can significantly increase air-sea heat flux and storm intensity of extra-tropical hurricanes over the Atlantic. However, the exact role of sea spray in western Pacific typhoons remains unclear.

In this paper, a western Pacific typhoon in 2002, Typhoon Fengshen, is simulated using a coupled atmosphere-sea-spray modeling system. Our objective in this study is to investigate whether the sea spray can affect the western Pacific typhoon and to determine what the sea spray effects are. 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 the medel. The results of a case study using this modeling system are presented in section 3. Concluding remarks are given in section 4.

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*

The 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 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 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 seconds. All simulations are initialized using the analysis data generated by the regional data assimilation system at Canadian Meteorological Center (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. For case studies presented here, MC2 simulations used a 6-h nesting interval to produce forecasts up to 48 h. No bogus initialization model was implemented.

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 Γ, sensible heat $H_{\rm s}$, and latent heat $H_{\rm L}$ are

$$\Gamma = \rho_{\rm a} C_D U_{\rm z_1}^2 \, , \qquad (1)$$

$$H_{\rm s} = \rho_{\rm a} C_{\rm pa} C_H U_{\rm z_1}(\theta_0 - \theta_{\rm z_1}) \, , \qquad (2)$$

$$H_l = \rho_{\rm a} L_\nu C_E U_{\rm z_1}(q_0 - q_{\rm z_1}) \, . \qquad (3)$$

Here, $U_{\rm z_1}$ is the mean horizontal wind speed, θ the potential temperature, q the specific humidity, $\rho_{\rm a}$ the density of air, $C_{\rm pa}$ the specific heat of moist air at constant pressure, and L_ν the latent heat of evaporation of water. The heat fluxes are defined as positive in the upward direction. The subscript $z_{\rm l}$ denotes the lowest model level, while 0 refers to the water surface. The exchange coefficients C_i ($i = D, H, E$) are determined

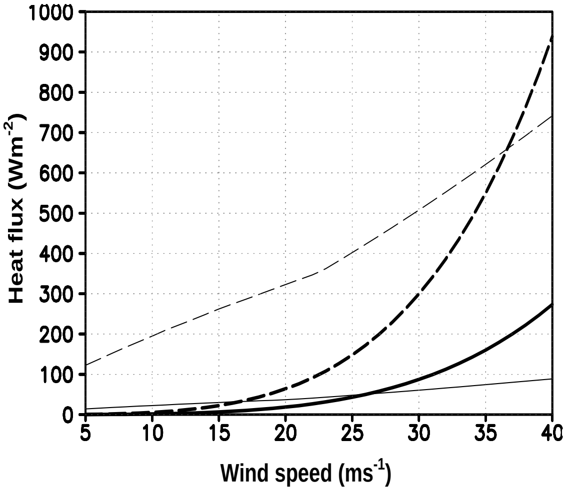

Fig. 1. Typical magnitude of the interfacial and spray-mediated sensible and latent heat fluxes as a function of wind speed. The fluxes have been calculated for: RH=80%, S=35 psu, P_s=980 hPa, $t_a = 25°$C, SST=27°C. Thick dashed line is $Q_{L,sp}$; Thin dashed line: H_L ; Thick solid line: $Q_{S,sp}$; Thin solid line: H_s.

from their neutral counterparts C_{iN}:

$$C_{DN} = \frac{\kappa^2}{\ln^2(z_l/z_{0m})} , \tag{4}$$

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

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

where κ 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 the 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 μm are important for this process. However, the transfers of latent and sensible heat related to these droplets are essentially decoupled–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 has very little effect on the radius timescale because the droplet is at its equilibrium temperature 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 momentum, and latent and sensible heat fluxes are represented

$$\Gamma_T = \Gamma + \Gamma_{sp} , \tag{7}$$

$$H_{L,T} = H_L + Q_{L,sp} , \tag{8}$$

$$H_{S,T} = H_S + Q_{S,sp} , \tag{9}$$

where

$$\Gamma_{sp} = 0.062U_*^4 , \tag{10}$$

$$Q_{L,sp} = \alpha\overline{Q}_L , \tag{11}$$

$$Q_{S,sp} = \beta\overline{Q}_S - (\alpha - \gamma)\overline{Q}_L \tag{12}$$

are the spray fluxes. Γ_{sp}, $Q_{S,sp}$, and $Q_{L,sp}$ are the sea-spray-mediated momentum flux, sensible heat flux, and latent heat flux, respectively. U_* is the friction velocity. $\bar{Q}_S$ and $\bar{Q}_L$ are 'nominal' values for spray sensible and latent heat fluxes, and α, β, and γ are

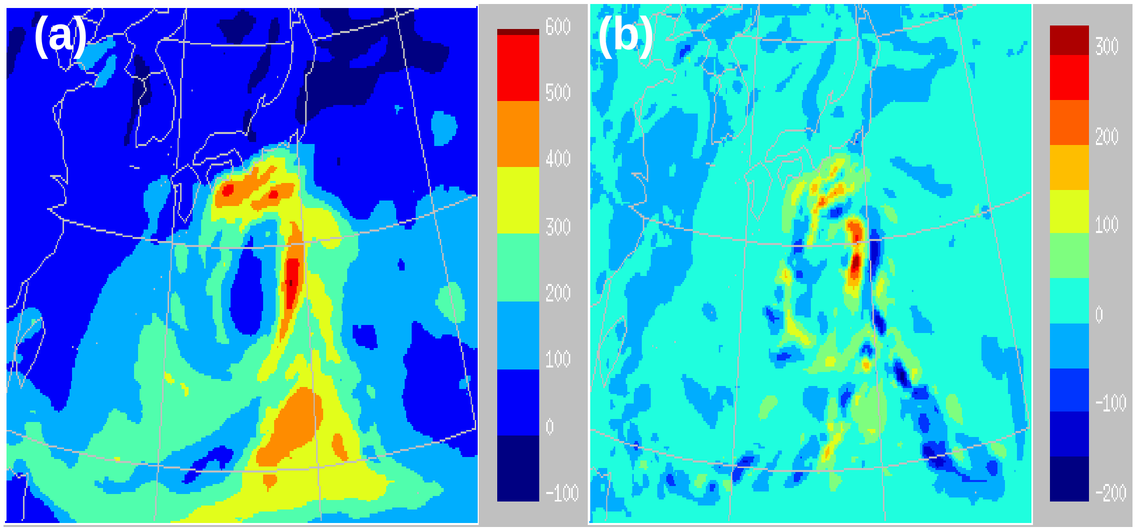

Fig. 2. Impacts of sea spray on latent heat flux at 0018 UTC 24 July 2002. (a) latent heat flux including effects of sea spray, (b) difference in latent heat flux with sea spray minus that without sea spray in the model simulation. (Units: W m^{-2})

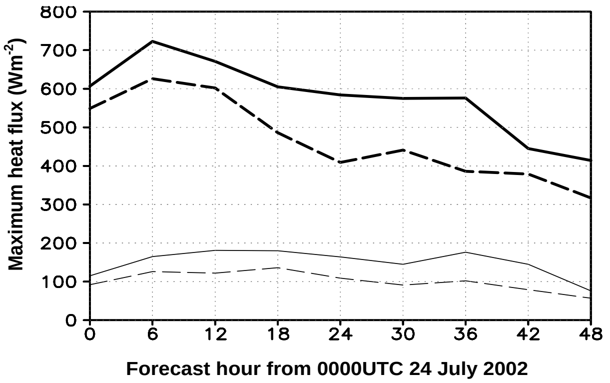

Fig. 3. Time series of maximum latent and sensible heat fluxes with and without sea spray, following the storm track. Thick solid line: latent heat fluxes with sea spray; Thick dashed line: latent heat fluxes without sea spray; Thin solid line: sensible heat fluxes with sea spray; Thin dashed line: sensible heat fluxes without sea spray. (Units: W m^{-2})

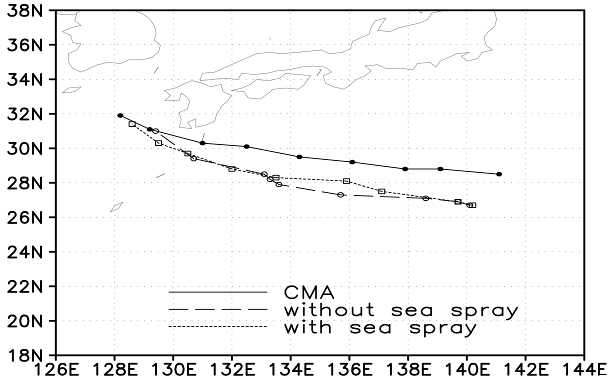

Fig. 4. Comparison of storm tracks of Typhoon Fengshen with and without sea spray simulations as well as CMA analysis. Storm center locations are plotted every 6 h. Simulation for Fengshen begins on 0000 UTC 24 July 2002.

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 by bulk formulae representations. Andreas (2003) provides more details of the bulk spray algorithm.

2.3 *Variation as a function of wind speed*

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 functions of wind speed at 18 m (the lowest MC2 model level in this study) in Fig. 1. The conditions for the calculation of the figure are more or less typical for the typhoon seasons over the western Pacific. It shows that the spray-mediated latent heat fluxes increase much more rapidly with wind speed than the interfacial fluxes. This supports the suggestion that latent heat fluxes rather than sensible heat fluxes are the key factor in the influences of sea spray on typhoons. The stronger the typhoon is, the more important the sea spray can be. Above the approximate typhoon-threshold wind speed, approximately 30 m s^{-1}, $Q_{L,sp}$ increases rapidly with increasing winds in this formulation.

3. Numerical results

While most earlier studies were concerned with the effects of sea spray on Atlantic hurricanes, we consider western Pacific typhoons. A recent typhoon case, super typhoon Fengshen from 2002, is investigated using the coupled atmosphere-sea-spray modeling system described in section 2 to show the impact of sea spray.

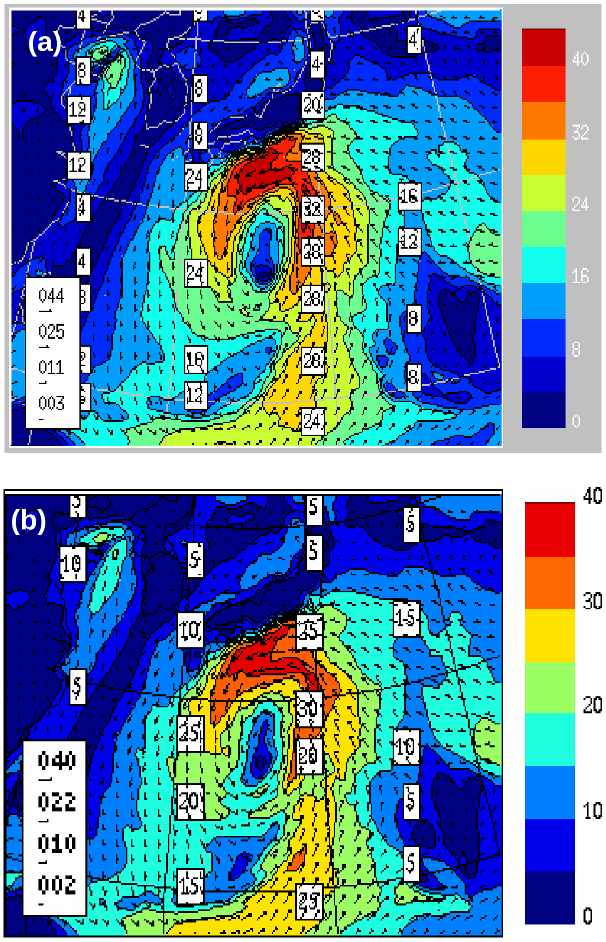

Fig. 5. 10-m winds: (a) simulation with sea spray, (b) simulation without sea spray, and (c) QUIKSCAT/NCEP blended wind fields. The three plots are at 0018 UTC 24 July 2002. The storm center is approximately at (28°N, 136°E) in the three plots. (Units: knots or 0.514 m s^{-1}).

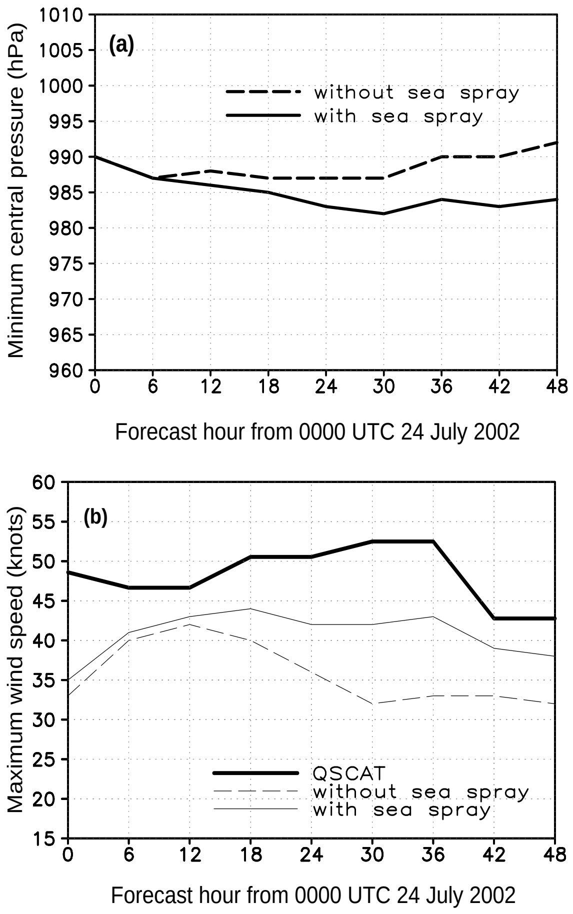

Fig. 6. (a) Minimum sea level pressure (SLP) (hPa) (a) and (b) 10-m wind speeds (Units: knots or 0.514 m s^{-1}) time series for Fengshen.

Typhoon Fengshen was the 9th typhoon of 2002, which formed on 14 July 2002 and became indistinct on 27 July 2002. The super typhoon Fengshen was a true monster over the western Pacific. Packing sustained winds up to 260 km h^{-1} made it a veritable Category 5 typhoon on the Saffir-Simpson scale, the worst our atmosphere is capable of. It would have easily caused catastrophic damage if it had reached land. Peak gusts were likely to reach up to 320 km h^{-1}. Storm surge and winds were likely to produce waves of 15 m and higher. Luckily Fengshen occured far off shore away from any populated areas.

In this study, we integrate the model from 0000 UTC 24 July 2002 to produce forecasts up to 48 h. Two experiments-simulations with and without sea spray-are carried out to evaluate whether and how the sea spray affects the air-sea fluxes and the evolution of the typhoon.

3.1 *Effects on surface fluxes*

To explain the sea spray impact on typhoon evolution we must describe the effects of sea spray on surface

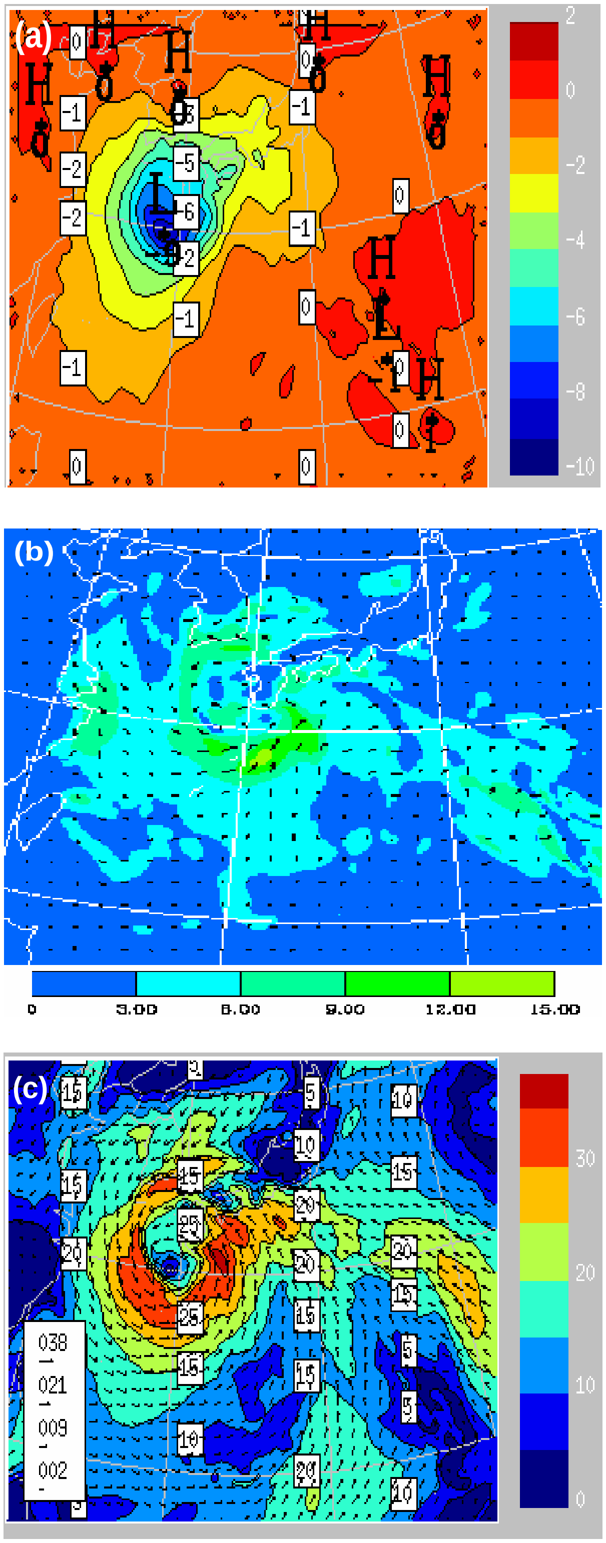

Fig. 7. (a) Differences in SLP (hPa) and (b) 10-m winds (knots) between the simulations, with and without sea spray, for Fengshen at 0000 UTC 26 July 2002, and (c) corresponding 10-m winds from the MC2 simulation with sea spray (Units: knots or 0.514 m s^{-1}).

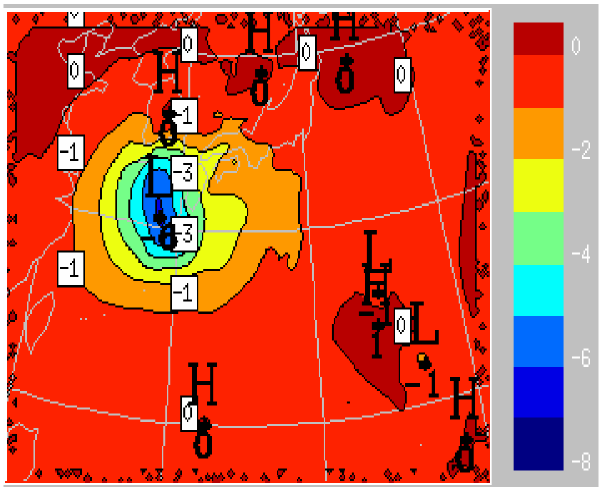

Fig. 8. Difference in 500 hPa height(dam), for simulations with and without sea spray at 0000 UTC 26 July 2002.

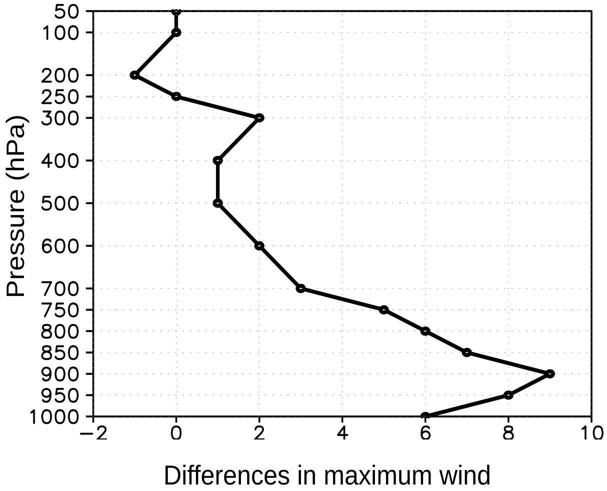

Fig. 9. Vertical profile of differences in maximum wind speed between simulations with and without sea spray, at 0000 UTC 26 July 2002. (Units: knots or 0.514 m s^{-1}).

fluxes. Figures 2a–b present the spatial distribution of the latent heat flux pattern and differences of latent heat fluxes, with and without sea spray, at the peak intensity of Fengshen's life cycle for the simulation with sea spray, 0018 UTC 24 July 2002. The figures demonstrate that latent heat flux has maximum values over the high wind regions around the storm center (Fig. 2a). This is also the region where the differences between latent heat fluxes (Fig. 2b), with and without the sea spray, have their maximum values, providing the mechanisms to intensify the storm, following Andreas and Emanuel (2001). Regions with negative values for the difference in latent fluxes in these two simulations are the result of small differences in the storm tracks.

The immediate impact of sea spray is to modify the heat fluxes across the air-sea interface through evaporation, as discussed by Andreas and Emanuel (2001). In Fig. 3, we show the time series of maximum latent and sensible heat fluxes for Typhoon Fengshen, following its actual and modeled storm tracks. It can be seen from the figure that for much of the Fengshen evolutions, the sea spray impacts on latent heat are on the order of about 100 W m^{-2}. The effect is significantly larger during model hours 24–36th when the surface 10-m winds experience the maximum differences between the simulations without and with sea spray (see Fig. 6b). The maximum increase of latent heat flux caused by sea spray can be up to 180 W m^{-2} (about 40%). The sea spray impact on sensible heat flux is much smaller compared to the impact on latent heat flux. For most model hours, spray sensible heat flux $Q_{\mathrm{S,sp}}$ is only about 25% of the corresponding latent heat flux $Q_{\mathrm{L,sp}}$ values. The maximum differences in sensible heat flux between the simulations with and without sea spray is only about 80 W m^{-2}. This suggests that sea spray affects the typhoon mainly by increasing latent heat flux across the air-sea interface.

3.2 *Effects on the typhoon evolution and spatial structure*

In the 48-h simulations, the MC2 model captures the evolution of the storm track reasonably well. Figure 4 shows a comparison of the storm tracks of Typhoon Fengshen from the coupled and uncoupled sea-spray simulations, as well as from the China Meteorological Administration (CMA) analysis. This shows that in both the coupled and uncoupled sea spray cases, the simulated tracks are quite close to the CMA analysis, although it seems the modeled typhoon track are displaced a little to the south of the CMA analysis tracks especially in the first half of the simulation. It is interesting to note that in our case study, sea spray seems to have biased the storm track a little to the high-wind side of the storm, particularly at the 18th model hour. This reflects the dominance that wind speed has on the sea spray formulation.

To verify whether the MC2 model gives a good baseline simulation of Typhoon Fengshen and to show whether the sea spray parameterization used in the model improves the overall structure of the simulated storm, we present a comparison of the MC2 simulations of the 10-m wind, with and without sea spray, to the Quick Scaterometer/National Center for Environmental Prediction (QUIKSCAT/NCEP) blended wind, available from Colorado Research Associates, USA, in Figs. 5a–c. This is for 0018 UTC 24 July 2002. Although the spatial projections for the QUIKSCAT/NCEP blended product and MC2 winds differ, the overall structure of the wind fields are quite similar. The simulations, with and without sea spray, and the QUIKSCAT/NCEP blended wind estimate almost the same storm centers at approximately (28°N, 136°E), and bear similar asymmetric structures with the high winds mainly to the northern part of the storm. It is worth mentioning that the simulated Typhoon Fengshen with sea spray included (Fig. 5a) is much more similar to the 'observations' (Fig. 5c), compare to the simulations without sea spray (Fig. 5b), which suggests that the sea spray parameterization used in the model may improve, to some extent, the overall structure of the simulated storm.

While the overall impact of sea spray on the storm track is small, the impact on storm intensity is rather significant. In Figs. 6a–b, we give the minimum sea level pressure (SLP) and corresponding maximum 10-m wind speeds over the storm center from simulations with and without sea spray for Typhoon Fengshen along the storm tracks. The Figures show that sea spray can increase the model storm intensity quite significantly. The maximum impact of sea spray on SLP is about 8 hPa at the final model hour. The maximum increase due to the inclusion of sea spray on the surface 10-m wind speed is about 30% (10 m s^{-1}, or 19 knots). It is notable that with sea spray included in the typhoon simulation, the modeled wind speed is much more close to the observation wind field (e.g., QuikSCAT surface wind), while the simulation without sea spray has greatly under-predicted the maximum wind in the typhoon. It is suggested that the inclusion of the sea spray parameterization can improve the estimates of storm maximum intensity in atmospheric models.

In section 2, we emphasized that spray-mediated fluxes are highly dependent on wind speed, which suggests that the maximum effects of sea spray will occur in the strong wind zone of the typhoon. The contour plots of differences in SLP and 10-m winds for simulations with and without sea spray and the corresponding wind fields are given in Figs. 7a–c. The figures show that sea spray deepens the sea level pressure over the whole storm region. In these plots, the maximum deepening of SLP due to sea spray is located on the high wind side near the storm center, with a 9-hPa maximum decrease at the 48th model hour (Fig. 7a). Besides the effects on SLP, sea spray increases surface winds over the whole storm region. The maximum increase of the 10-m winds is also located mainly over the south of the storm center, where the high wind zone of Typhoon Fengshen is at that moment (see Fig. 7c).

The effects of sea spray diminish with increasing height. In Fig. 8, we present the difference plots for 500-hPa heights corresponding to the difference plots for SLP in Fig. 7a. This shows a relatively weak signal for sea spray. Vertical profiles for maximum wind speeds, comparing the differences in simulations with and without sea spray (Fig. 9), also show that the effects of sea spray are mainly felt at the low levels. Maximum differences occur at about 800 hPa with a 9-knot increase while taking into account the effects of sea spray. At 400–500 hPa, the difference profile reduces to values close to zero. This suggests that the spray's effects are mainly felt in the lower part of the troposphere.

4. Conclusions

In this study, the impact of sea spray on the air-sea fluxes and the evolution of a western Pacific typhoon is investigated using a coupled atmosphere/sea spray modeling system. The recent case of super typhoon Fengshen from 2002 is analyzed. We found that (1) Sea spray can cause a significant latent heat flux increase of up to 40% of the interfacial fluxes in Fengshen; (2) Taking into account the effects of sea spray, the intensity of modeled Fengshen can be increased by 30% in the 10-m wind speed, which may improve estimates of storm maximum intensity and may, to some extent, improve the simulations of overall storm structure in the atmospheric model; (3) The effects of sea spray are mainly focused over the high wind regions around the storm center and are mainly felt in the lower part of the troposphere.

Bearing in mind the complexities of typhoon mechanisms and the uncertainties in the spray parameterizations, we acknowledge that our study is very preliminary, and that we need to do further investigations with more case studies of western Pacific typhoons to identify the effects of sea spray.

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