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IMPACT OF SEA SPRAY ON TROPICAL CYCLONE STRUCTURE AND INTENSITY CHANGE

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Abstract: In this paper, the effects of sea spray on tropical cyclone (TC) structure and intensity variation are evaluated through numerical simulations using an advanced sea-spray parameterization from the National Oceanic and Atmospheric Administration/Earth System Research Laboratory (NOAA/ESRL), which is incorporated in the idealized Advanced Research version of the Weather Research and Forecast (WRF-ARW) model. The effect of sea spray on TC boundary-layer structure is also analyzed. The results show that there is a significant increase in TC intensity when its boundary-layer wind includes the radial and tangential winds, their structure change, and the total surface wind speed change. Diagnosis of the vorticity budget shows that an increase of convergence in TC boundary layer enhances TC vorticity due to the dynamic effect of sea spay. The main kinematic effect of the friction velocity reduction by sea spray produces an increment of large-scale convergence in the TC boundary layer, while the radial and tangential winds significantly increase with an increment of the horizontal gradient maximum of the radial wind, resulting in a final increase in the simulated TC intensity. The surface enthalpy flux enlarges TC intensity and reduces storm structure change to some degree, which results in a secondary thermodynamic impact on TC intensification. Implications of the new interpretation of sea-spray effects on TC intensification are also discussed.

Key words: sea spray; tropical cyclone; structure and intensity change; numerical simulation

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1 INTRODUCTION

Both theoretical analysis[1] and numerical experiments[2-5] show that the intensity of tropical cyclones (TCs) depends strongly on transfer coefficients of momentum (Cd) and enthalpy (Ck) between oceanic and atmospheric boundary layers. This is because surface fluxes of momentum and enthalpy are vital to the development and maintenance of TCs[5-6]. Emanuel[2] and Bister and Emanuel[7] showed that the maximum potential intensity (MPI) of a TC is directly proportional to $(Ck/Cd)^{1/2}$ in the high-wind-speed core of the storm. They also found that the simulated intensity of TC could not achieve the observed intensity when the estimated exchange coefficient from a low wind speed was applied to a high speed. Therefore, there may be some mechanisms, such as one via sea spray, that help to redistribute air-sea enthalpy transfer at a high wind speed.

Sea spray generated by strong winds of severe weather systems over the open ocean can redistribute enthalpy between temperature and humidity fields in the marine boundary layer. Riehl[8] first suggested that sea spray could supply substantial amount of heat to generate and maintain TCs. Fairall et al.[9] incorporated a reasonable sea-spray parameterization into a larger-scale cyclone model. They indicated that the TC boundary layer would develop in an unrealistic way without evaporating spray droplets or some other sources of latent heat, although they did not give any conclusions about whether sea spray had any effect on

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the intensity of their modeled storm. Kepert et al.[10] showed that sea spray could increase TC intensity substantially. Wang et al.[11] reported that by using a previously developed hydrostatic model named TCM3, sea spray produced a moderately enhanced intensity of a modeled TC. Lighthill et al.[12] argued, however, that by reducing the surface layer temperature, evaporating sea spray would actually weaken TCs. Andreas and Emanuel[13] concluded that the intensity of TCs is sensitive to the rate at which enthalpy and momentum are transferred between sea and air in the high-wind core of the storm. They indicated that enthalpy transfer enhanced by sea spray and momentum flux associated with sea spray are important energy sinks that moderate the effect of the sea-spray enthalpy flux. Bao et al.[14] investigated the impact of sea spray on the development of a simulated hurricane using a coupled atmosphere–ocean–wave model. They found that storm intensity would increase when the ratio of evaporating sea spray to the total mass was small, and that sea spray had a negligible effect on storm intensity when the ratio was large, due to dominant evaporation by sea spray in the marine boundary layer, as suggested by Emanuel[2].

Numerical model studies show remarkable sensitivity of modeled TC intensity to details of sea-spray parameterization[11-14], while the lack of observations at extreme wind conditions inhibits an accurate parameterization. Recent results from laboratory experiments show that Ck starts to decrease when wind speed exceeds 25 m s^{-1}[15]. This reduction tendency has recently been verified by Powell et al.[16] based on the Global Positioning System (GPS) dropwindsonde data, which shows that a transition occurs at the wind speed of about 40 m s^{-1}. Laboratory experiments by Donelan et al.[17] showed that the drag coefficient reached a saturation point at wind speeds greater than about 33 m s^{-1}. The above result from laboratory experiments is supported by the airborne turbulence flux measurements from CBLAST-Hurricane field experiments in the North Atlantic[18-19]. On the other hand, the first measurements of enthalpy flux in the CBLAT-Hurricane boundary layer showed that the exchange coefficient (Ck) is almost independent of wind speed[18, 20]. Although there have been some efforts in direct measurement of sea-air flux at extremely high wind conditions, many uncertainties still remain in parameterizing accurate drag and exchange coefficients at high wind speeds, which are affected significantly by ocean waves and sea spray since the classic Monin-Obukhov similarity theory does not explicitly take into account the full physics of surface waves and sea spray.

In this study, an advanced sea-spray parameterization is incorporated in the Advanced Research version of the Weather Research and Forecast (WRF-ARW) model simulations, and used to investigate the thermodynamic and dynamic impacts of sea spray on the boundary layer structure and intensity change of a simulated TC. Section 2 describes the experimental design of the numerical simulations and the sea-spray parameterization. Section 3 presents our results and vorticity budget analysis. Section 4 provides a physical explanation about the effect of sea spray on the intensification of TCs. And section 5 gives our conclusions.

2 EXPERIMENTAL SETUP AND SEA-SPRAY SCHEME

All simulations were performed using version 3.0 of the WRF- ARW. The model is a three-dimensional, fully compressible, nonhydrostatic model with a terrain-following coordinate in the vertical. It has 50 levels, with the model top at 50 hPa. The model includes grid-scale cloud and precipitation schemes, namely, the National Centers for Environmental Prediction (NCEP) WSM6 cloud microphysics scheme[21] and the Yonsei University (YSU) planetary boundary layer scheme[22]. Since no large-scale environmental flow is included in this study, convection is mainly active in the inner-core region and in the spiral rainbands that are within a radius of about 200 km from the cyclone center, and thus is covered by the finest innermost domain. As a result, cumulus parameterization is not considered even in the two outermost coarse meshes in this study. In the current model settings, the model domain is quadruply nested with resolutions of 54, 18, 6, and 2 km for the four meshes, respectively.

An axisymmetric cyclonic vortex for the model is initialized on an *f*-plane of 12.5°N in a quiescent environment over the ocean that has a constant sea surface temperature (SST) of 29°C. The initial thermodynamic structure of the model background atmosphere is defined as the western Pacific clear-sky condition given by Gray et al.[23]. The tangential wind of the initial cyclonic vortex is defined by

$$V_{\mathrm{T}}(r,\sigma)=\begin{cases} V(r)\sin\left[\dfrac{\pi}{2}\left(\dfrac{\sigma-\sigma_T}{1-\sigma_T}\right)\right], & \sigma>\sigma_u; \\ 0, & \sigma\le\sigma_u; \end{cases} \quad (1)$$

where u = 0.15, and

$$V(r)=\begin{cases} V_{\mathrm{m}}(\frac{r}{r_{\mathrm{m}}})\left\{\exp\frac{1}{b}\left[1-(\frac{r}{r_{\mathrm{m}}})^{b}\right]-\frac{|r-r_{\mathrm{m}}|}{R_{\mathrm{o}}-r_{\mathrm{m}}}\exp\frac{1}{b}\left[1-(\frac{R_{\mathrm{o}}}{r_{\mathrm{m}}})^{b}\right]\right\}, & r\le R_{\mathrm{o}}; \\ 0, & r>R_{\mathrm{o}}; \end{cases} \tag{2}$$

where V_{m} is the maximum tangential wind at the radius r_{m}, which is the radius of the maximum tangential wind, r is the radius, b is a non-dimensional parameter that indicates the rate of radial decay of tangential wind outside the radius of maximum wind, and R_{o} is the radius outside of which the vortex wind vanishes. The mass and thermodynamic fields associated with the vortex are obtained by solution of the nonlinear balance equation as illustrated in the appendix of Wang[24]. In all numerical experiments discussed in this study, we set V_{m} = 25 m s^{-1}, r_{m} = 80 km, b = 1.0, and R_{o} = 900 km. This initial vortex wind profile is the same as that used by Wang[25].

To evaluate the effect of different sea-spray parameterizations on the simulated TC structure and intensity, four experiments were performed (Table 1). The first experiment is a control simulation (Exp Cntrl). The second (Exp Heatonly) is similar to the first, but only with the total enthalpy flux exchange to allow an examination of the thermodynamic effect due to sea spray. The third (Exp Ustonly) is similar to the first, but only with the low frictional velocity of spray droplets to investigate the dynamic effect due to sea spray. The fourth experiment (Exp Ustheat) is similar to the first, but with heat flux and low frictional velocity contribution to explore combined thermodynamic and dynamic effect of sea spray on the TC structure and intensity change. The model TC used is simulated from a mature vortex with the wind speed of 71.5 m s^{-1} at the surface after 24-h integration and is integrated for another 24 hours for all the experiments, because the impact of sea spray is significant with the extreme wind speed conditions.

Table 1. Summary of the four experiments performed to evaluate the effect of sea spray on the modeled storm structure and intensity. The four experiments are Cntrl, Heatonly, Ustonly, and Ustheat.

Experiments	Cntrl	Heatonly	Ustonly	Ustheat
Feature implication	Control simulation	Thermodynamic effect	Dynamic effect	Combination effect

The current version of the National Oceanic and Atmospheric Administration/Earth System Research Laboratory (NOAA/ESRL) sea-spray scheme is based on Fairall et al.[9] and Bao et al.[14]. It includes three physical processes: 1) the cooling of spray droplets from SST to the atmospheric temperature that occurs by heat conduction to the atmosphere, producing spray-induced sensible-heat flux; 2) the cooling of spray droplets from the atmospheric temperature to the wet-bulb temperature (corrected for salinity and droplet curvature effects) that occurs by evaporation, producing latent-heat flux; and 3) additional evaporation of spray droplets that occurs by evaporation of spray droplets at the expense of cooling the atmosphere, producing additional latent-heat flux.

The unique aspect of the sea-spray scheme includes parameterizing the kinematic effects of spray in which the spray-filled surface layer is not resolved. The first principle of the Monin-Obukhov similarity theory must be applied. Our parameterization scheme takes into account the kinematic effects of spray in the friction velocity calculation. Following the procedure summarized in Lykossov[26], the applications of steady turbulence kinetic energy (TKE) and spray-droplet transport equations in the spray-filled surface layer lead to the similarity formulation for the friction velocity, in which the kinematic effects of sea spray are described by an additional logarithmic term in the mean wind profile. Figure 1 presents the spray-modified drag coefficient and heat exchange coefficient at z = 25 m above the mean sea surface (regarded as the lowest model level).

3 RESULTS AND ANALYSIS

3.1 *Storm intensity*

Figure 2 shows the evolution of the maximum surface wind speed ($V_{\max}$) and the minimum surface pressure (MinPsfc) in the four experiments listed in Table 1. Regardless of whether it is the control simulation (Exp Cntrl) or one of the sensitivity experiments (Exps Heatonly, Ustonly, and Ustheat), there is little difference in the intensification tendency for all the simulation time. In all the experiments listed in Table 1, the modeled TC $V_{\max}$ generally increases during the 24-h simulation. In Exp Cntrl, the simulated TC $V_{\max}$ has a stable increase above 71.5 m s^{-1} for the first 9-h simulation, and then has a fluctuating increase up to 81.2 m s^{-1} associated with the TC structure adjustment in the inner-core region. The Exp Heatonly for TC $V_{\max}$ is larger than that in Exp Cntrl, especially in the first 9-h simulation, reaching the peak of 6.1 m s^{-1} at 6 h. However, the TC

V_{max} in Exp Heatonly is a little smaller than that in Exp Cntrl between 14 and 18 h, which might be related to the adjustment of the modeled TC structure. The TC V_{max} values for Exps Ustonly and Ustheat with the effect of frictional velocity are significantly larger, up to 117.2 m s^{-1} and 122.0 m s^{-1}, respectively, indicating the spray dynamic effect is more sensitive than that in Exp Cntrl for the simulated TC intensification, which is consistent with the results from Zeng et al.[4]. From Exps Heatonly and Ustheat, we found that the spray enthalpy flux had a negligible effect on TC intensity, as suggested by Emauel[2] and Bao et al.[14]. A possible physical explanation for this insensitivity is that the increment in the frictional dissipation, due to the vertical turbulence associated with the surface enthalpy flux, could decrease the convergence of the modeled TC boundary layer, resulting in weakened storm intensity. This phenomenon is significant during TC's adjustment period. As a result, the storm is always strong in the experiment with the frictional velocity effect (Figure 2).

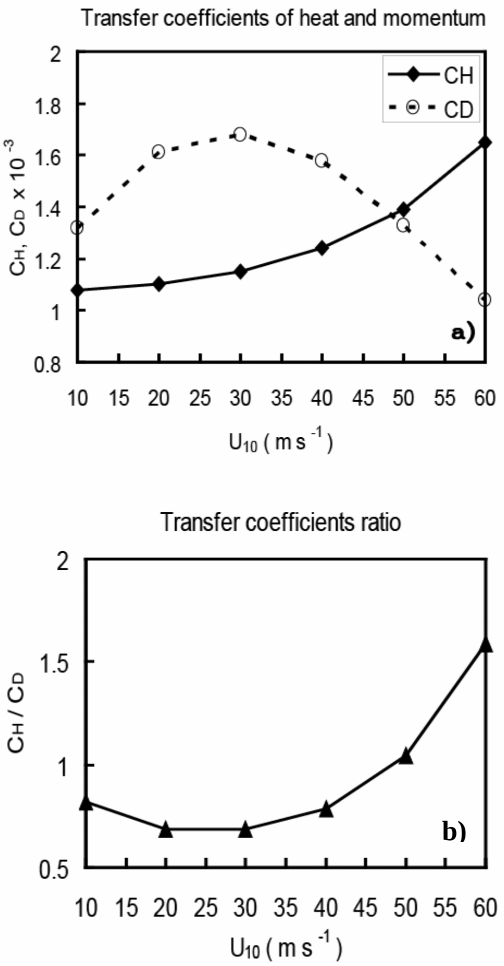

Figure 1. The upper panel shows the drag coefficient (CD) and the heat exchange coefficient (CH) at z = 25 m above the mean sea surface. The lower panel is the ratio of CH/CD. It is assumed that spray droplets are ejected at z = 10 m above the mean sea surface.

These general features mentioned above remain unchanged even after the minimum surface pressure (MinPsfc) was examined. From Figure 2, we can see a decreasing tendency of TC MinPsfc in time, opposite to the result of TC V_{max}, indicating an overall positive effect of sea spray on TC intensity. TC MinPsfc for Exps Ustonly and Ustheat with the effect of the frictional velocity are significantly reduced to 889.6 hPa and 879.7 hPa, respectively, indicating the spray dynamic effect is more sensitive than that in Exp Cntrl for the simulated TC intensification, which is consistent with the results of Zeng et al.[4].

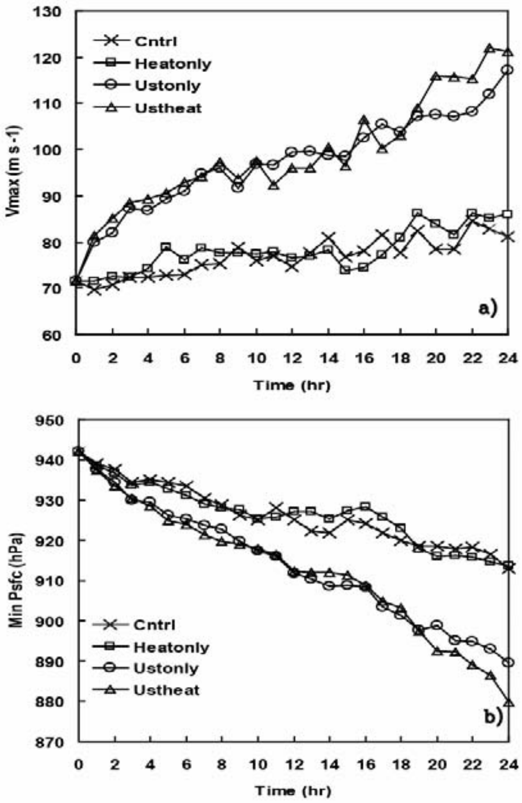

Figure 2. The evolutions of maximum wind speed (upper panel) and minimum surface pressure (lower panel) of the simulated TC during a 24-h period in the four experiments listed in Table 1. V_{max} is the maximum surface wind, and MinPsfc is the minimum surface pressure.

3.2 *Storm structure*

Figure 3 is the radial-time HovmÖller diagram of the averaged total 10-m-height wind of the simulated TC for all the experiments listed in Table 1. Consistent with the increase in V_{max} at the lowest model level given in Figure 2, total 10-m-height wind with the friction velocity parameterization (Ustheat and Ustonly) is generally stronger than that with the enthalpy flux parameterization (Heatonly) and control simulation (Cntrl), only under the eye wall region at a radius of 20 km from the storm center. This indicates that the use of the sea-spray parameterization only increases the inner-core intensity of the modeled TC, and has little effect on the wind strength for the storm outside the core. The maximum total 10-m-height wind with the friction velocity parameterization (Ustheat and Ustonly) is above 90 m s^{-1}, while the maximum total 10-m-height wind only reaches about 70 m s^{-1} with the enthalpy flux parameterization (Heatonly), which is almost the same as the control simulation (Cntrl).

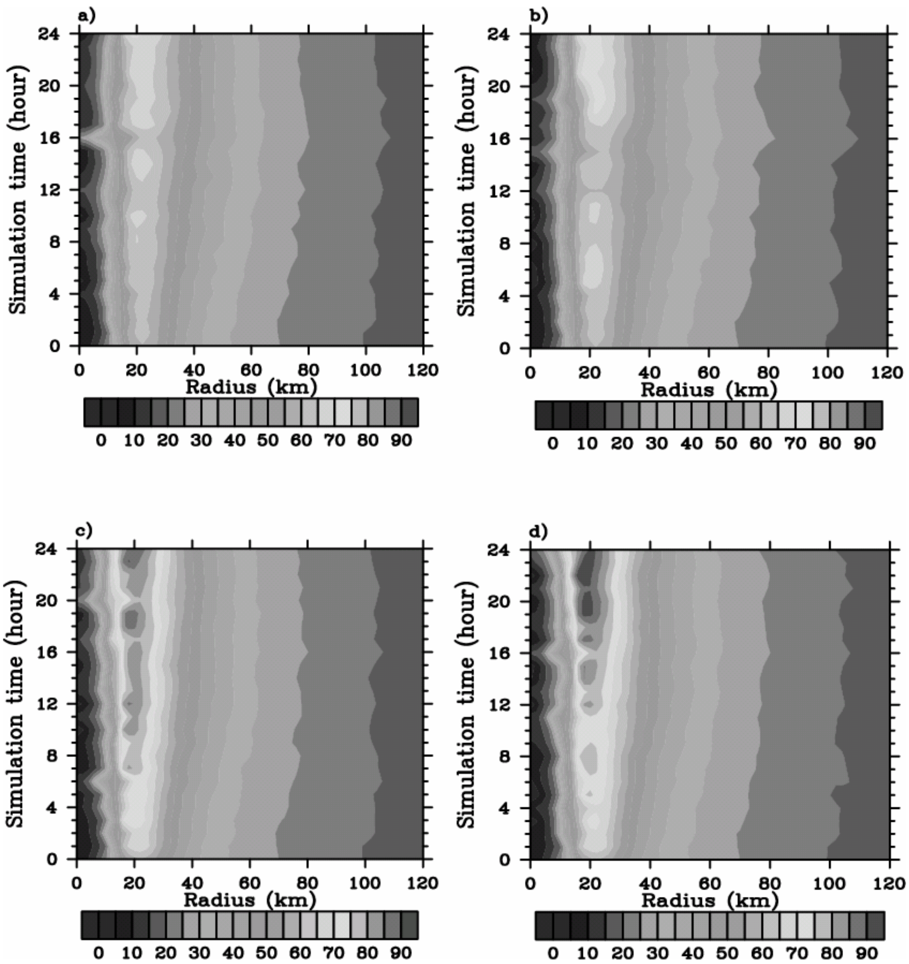

Figure 3. The radial-time HovmÖller diagram of averaged total 10-m-height wind of simulated TC from (a) Exp Cntrl, (b) Exp Heatonly, (c) Exp Ustonly, and (d) Exp Ustheat, for all the experiments listed in Table 1. Shading interval is 10 m s^{-1}.

Figure 4 shows the radial and tangential wind structures within a 1.6-km-height boundary layer for the TC simulation at 9 h for all the experiments listed in Table 1. From Figure 4a, we found that there was a prevailing radial circulation in the outer TC eye-wall region with a strong inflow, especially in the 1.2-km-height zone. Within a radius of 20 km from the storm center of the modeled TC inner-core region, there is a maximum of the horizontal gradient of radial wind, within a supergradient wind between 0.8- and 1.2-km-height zones. However, the prevailing radial circulation in the TC boundary layer can spread across the modeled TC eye wall extending into the TC center, which is consistent with the result in Smith et al.[27].

Compared with those of Exp Cntrl, the radial and tangential winds with effects of the frictional velocity (Exps Ustonly and Ustheat) are significantly large (Figures 4c and 4d), indicating that the effect of spray dynamics is sensitive to the simulated TC intensification, consistent with the results in Figures 2 and 3. Due to the decrease in friction dissipation from the sea-spray low frictional velocity parameterization, the convergence increases, leading to significant increases of the radial and tangential winds in the TC boundary layer. However，the radial and tangential winds for the effect of the heat flux experiment (Exp Heatonly), is smaller than those of Exp Cntrl (Figure 4b). The increase in frictional dissipation, arisen directly from the vertical turbulence associated with the surface enthalpy flux, might decrease the convergence of the modeled TC boundary layer, resulting in decreases of the radial and tangential winds in the TC boundary layer, which is consistent with the results seen in Figure 2. Therefore, the radial and tangential wind structures in the TC boundary layer associated with sea-spray effect show significant changes. As a result, there are changes in the modeled

TC structure and intensity arisen from sea-spray impact on the TC boundary layer (Figures 2 and 3).

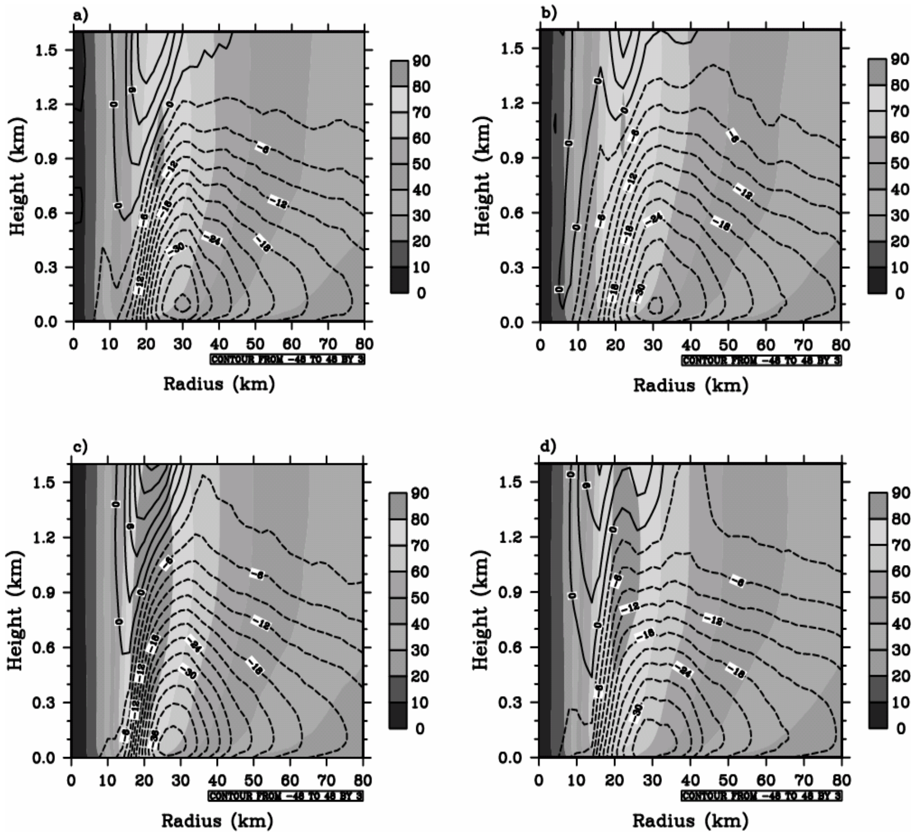

Figure 4. The radial and tangential wind structures within a 1.6-km-height boundary layer of the simulated TC from (a) Exp Cntrl, (b) Exp Heatonly, (c) Exp Ustonly, and (d) Exp Ustheat, for all the experiments listed in Table 1. Contour interval is 4 m s^{-1}. Shading interval is 10 m s^{-1}.

3.3 *Surface flux parameters*

Figure 5 shows the radial-time HovmÖller diagram for the averaged surface enthalpy flux derived from the simulated TC for the four experiments listed in Table 1. The maximum averaged surface enthalpy flux occurred in the TC inner-core region for all the experiments (Figures 5a–5d), which is consistent with the results of the averaged total 10-m-height wind temporal structure in Figure 3. After 18-h simulation, the highest averaged surface enthalpy flux in Exp Heatonly was above 3500 W m^{-2} (Figure 5b), but the averaged total 10-m-height wind was only about 70–75 m s^{-1} (Figure 3b). Although there is relatively low averaged surface enthalpy flux in Exp Ustonly (Figure 5c), the averaged total 10-m-height wind is above 90 m s^{-1} (Figure 3c). Clearly, the largest averaged surface enthalpy flux does not correspond to the highest averaged total 10-m-height wind, indicating the presence of other factors that enhance the TC intensity.

One candidate for enhancing TC intensity is frictional velocity. Figure 6 shows the radial-time HovmÖller diagram for the averaged frictional velocity of the simulated TC for all the experiments listed in Table 1. We found that the maximum averaged frictional velocity occurred in the TC inner-core region for all the experiments (Figures 6a–6d), which is consistent with the results in the averaged total 10-m-height wind and surface enthalpy flux (Figs. 3 and 5). Comparing the experiments with frictional velocity (Ustonly and Ustheat, Figures 6c–6d) to the experiments without frictional velocity (Cntrl and Heatonly; Figures 6a–6b), the averaged frictional velocity is dramatically decreased with the increase of averaged total 10-m-height wind in the TC inner-core region (Figures 3 and 6), consistent with the results in Powell et al.[16] and Zeng et al.[4]. A possible physical explanation is the development of a sea foam layer at the air-sea interface[16]. As surface wind exceeds the threshold from 30 to 40 m s^{-1}, the sea surface becomes completely covered by foams, which impedes the transfer of momentum from the atmosphere to the ocean, leading to a decrease in frictional velocity with increasing wind speed. Comparisons of the experiments with enthalpy flux (Heatonly and Ustheat; Figures 6b–6d) to the experiments without enthalpy flux (Cntrl and Ustonly; Figures 6a–6c) showed that the averaged frictional velocity increased with the increase in heat transfer of the modeled TC, implying that an increase in direct vertical turbulence of the TC related to enthalpy flux can produce an increase in frictional dissipation.

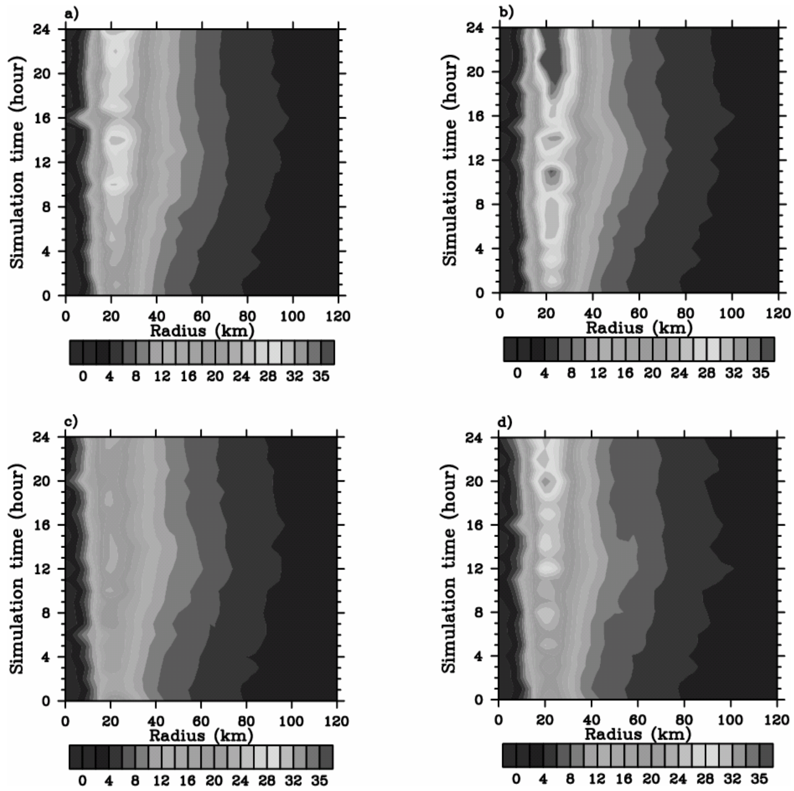

Figure 5. The radial-time HovmÖller diagram of averaged surface enthalpy flux (W/m^2) of the simulated TC from (a) Exp Cntrl, (b) Exp Heatonly, (c) Exp Ustonly, and (d) Exp Ustheat, for all the experiments listed in Table 1. Shading interval is 200 W/m^2.

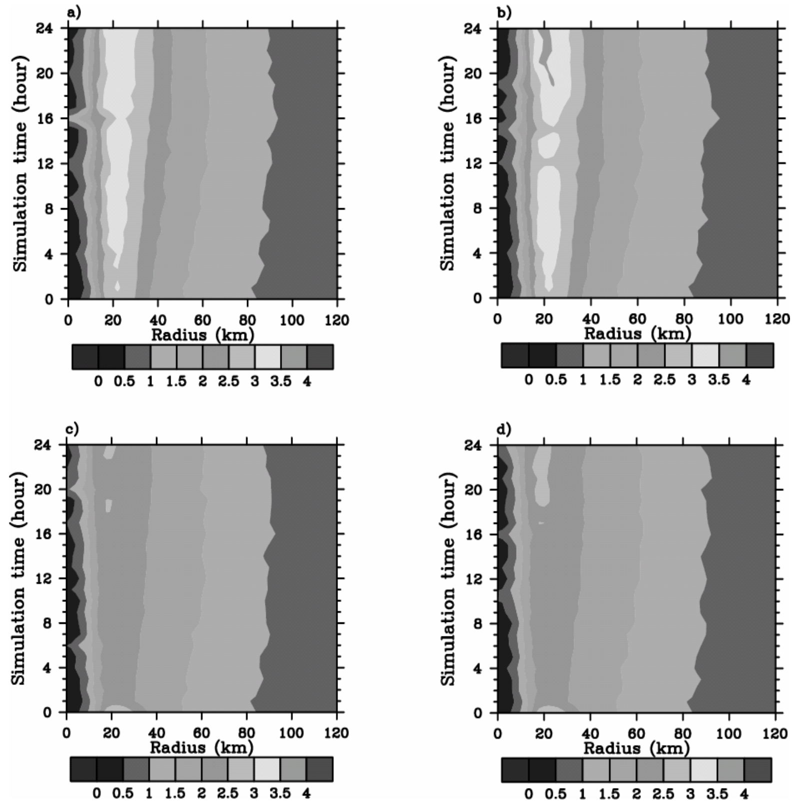

Figure 6. Same as in Figure 5, except for frictional velocity (m s^{-1}). Note that the shading interval is 0.5 m s^{-1}.

3.4 *Vorticity change*

To quantify the effect of different sea-spray parameterizations on the simulated TC structure and intensity, we performed a vorticity budget based on Holton[28]. The vorticity budget is written as

$$\frac{\partial \zeta}{\partial t} = \underbrace{-u\frac{\partial \zeta}{\partial x} - v\frac{\partial \zeta}{\partial y}}_{V\mathrm{adv}} \underbrace{- w\frac{\partial \zeta}{\partial z}}_{VW\mathrm{adv}} \underbrace{- \zeta\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)}_{V\mathrm{div}} \underbrace{- \left(\frac{\partial w}{\partial x}\frac{\partial v}{\partial z} - \frac{\partial w}{\partial y}\frac{\partial u}{\partial z}\right)}_{V\mathrm{tilt}} \quad (3)$$

where *u*, *v*, and *w* are zonal, meridional, and vertical wind components, respectively, *x*, *y*, *z*, and *t* are three-dimensional coordinates and time, respectively, and ζ is relative vorticity. The tendency term on the left hand side of Eq. (3) represents the local variation of relative vorticity. *V*adv is the horizontal advection term caused by the non-uniform horizontal distribution of relative vorticity. *VW*adv is the convective term, which denotes the vertical advection of relative vorticity from vertical motion. *V*div denotes the divergence (stretching) term, representing the amplification (reduction) of pre-existing vertical vorticity from horizontal convergence (divergence). *V*tilt is the tilting term, denoting the vertical vorticity created from the tilting of horizontal vorticity by horizontally non-uniform distribution of vertical motion.

Since no large-scale environmental flow is included in this study, *V*adv and *VW*adv are not considered here. We calculated the domain-averaged *V*div, *V*tilt, and the positive relative vorticity tendency in a 100×100 km^2 domain around the TC center.

Figure 7a presents the temporal evolution of the vorticity divergence term (*V*div) at the bottom level of the simulated TC from all the experiments listed in Table 1. In all the simulations, vorticity convergence in the simulated TC increased with the integrating time, indicating TC intensification with its vorticity convergence increment shown in Figure 7a. As shown in comparisons with Exp Cntrl, there is a significant increase in the vorticity convergence in modeled TC in the three sensitivity experiments (Heatonly, Ustonly, and Ustheat), especially in Exps Ustonly and Ustheat, which indicates the vorticity convergence increase from sea spray had a positive effect on TC intensification.

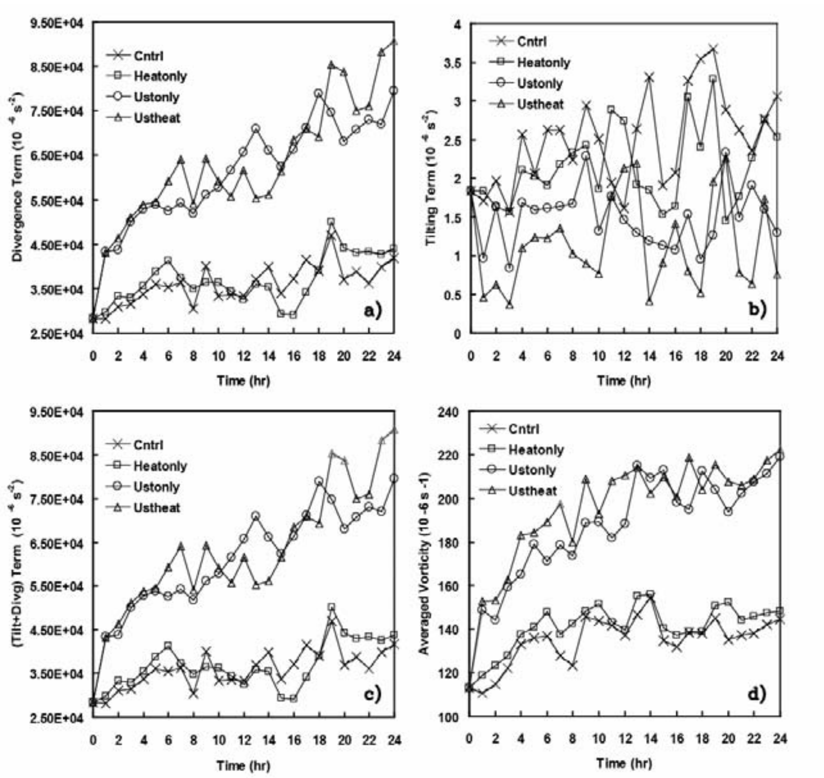

Figure 7. Temporal evolution of (a) vorticity divergence (10^{-6} s^{-2}), (b) vorticity tilting (10^{-6} s^{-2}), (c) sum of the vorticity divergence and the vorticity tilting (10^{-6} s^{-2}) and (d) the averaged positive vorticity (10^{-6} s^{-1}) at the bottom level of the simulated TC from all the experiments listed in Table 1.

Figure 7b shows the temporal evolution of the vorticity tilting term (*V*tilt) at the bottom level of the simulated TC from all the experiments. In all the simulations, vorticity tilting in the simulated TC increased with time, which indicates that there is a positive correlation between the TC local relative vorticity and vorticity tiling (Figures 7b–7d). This also means that the vorticity tiling increase from sea spray also results in TC intensification.

Compared with Exp Cntrl, the vorticity tilting of the modeled TC in the sensitivity experiments (Heatonly, Ustonly, and Ustheat) has a decreasing tendency, which comes from TC vertical mixing increase from sea spray that reduces the vertical wind shear in the bottom layer of the TC. Although the order of magnitude of the vorticity tilting is smaller than that of the vorticity convergence, the vorticity tilting is crucial to trigger the genesis of the modeled TC (Figure 7c). As a result, the local averaged positive relative vortices in all the sensitivity experiments (Heatonly, Ustonly, and Ustheat) are larger than that in Exp Cntrl, especially in Exp Ustheat (Figure 7d). However, there is a short adjustment period in the averaged positive relative vorticity after a stable increase in the first 9-h simulation, consistent with the adjustment time seen in Figure 2.

4 PHYSICAL INTERPRETATION OF SEA-SPRAY EFFECT ON TC INTENSITY

To summarize these results, we use a physical conceptual model to illustrate the effect of sea spray on the boundary layer of the simulated TC (Figure 8). There is a negative correlation between frictional velocity and surface wind speed if the effect of sea spray is considered in the model. The large-scale dynamic convergence increases with decreasing surface friction in the TC inner core, which results in the merge of TC components, such as vertical hot towers (VHTs), leading to intensification of averaged positive vorticity in TC. This mechanism of TC intensification agrees with the view of Houze[29].

Moreover, the surface enthalpy flux has a secondary effect on TC intensification, similar to the dynamic effect of sea spray on TC intensity change. Although the surface enthalpy flux can be redistributed and enhanced by the sensible heat, Hs, and latent heat, Qs, from the effect of sea spray, the increase in the frictional dissipation, arising directly from the vertical turbulence associated with the surface enthalpy flux, weakens the convergence of the modeled TC boundary layer, resulting in reduced radial and tangential winds in the TC boundary layer. The difference associated with the heat fluxes from the control simulation and sensitivity experiments decreases for the TC boundary layer structures, which coincides with the result from the dissipated heating effect of Zeng et al.[4]. The surface heat flux enhances TC intensity while reducing storm structure change to some degree.

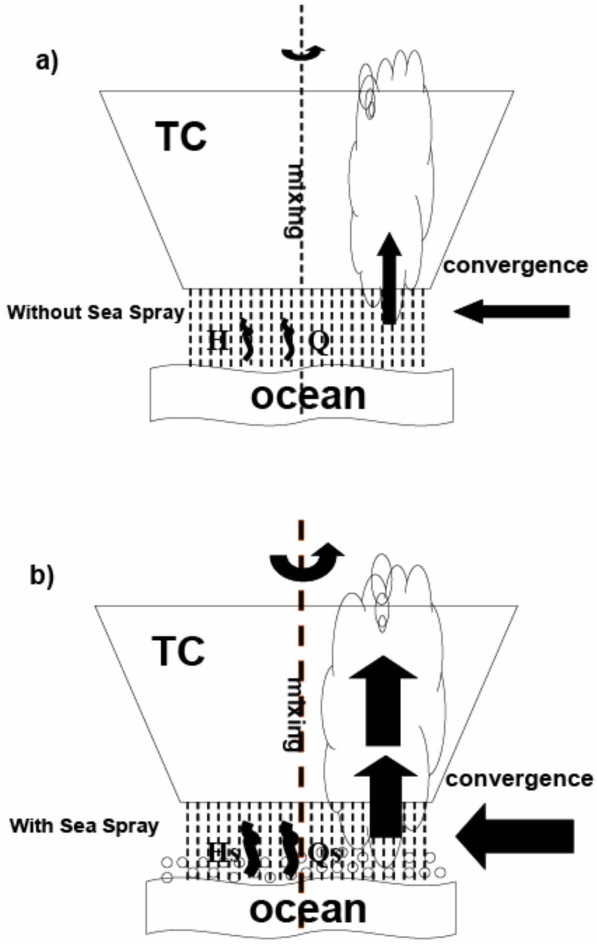

Figure 8. A conceptual pattern about the effect of sea spray on the boundary layer of the simulated TC. Hs and Qs (H and Q) are the sensible heat and latent heat with (without) the effect of sea spray, respectively. The rotating vector stands for the relative vorticity.

5 CONCLUSIONS AND DISCUSSIONS

Results of our numerical simulation and theoretical analysis show sensitivity of the maximum TC intensity to the ratio of the enthalpy exchange coefficient to the momentum drag coefficient. Both the drag and exchange coefficients, however, are extrapolated from the low-wind regime based on limited observations up to wind speed of about 25 m s^{-1} in most TC models. This extrapolation predicts a monotonic increase of drag coefficient as wind speed increases. Recent observations from GPS dropsondes provide boundary layer winds under TCs. Analysis of these data shows a reduced drag coefficient for wind speed higher than 40 m s^{-1}[16]. Incorporated with the NOAA/ESRL sea-spray scheme, which takes into account the kinematic effect of sea spray on the friction velocity calculation associated with the drag and exchange coefficients, an idealized WRF-ARW model with a multiply nested and one-way feedback is used to evaluate the effect of sea spray on the simulated TC structure and intensity changes and to analyze the effect of sea spray on the TC boundary layer structure in this study. The results show that there is a significant increase in TC intensity with its boundary layer winds, including the radial and tangential winds, structure changes, and its total surface wind-speed change.

Diagnosis of the vorticity budget shows that an increase of convergence in the TC boundary layer gives rise to enhanced TC vorticity due to the dynamic effect of sea spay. The major kinematic effect of the friction velocity decreased by sea spray enhances the large-scale convergence in the TC boundary layer, while radial and tangential winds are significantly correlated with the horizontal gradient maximum of the radial wind, resulting in an increase in the simulated TC intensity. Moreover, the increment in the frictional dissipation, due to the vertical turbulence associated with the surface enthalpy flux, could decrease the convergence of the modeled TC boundary layer, resulting in weakened storm intensity.

The surface heat flux enhances TC intensity and reduces storm structure change to some degree. As a result, the surface enthalpy flux has a secondary thermodynamic impact on TC intensification.

The new interpretation of sea spray effects on TC intensification provides more accurate estimation of the impact mechanisms on TC structure and intensity changes; thus, it improves our understanding of the factors that control TC intensity. A possible application of sea-spray parameterizations is to improve TC numerical models, which would be useful to both theoretical study and operational forecast of TC structure and intensity changes. It should be noted that although the qualitative explanation of the kinematic effects of spray is based on the physics of turbulence in the spray-filled surface layer, the quantitative aspect of our parameterization requires further evaluation; in particular, the relationship between the wave-induced drag on the spray-modified drag should be investigated.

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