The Final Report of the Project Entitled "Evaluation and Improvement of Spray-Modified Air-Sea Enthalpy and Momentum Flux Parameterizations for Operational Hurricane Prediction"

Prepared for:

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Submitted on November 30, 2009

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1. EXECUTIVE SUMMARY

This report summarizes the results from a two-year project sponsored by the Joint Hurricane Testbed, in which a bulk parameterization scheme of air-sea sensible and latent heat fluxes developed at NOAA/Earth System Research Laboratory (ESRL) was implemented and tested in the operational hurricane weather research and forecast (HWRF) model. During the first year, the version of NOAA/ESRL sea-spray scheme that only took into account the feedback of sea spray on the thermal fluxes in the surface boundary layer stability was added to the HWRF model physics suite. Experimental runs of the model with the scheme were carried out for five historical major hurricane events to examine the sensitivity of the HWRF model to the sea-spray physics. It was found that the impact of the sea-spray scheme on the HWRF model was significant. The preliminary results from the performance evaluation of the scheme indicated that the scheme improved the HWRF model's intensity prediction with little impact on the track prediction.

During the second year of this project, in addition to the further evaluation of the sea-spray parameterization scheme in the HWRF model, the explicit sea-spray model of Kepert et al. (1999) coupled with the 1-D Mellor-Yamada turbulence mixing model was used to investigate both the thermal and kinematic feedback effects. This explicit spray model is capable of simulating the evaporation and dispersion of saline water droplets of various sizes. There is full coupling among the spray-droplet microphysics, turbulence mixing, and droplet transport. Results from the investigation using the explicit sea spray model revealed important characteristics of the way in which evaporating droplets of various sizes modify the turbulence mixing near the surface, which in turn affects further droplet evaporation. Based on these results, a parameterization accounting for the kinematic effect of sea spray in the surface thermal

and momentum fluxes was developed. The ESRL sea-spray scheme was then improved based on the results obtained from the abovementioned 1-D explicit sea-spray simulations by taking into account the feedback effect of sea spray on the momentum flux in the surface boundary layer. Testing of the scheme was conducted in the operational cycling mode in the HWRF model for five benchmark historical hurricane cases. This is the first time the ESRL sea-spray scheme was evaluated in cycled operational forecasts. The preliminary results of the evaluation statistics for three of the five benchmark cases indicate that for strong storms (such as Katrina and Rita), the scheme tends to produce a greater positive bias of intensity during the first 48-72 hours than the control runs, while the impact on the track is small. For weak storms (such as Dennis), the scheme tends to produce an intensity bias that varies around that of the control runs, while the track is degraded slightly after 72 hours.

The major outcome of this 2-year project is that the NOAA/ESRL sea-spray parameterization has been added to the atmospheric boundary layer physics subroutine of the operational HWRF model and evaluated in cycled operational forecasts for some HWRF benchmark cases. Due to the sound physics in the parameterization scheme and the positive results from the evaluation, a consensus has been reached between EMC and ESRL that the scheme will be included in the future version of the operational HWRF model as an option in the model physics configuration. There are also two journal articles in preparation presenting scientific findings from this project in more detail.

2. INTRODUCTION

During the past two years, a bulk parameterization scheme of air-sea sensible and latent heat fluxes developed at NOAA/ESRL was implemented, tested and evaluated in the newly developed hurricane WRF-NMM (HWRF) model. This scheme was developed as an extension of the TOGA-COARE bulk flux model (Fairall et al. 1994), and has been refined with observations from new field campaigns (such as the CBLAST experiment) and updated theoretical understanding (Fairall et al. 2009). During the first year of this project, the scheme only took into account the feedback of sea spray on the thermal fluxes in the surface boundary layer stability. The objectives of the project for the first year were accomplished with great help from Dr. Naomi Surgi's group at NCEP of NOAA/NWS. The NOAA/ESRL team visited NCEP in July 2007 to coordinate with Naomi Surgi's group. Collaborative effort was also started with Dr. Isaac Ginis' group at the University of Rhode Island to further the physical understanding of the impact of the spray-mediated thermal and momentum fluxes on the marine atmospheric boundary layer dynamics.

During the second year of this project the ESRL parameterization scheme of sea-spray mediated fluxes was improved by taking into account the feedback effects on the momentum flux across the air-sea interface. The improvement was made based on an improved understanding of the dynamical aspects of the sea-spray feedback effects via the balance of TKE and enthalpy in the spray-laden surface layer and the extension of the Monin-Obukhov similarity assumption. In order to fully test the improved scheme in the HWRF model at NCEP/EMC, the NOAA/ESRL team visited NCEP in March 2008 to coordinate with Naomi Surgi's group for the purpose of testing the scheme in the operation setup of the HWRF model for the 2008 season. Collaboration with Dr. Isaac Ginis' group at the University of Rhode Island was continued to further the physical understanding of the impact of the spray-mediated thermal and momentum fluxes on the wave atmospheric boundary layer dynamics.

3. OPERATIONAL MODEL SETUP

The HWRF model was set up by Drs. Naomi Surgi, Vijay Tallapragada and Young Kwon at NCEP in the same way as the operational prediction experiment, in which a two-way nested grid included a moving inner grid which followed the storm center. The NOAA/ESRL sea-spray parameterization was added to the atmospheric boundary layer physics subroutine. After consulting Drs. Naomi Surgi and Young Kwon, five hurricane cases were chosen to test and calibrate the scheme: Katrina (2005), Rita (2005), Emily (2005), Dennis (2005) and Helene (2006). All the HWRF model forecasts presented in this report were run on the IBM supercomputer system at NCEP.

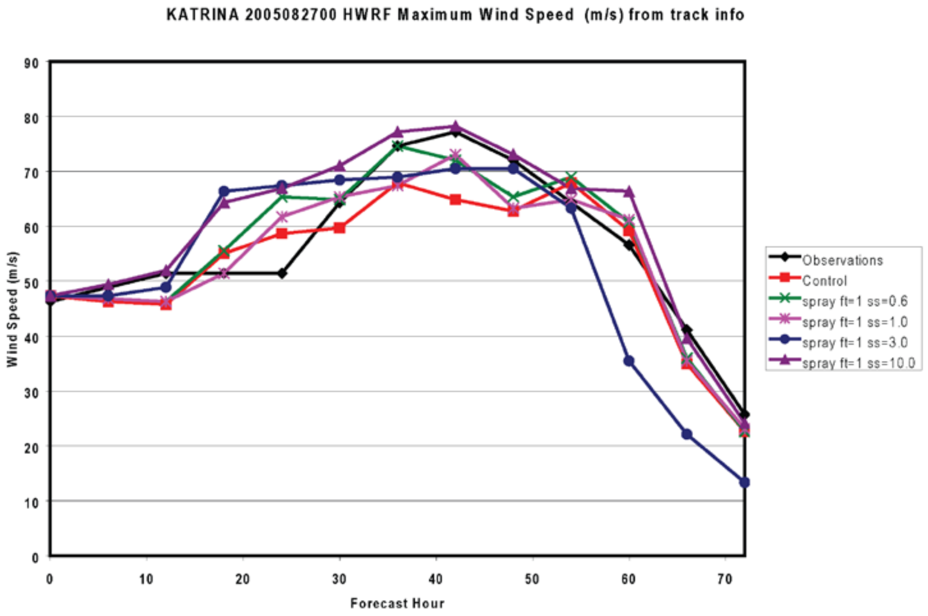
Both the earlier and the improved versions of the NOAA/ESRL sea-spray scheme have two tunable parameters — the droplet source strength, *ss*, and the feedback strength, *ft*. The determination of appropriate values of these two parameters is still *ad hoc* due to the lack of observational information to quantify how sea-spray droplets modify the mean temperature and moisture profiles in the surface layer. The approach to specifying the two parameters for a given model is to permute (*ft*, *ss*) with various possible values, and to examine the sensitivity of the hurricane simulations to various permutations of (*ft*, *ss*) by comparing the simulation results with the best track information. When the improved NOAA/ESRL sea-spray scheme was tested, the two tunable parameters associated with the functional formulas of the droplet source strength and the feedback strength were set as $ss = 1$ and $ft = 1$. In general, the uncertainty of the first parameter is due to the lack of observational information on the connection of the spray generation and the wave breaking dynamics, while the uncertainty in the second parameter is associated with the lack of observations to quantify how sea-spray droplets modify the mean wind, temperature and moisture profiles in the surface layer. Although reliable laboratory and field-experiment data are required to calibrate these two parameters, tuning them in the HWRF model is necessary as the model evolves because error compensation exists in the model physics.

4. RESULTS OF MODEL EVALUATION STATISTICS IN THE FISRT YEAR

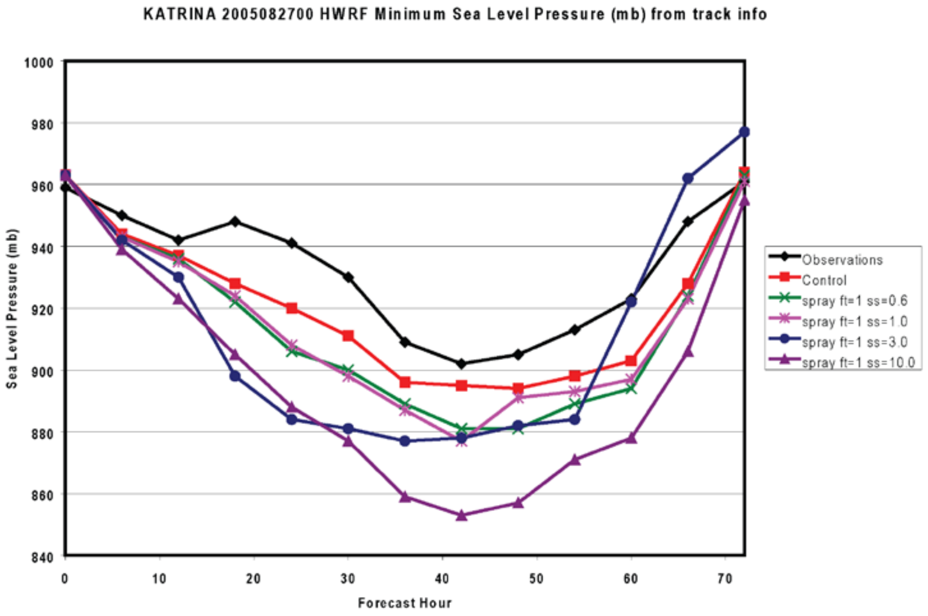
This section summarizes the results from the first year's activities to calibrate the two tunable parameters, *ss* and *ft*, in the NOAA/ESRL sea-spray parameterization scheme. Only the results from the HWRF runs with *ss* = 0.6, 1, 3 and 10 while *ft* = 1 are discussed by comparison with the control run in which the sea-spray parameterization is turned off.

4.1 Katrina (2005)

Figure 1 shows the maximum surface winds (Fig. 1a) and sea-level pressure (Fig. 1b) for the predictions of Hurricane Katrina (2005) with ss = 0.6, 1, 3 and 10 while *ft* = 1. The model was initialized at 0000 UTC 27 August 2005. It is seen that for a fixed *ft*, there is a general trend that the predicted intensity at the peak of the intensification increases with *ss*. Although the predicted minimum sea-level pressure decreases as the intensity increases, the predicted minimum sea-level pressure is lower than the best track estimate. It is encouraging that even though the predicted intensity varies with different values of *ss*, the predicted track does not change significantly (Table 1) in comparison with the control run in which the sea-spray effect is not included. This indicates that the sea-spray modification to the air-sea enthalpy exchange does not affect the track. It should also be pointed out that the differences among various runs are not proportional to differences in the values of *ss*, indicating that the relationship between the intensity at a given time results from a very nonlinear interaction between the storm dynamics and the air-sea thermal fluxes.



(a)



(b)

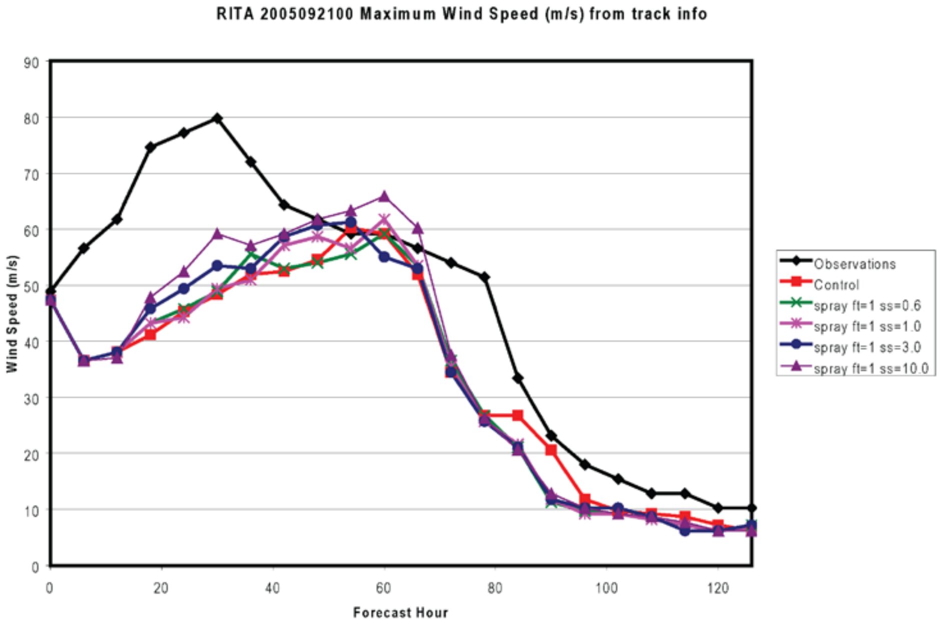
Figure 1: The maximum surface winds (ms^{-1}) (a) and sea-level pressure (mb) (b) for Hurricane Katrina (2005) with *ss* = 0.6, 1, 3 and 10 while ft = 1. The black line (labeled as Observations) is the best track estimate. The red line is the control run without the sea-spray parameterization. The model was initialized at 0000 UTC 27 August 2005.

forecast hour	Control lat	Control lon	*ss*=0.6 lat	*ss*=0.6 lon	*ss*=1 lat	*ss*=1 lon	*ss*=3 lat	*ss*=3 lon	*ss*=10 lat	*ss*=10 lon
0	25.0N	82.9W	25.0N	82.9W	25.0N	82.9W	25.0N	82.9W	25.0N	82.9W
6	25.1N	83.9W	25.1N	83.9W	25.1N	83.9W	25.1N	83.9W	25.1N	83.9W
12	25.1N	84.8W	25.1N	84.8W	25.1N	84.8W	25.1N	848.W	25.1N	84.8W
18	25.2N	85.7W	25.2N	85.7W	25.2N	85.7W	25.2N	85.7W	25.2N	85.7W
24	25.5N	86.5W	25.5N	86.5W	25.5N	86.5W	25.5N	86.5W	25.5N	86.5W
30	25.9N	87.5W	25.9N	87.5W	25.9N	87.5W	25.9N	875W	25.9N	87.5W
36	26.5N	88.4W	26.4N	88.4W	26.5N	88.4W	26.5N	88.5W	26.5N	88.4W
42	27.1N	89.3W	27.1N	89.3W	27.2N	89.4W	27.2N	89.3W	27.1N	89.4W
48	27.8N	89.7W	27.8N	89.8W	27.8N	89.9W	27.9N	89.8W	27.8N	89.8W
54	28.8N	90.0W	28.8N	90.1W	28.8N	90.0W	28.9N	90.0W	28.8N	90.1W
60	29.9N	90.0W	29.9N	90.2W	29.9N	90.1W	30.1N	90.0W	29.8N	90.2W
66	31.1N	90.0W	31.0N	90.0W	31.1N	89.9W	31.2N	89.9W	31.1N	90.1W
72	32.1N	89.3W	32.1N	89.5W	32.1N	89.4W	32.3N	89.2W	32.1N	895.W
78	33.1N	88.6W	33.2N	88.7W	33.1N	88.6W	33.4N	88.4W	33.2N	88.8W
84	34.3N	87.4W	34.3N	87.6W	34.4N	87.4W	34.7N	87.3W	34.5N	87.7W
90	35.8N	86.2W	35.8N	86.3W	35.9N	86.2W	36.2N	86.1W	35.9N	86.4W
96	37.3N	84.9W	37.3N	85.1W	37.3N	84.7W	37.3N	84.6W	37.0N	85.0W
102	38.1N	83.6W	38.0N	83.9W	38.4N	83.3W	38.6N	83.1W	38.2N	83.6W
108	38.9N	81.8W	38.9N	82.1W	39.0N	81.9W	39.1N	81.6W	39.0N	82.0W
114	39.9N	79.3W	30.5N	79.9W	40.1N	79.4W	399N	79.6W	39.5N	80.0W
120	40.6N	77.0W	39.8N	77.5W	40.8N	76.9W	40.6N	76.9W	39.3N	77.2W
126	41.0N	74.9W	40.5N	75.3W	41.5N	74.1W	41.7N	74.5W	40.5N	74.7W

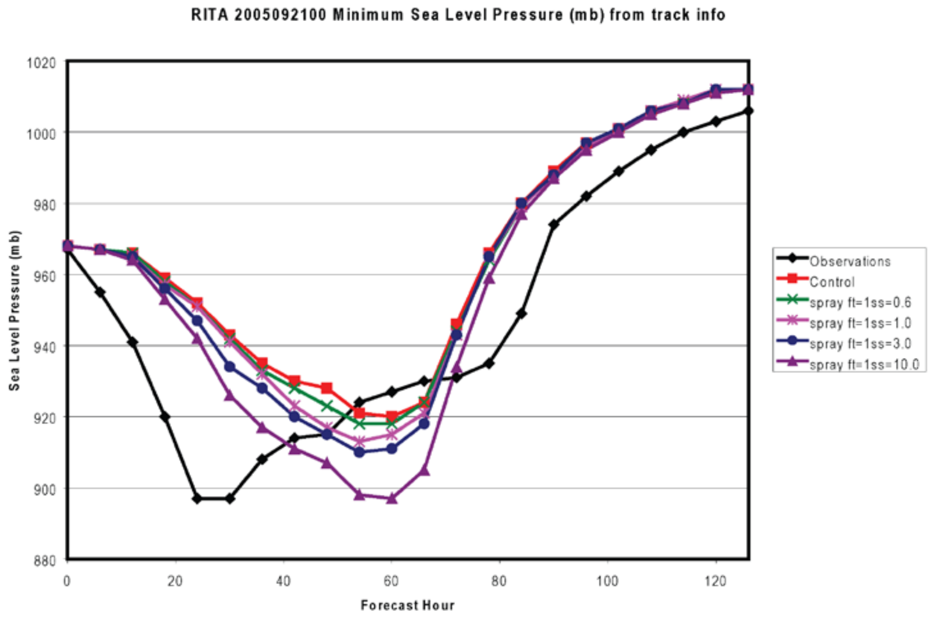
Table 1: Predicted track locations of Hurricane Katrina without the sea-spray parameterization (control) and with the sea-spray parameterization in which *ss* = 0.6, 1, 3 and 10 while ft = 1.

4.2 Rita (2005)

The results from the experiment with Hurricane Rita (2005) are shown in Figure 2 and Table 2. The model was initialized at 0000 UTC 21 September 2005. As in the Katrina case, for a fixed ***ft*****,** the predicted intensity of the hurricane increases with *ss*. Again, while the predicted intensity changes with different values of *ss*, the predicted track does not change significantly (Table 2). Also, the nonlinear variation of the predicted intensity with *ss* is very similar to that shown in the Katrina case. It should be pointed out that, unlike the Katrina case, there is delay in the predicted intensification in all the runs when compared with the best track estimate and the sea-spray effect is not able to make any improvement in the timing bias of intensification. It is interesting to note, that while the run with *ss* = 10 is in fairly good agreement with the strength of Hurricane Rita in terms of sea level pressure, the maximum wind speed at the time of the minimum sea level pressure is too weak by about 15 ms^{-1}.



(a)



(b)

Figure 2: The maximum surface winds (ms^{-1}) (a) and sea-level pressure (mb) (b) for Hurricane Rita (2005) with *ss* = 0.6, 1, 3 and 10 while *ft* = 1. The black line (labeled as Observations) is the best track estimate. The red line is the control run without the sea-spray parameterization. The model was initialized at 0000 UTC 21 September 2005.

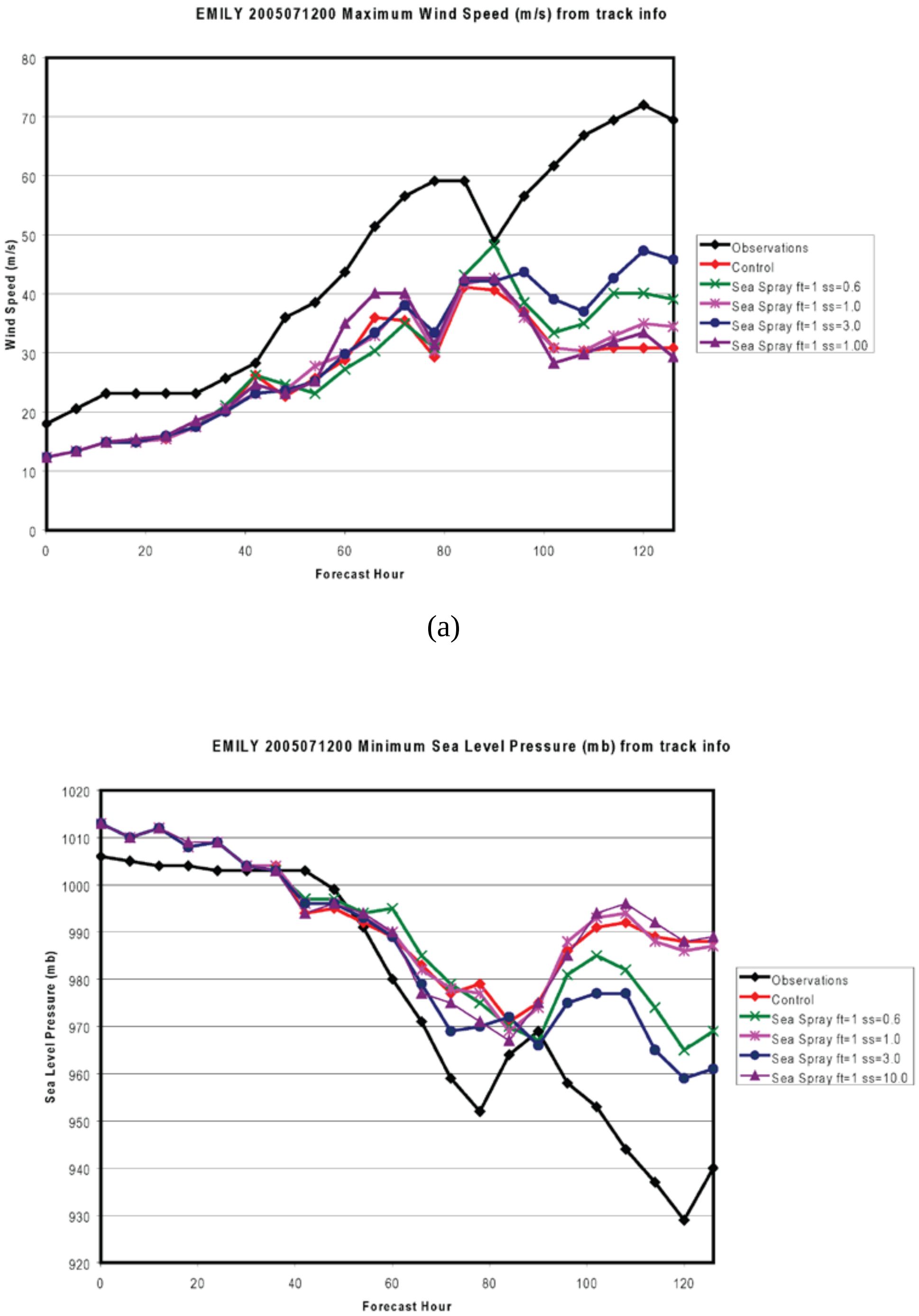
forecast hour	Control lat	Control lon	*ss*=0.6 lat	*ss*=0.6 lon	*ss*=1 lat	*ss*=1 lon	*ss*=3 lat	*ss*=3 lon	*ss*=10 lat	*ss*=10 lon
0	24.0N	82.6W	24.0N	82.6W	24.0N	82.6W	24.N	82.6W	24.0N	82.6W
6	24.1N	84.1W	24.1N	84.1W	241N	84.1W	24.1N	84.1W	24.1N	84.1W
12	24.1N	85.2W	24.1N	85.2W	24.1N	85.2W	24.1N	85.2W	24.1N	85.2W
18	24.4N	86.4W	24.3N	86.5W	24.4N	86.4W	24.3N	86.5W	24.3N	86.5W
24	24.5N	87.6W	24.4N	87.6W	24.4N	87.6W	244N	876W	244N	876W
30	24.7N	88.6W	24.7N	88.6W	24.7N	88.7W	24.7N	887W	248N	88.7W
36	25.2N	89.5W	25.2N	89.6W	25.2N	89.6W	25.1N	89.6W	251.N	89.7W
42	25.8N	90.6W	25.8N	90.6W	25.7N	90.7W	25.8N	90.7W	25.8N	90.8W
48	26.5N	91.6W	26.5N	91.6W	26.4N	91.6W	26.5N	91.7W	26.5N	91.8W
54	273N	92.6W	27.2N	92.6W	27.3N	92.7W	27.3N	92.8W	27.3N	92.8W
60	28.3N	93.3W	28.2N	93.4W	28.2N	93.5W	28.3N	93.6W	28.3N	93.6W
66	29.3N	94.2W	29.2N	94.2W	29.2N	94.4W	29.3N	94.4W	29.2N	94.5W
72	30.2N	94.6W	30.2N	94.6W	30.1N	94.7W	30.3N	94.8W	30.2N	94.9W

78	31.1N	94.8W	31.0N	94.8W	31.0N	95.1W	31.1N	95.1W	31.1N	95.2W
84	31.9N	94.8W	31.8N	94.9W	31.8N	95.1W	31.8N	95.1W	31.8N	95.3W
90	32.5N	94.7W	32.5N	94.7W	32.5N	95.0W	32.6N	95.0W	32.5N	95.2W
96	33.0N	94.5W	33.0N	94.6W	33.1N	94.7W	33.1N	94.7W	33.2N	94.7W
102	33.4N	94.1W	33.3N	94.1W	33.4N	94.4W	33.5N	94.3W	33.6N	94.4W
108	33.6N	93.6W	33.5N	93.6W	33.6N	93.8W	33.7N	93.7W	33.8N	93.8W
114	33.6N	93.1W	33.4N	93.3W	33.5N	93.4W	33.6N	93.3W	33.6N	93.3W
120	33.4N	92.7W	33.1N	93.0W	33.3N	930W	334N	92.8W	33.3N	92.7W
126	32.9N	92.9W	32.5N	93.2W	32.7N	93.3W	32.8N	93.0W	32.8N	92.8W

Table 2: Predicted track locations of Hurricane Rita without the sea-spray parameterization (control) and with the sea-spray parameterization in which *ss* = 0.6, 1, 3 and 10 while *ft* = 1.

4.3 Emily (2005)

The results from the sensitivity runs with Hurricane Emily (2005) are shown in Figure 3 and Table 3. The model was initialized at 0000 UTC 12 July 2005. While the predicted intensity is sensitive to *ss*, the predicted track does not show any significant sensitivity (Table 3). The nonlinear variation of the predicted intensity with *ss* is very similar to that shown in the Katrina and Rita cases. However, there is a delay in the predicted intensification and the second intensification shown in the best track estimate is significantly underestimated in the forecast. The inclusion of the sea spray effect does not help alleviate this problem.



(a)

(b)

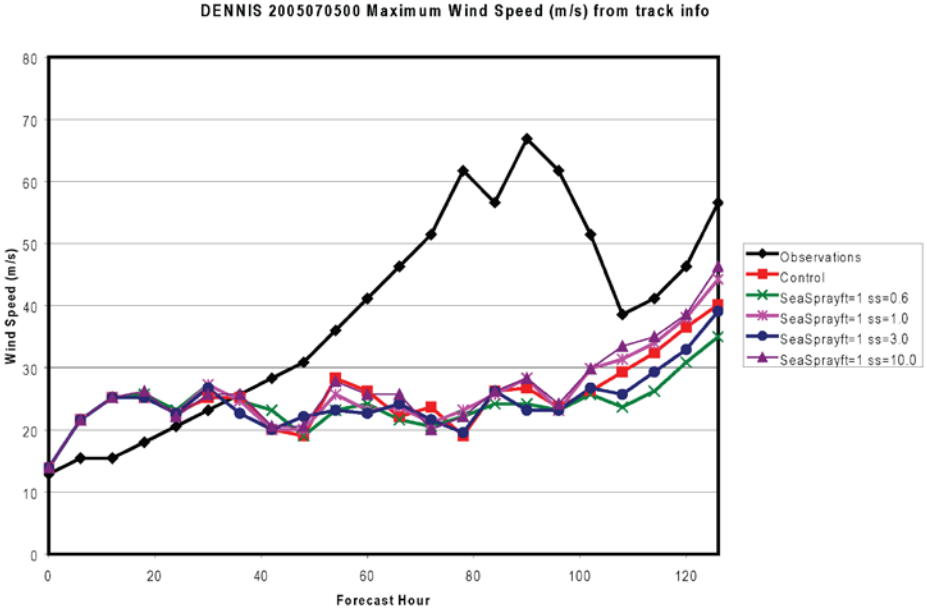
Figure 3: The maximum surface winds (ms^{-1}) (a) and sea-level pressure (mb) (b) for Hurricane Emily (2005) with *ss* = 0.6, 1, 3 and 10 while *ft* = 1. The black line (labeled as Observations) is the best track estimate. The red line is the control run without the sea-spray parameterization. The model was initialized at 0000 UTC 12 July 2005.

forecast hour	Control lat	Control lon	*ss*=0.6 lat	*ss*=0.6 lon	*ss*=1 lat	*ss*=1 lon	*ss*=3 lat	*ss*=3 lon	*ss*=10 lat	*ss*=10 lon
0	11.2N	46.3W	11.2N	46.3W	11.2N	46.3W	11.2N	46.3W	11.2N	46.3W
6	11.5N	47.7W	11.5N	47.8W	11.5N	47.7W	11.5N	47.7W	11.5N	47.7W
12	11.9N	49.3W	11.9N	49.3W	11.9N	49.3W	12.0N	49.3W	11.9N	49.3W
18	12.5N	51.1W	12.5N	51.0W	12.4N	51.1W	12.3N	51.2W	12.4N	51.2W
24	13.0N	52.5W	13.0N	52.5W	13.0N	52.5W	13.0N	5.26W	12.9N	52.5W
30	13.6N	54.1W	13.6N	54.0W	13.6N	54.0W	13.6N	54.0W	13.6N	54.0W
36	14.2N	55.7W	14.2N	55.8W	14.2N	55.8W	14.2N	55.8W	14.2N	55.8W
42	14.7N	57.5W	14.7N	57.7W	14.8N	575W	147N	57.6W	14.8N	57.6W
48	15.3N	59.1W	15.2N	59.3W	15.1N	59.2W	15.1N	59.2W	15.2N	59.1W
54	15.7N	61.0W	15.5N	61.0W	15.6N	61.0W	15.8N	60.9W	15.7N	60.9W
60	16.3N	62.5W	16.3N	62.4W	16.1N	62.5W	16.3N	62.5W	16.3N	62.6W
66	16.8N	64.1W	16.9N	64.1W	16.8N	64.1W	16.9N	64.1W	16.7N	64.0W
72	17.4N	65.4W	17.4N	65.4W	17.4N	65.4W	17.4N	65.4W	17.3N	65.4W
78	18.0N	66.9W	18.0N	66.9W	18.1N	67.0W	18.0N	66.8W	17.9N	66.9W
84	18.4N	68.2W	18.6N	68.1W	18.6N	68.3W	18.6N	68.0W	18.4N	68.2W
90	18.9N	69.4W	19.1N	69.3W	19.0N	69.6W	19.1N	69.1W	18.8N	69.4W
96	19.5N	70.5W	19.7N	70.4W	19.6N	70.7W	19.7N	70.3W	19.4N	70.6W
102	19.8N	71.9W	20.0N	71.8W	19.9N	72.0W	20.1N	71.6W	19.7N	71.9W
108	20.0N	72.9W	20.3N	72.8W	20.0N	73.1W	20.2N	72.8W	19.8N	72.9W
114	20.2N	74.0W	20.4N	74.0W	20.3N	740.W	20.3N	73.9W	20.2N	73.8W
120	20.8N	76.5W	20.6N	75.0W	20.6N	75.2W	20.4N	74.9W	20.5N	75.1W
126	20.8N	76.5W	20.9N	76.2W	21.0N	76.4W	20.8N	76.2W	20.7N	76.5W

Table 3: Predicted track locations of Hurricane Emily without the sea-spray parameterization (control) and with the sea-spray parameterization in which *ss* = 0.6, 1, 3 and 10 while *ft* = 1

4.4 Dennis (2005)

Figure 4 and Table 4 show the results from the sensitivity runs with Hurricane Dennis (2005). The model was initialized at 0000 UTC 05 July 2005. Like in the previous cases, while the predicted intensity is sensitive to *ss*, the predicted track does not show significant sensitivity. The variation of the predicted intensity with *ss* is also very nonlinear. It is interesting to note that predicted storm does not intensify in any of the runs**.** This is due to the fact that all the predicted tracks are much farther northward than the best track estimate such that they all pass over the Caribbean Islands when the real storm was still over the open water and intensifying. Again, the inclusion of sea-spray effect is not capable of correcting the track prediction. Additionally, the intensity of Hurricane Dennis is not as sensitive to *ss* as seen in the previous cases. This can be attributed to the fact that the predicted track from all the runs has such great errors that the predicted storm does not intensify and the maximum wind speeds do not reach 30 ms^{-1} until after 100 hours into the forecast. The sea-spray parameterization scheme has little effect on intensity until wind speeds are greater than 30 ms^{-1}, which is consistent with the observational finding that the impact of sea spray on air-sea thermal fluxes is insignificant for wind speed less than 30 ms^{-1}.



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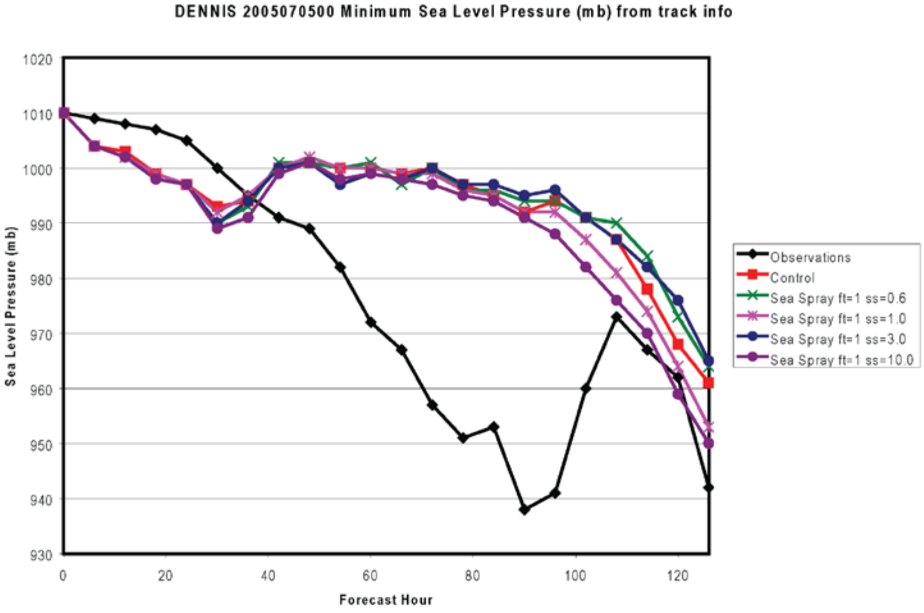


(b)

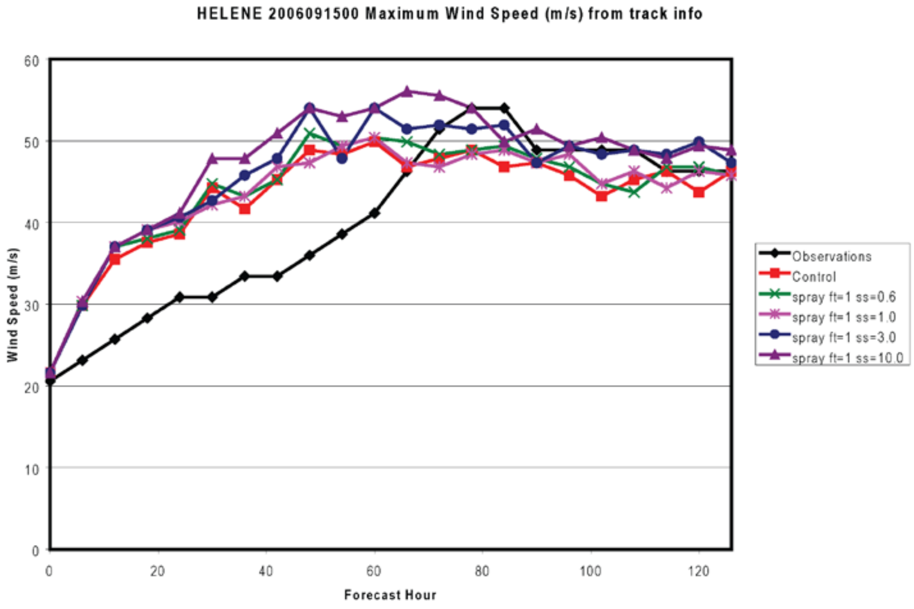
Figure 4: The maximum surface winds (ms^{-1}) (a) and sea-level pressure (mb) (b) for Hurricane Dennis (2005) with *ss* = 0.6, 1, 3 and 10 while *ft* = 1. The black line (labeled as Observations) is the best track estimate. The red line is the control run without the sea-spray parameterization. The model was initialized at 0000 UTC 05 July 2005.

forecast hour	Control lat	Control lon	*ss*=0.6 lat	*ss*=0.6 lon	*ss*=1 lat	*ss*=1 lon	*ss*=3 lat	*ss*=3 lon	*ss*=10 lat	*ss*=10 lon
0	12.2N	62.3W	12.2N	62.3W	12.2N	62.3W	12.2N	62.3W	12.2N	62.3W
6	12.7N	63.6W	12.7N	63.7W	12.8N	63.7W	12.8.N	63.7W	12.8N	63.7W
12	13.9N	65.2W	13.9N	65.3W	13.9N	65.2W	13.9N	65.3W	13.9N	65.3W
18	15.2N	66.9W	15.2N	66.9W	15.2N	66.9W	15.2N	66.9W	15.2N	66.9W
24	16.5N	68.3W	16.5N	68.3W	16.5N	68.4W	16.5N	68.3W	16.5N	68.3W
30	17.3N	69.8W	17.3N	69.8W	17.3N	69.8W	17.3N	69.7W	17.2N	69.9W
36	18.3N	71.2W	18.3N	71.3W	18.2N	71.4W	18.3N	71.3W	18.3N	71.4W
42	19.1N	72.7W	19.2N	72.6W	19.1N	72.5W	19.1N	72.8W	19.0N	72.6W
48	19.6N	73.5W	19.8N	73.6W	19.7N	73.5W	19.4N	73.5W	19.8N	73.5W
54	20.3N	74.2W	20.2N	74.5W	20.3N	74.2W	20.4N	74.3W	20.1N	74.4W
60	21.4N	75.0W	21.5N	75.0W	21.5N	75.1W	21.3N	75.1W	21.3N	75.3W
66	22.6N	75.9W	22.7N	76.2W	22.4N	76.0W	22.7N	76.0W	22.4N	76.2W
72	23.5N	77.0W	23.1N	77.1W	23.3N	77.0W	23.5N	77.3W	23.2N	77.4W
78	23.9N	78.2W	23.4N	78.1W	23.9N	77.9W	23.6N	78.1W	23.4N	78.1W
84	24.1N	78.6W	24.5N	78.4W	24.4N	78.5W	24.7N	78.3W	24.5N	78.5W
90	25.1N	78.7W	25.4N	78.8W	25.4N	78.8W	25.5N	78.8W	25.4N	78.7W
96	26.3N	78.7W	264.N	78.9W	26.5N	78.9W	26.7N	78.9W	26.9N	79.2W
102	27.5N	78.9W	27.5N	78.7W	27.5N	79.0W	27.6N	79.0W	27.7N	79.3W
108	28.9N	78.8W	29.3N	78.7W	28.9N	78.7W	29.2N	78.7W	29..4N	78.9W
114	30.4N	78.6W	30.9N	78.5W	30.4N	78.6W	30.9N	78.4W	31.1N	78.7W
120	31.9N	77.8W	32.4N	77.7W	32.0N	77.7W	32.5N	77.9W	32.9N	78.0W
126	33.4N	76.6W	34.0N	76.5W	33.5N	76.8W	34.3N	76.8W	34.6N	77.0W

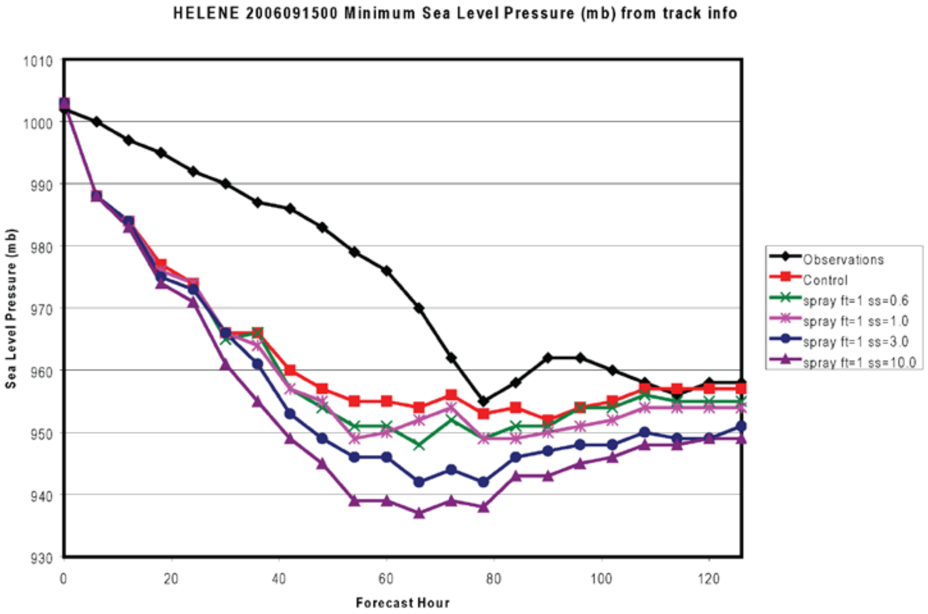
Table 4: Predicted track locations of Hurricane Dennis without the sea-spray parameterization (control) and with the sea-spray parameterization in which *ss* = 0.6, 1, 3 and 10 while *ft* = 1.

4.5 Helene (2006)

The results from the sensitivity runs with Hurricane Helene (2006) (initialized at 0000 UTC 15 September 2006) are different from the previous cases (see Fig. 5). In this case, the predicted intensity in the control run is greater than the best track estimate. When the sea-spray effect is included, the predicted storm deepens even more than that from the control run, further worsening the over-prediction of the intensity. However, as in the previous cases, while the predicted intensity is sensitive to *ss*, the predicted track does not show significant sensitivity and the variation of the predicted intensity with *ss* is similarly nonlinear. On the other hand, unlike



(a)



(b)

Figure 5: The maximum surface winds (ms^{-1}) (a) and sea-level pressure (mb) (b) for Hurricane Helene (2006) with *ss* = 0.6, 1, 3 and 10 while *ft* = 1. The black line (labeled as Observations) is the best track estimate. The red line is the control run without the sea-spray parameterization. The model was initialized at 0000 UTC 15 September 2006.

the previous cases, the predicted intensification takes place earlier and faster than the best track estimate shows. This is, perhaps, related to the fact that the predicted track in all the runs are so much different than the best track estimate (see Table 5) that the predicted storm is under the influence of different background winds and the underneath sea-surface temperatures than the real storm. Further study is required to pin down the real causes for the discrepancy between the forecast and the best track estimate.

forecast hour	Control lat	Control lon	*ss*=0.6 lat	*ss*=0.6 lon	*ss*=1 lat	*ss*=1 lon	*ss*=3 lat	*ss*=3 lon	*ss*=10 lat	*ss*=10 lon
0	14.2N	38.3W	14.2N	38.3W	14.2N	38.3W	14.2N	38.3W	14.2N	38.3W
6	14.9N	39.5W	14.9N	39.5W	14.9N	39.5W	14.9N	39.5W	14.9N	39.5W
12	15.8N	40.7W	15.8N	40.7W	15.8N	40.7W	15.8N	40.7W	15.8N	40.7W
18	16.6N	41.7W	16.6N	41.7W	16.7N	41.7W	16.6N	41.7W	16.6N	41.7W
24	17.3N	42.5W	17.3N	42.5W	17.3N	42.6W	17.3N	42.5W	17.3N	42.5W
30	18.0N	43.7W	18.0N	43.7W	18.0N	43.6W	18.0N	43.5W	18.0N	43.6W
36	18.5N	44.2W	18.5N	44.3W	18.4N	44.0W	18.5N	44.1W	18.5N	44.4W
42	19.1N	44.8W	19.1N	45.0W	19.0N	44.8W	19.1N	44.8W	19.1N	45.0W
48	19.5N	45.5W	19.5N	45.6W	19.5N	45.4W	19.5N	45.4W	19.5N	45.5W
54	19.9N	46.0W	19.9N	46.1W	19.8N	45.9W	19.9N	45.8W	19.9N	46.1W
60	20.2N	46.3W	20.2N	46.6W	20.2N	46.2W	20.3N	46.3W	20.3N	46.5W
66	20.6N	46.6W	20.6N	47.0W	20.6N	46.6W	20.7N	46.8W	20.7N	46.9W
72	21.2N	46.9W	21.1N	47.3W	21.2N	46.9W	21.2N	47.0W	21.4N	47.1W
78	21.8N	47.3W	21.8N	47.6W	21.7N	47.2W	21.9N	47.3W	22.0N	47.6W
84	22.5N	47.7W	22.5N	48.0W	22.5N	47.5W	22.6N	47.7W	22.7N	48.0W
90	23.2N	48.0W	23.2N	48.4W	23.2N	48.1W	23.4N	48.1W	23.4N	48.5W
96	24.0N	48.4W	23.9N	48.7W	24.0N	48.3W	24.1N	48.4W	24.2N	48.8W
102	24.7N	48.8W	24.7N	49.1W	24.8N	48.8W	24.9N	48.9W	24.9N	49.2W
108	25.5N	49.3W	25.4N	49.6W	25.5N	49.2W	25.7N	49.4W	25.7N	49.7W
114	26.3N	49.7W	26.2N	49.9W	26.3N	49.7W	26.6N	49.8W	26.6N	50.0W
120	27.2N	50.3W	27.1N	50.4W	27.1N	50.2W	27.5N	50.3W	27.6N	50.5W
126	28.3N	50.8W	28.2N	50.9W	28.1N	50.8W	28.6N	50.8W	28.7N	51.0W

Table 5: Predicted track locations of Hurricane Helene without the sea-spray parameterization (control) and with the sea-spray parameterization in which *ss* = 0.6, 1, 3 and 10 while *ft* = 1.

4.6 Summary of the first-year accomplishments

During the first year of our Joint Hurricane Testbed project, the bulk parameterization scheme of air-sea sensible and latent heat fluxes developed at NOAA/ESRL was implemented and tested in the HWRF model. Testing of the scheme with the current operational setup of the HWRF model indicated that the scheme performed as well as expected. The major findings from all the sensitivity runs so far are:

- The NOAA/ESRL sea-spray parameterization scheme is an effective physics option to alleviate the underestimate bias in the HWRF predicted intensity.
- The impact of the inclusion of the sea-spray effect on the hurricane track prediction is so small that it can be neglected.
- There is significant sensitivity in the HWRF predicted intensity to the uncertainties of two parameters, droplet source strength and feedback strength**,** in the sea-spray parameterization scheme.
- Due to the nonlinear interaction between the air-sea thermal fluxes and dynamical processes associated with the hurricane intensification, the response of the predicted storm intensity is noticeably nonlinear to the change of droplet source strength and feedback strength.
- The fact that the inclusion of the sea-spray only increases the intensification upon the control run strongly suggests that errors in the HWRF model forecast can only be partially attribute to the errors in the thermal fluxes across the air-sea interface. The errors in other controlling factors in the intensification forecast such as the background wind shear and the eye-wall contraction dynamics are as significant as those in the air-sea fluxes.

5. RESULTS OF THEORETCIAL STUDY AND MODEL EVALUATION STATISTICS IN THE SECOND YEAR

5.1 Theoretical study

As the project progressed into the second year, in addition to the further testing of the sea-spray parameterization scheme in the HWRF model, the explicit sea-spray model of Kepert et al. (1999) coupled with the 1-D Mellor-Yamada turbulence mixing model was used to investigate the thermal and kinematic feedback effects. This explicit spray model is capable of simulating the evaporation and dispersion of saline water droplets of various sizes. There is full coupling among the spray-droplet microphysics, turbulence mixing, and droplet transport. Results from the investigation using the explicit sea spray model revealed important characteristics of the way in which evaporating droplets of various sizes modify the turbulence mixing near the surface, which in turn affects further droplet evaporation. Based on these results, a parameterization accounting for the kinematic effect of sea spray in the surface thermal and momentum fluxes was developed.

The parameterization of the effects of sea spray on the surface momentum flux is motivated by the notion that the same turbulence that transports heat across the air-sea interface is also responsible for the momentum transport and the generation of sea spray. Progress has been made over the past year in using the explicit sea-spray model to understand and parameterize the effects of sea spray on the momentum flux across the air-sea interface. These effects were recognized as significant under high winds in previous studies (see, e.g., Pielke and Lee 1991 and Andreas 2004). The explicit sea-spray model of Kepert et al. (1999), due to its original intention to examine the thermal feedback of sea spray, did not include the effects of sea spray on the surface momentum flux. In order to use the same model to investigate the

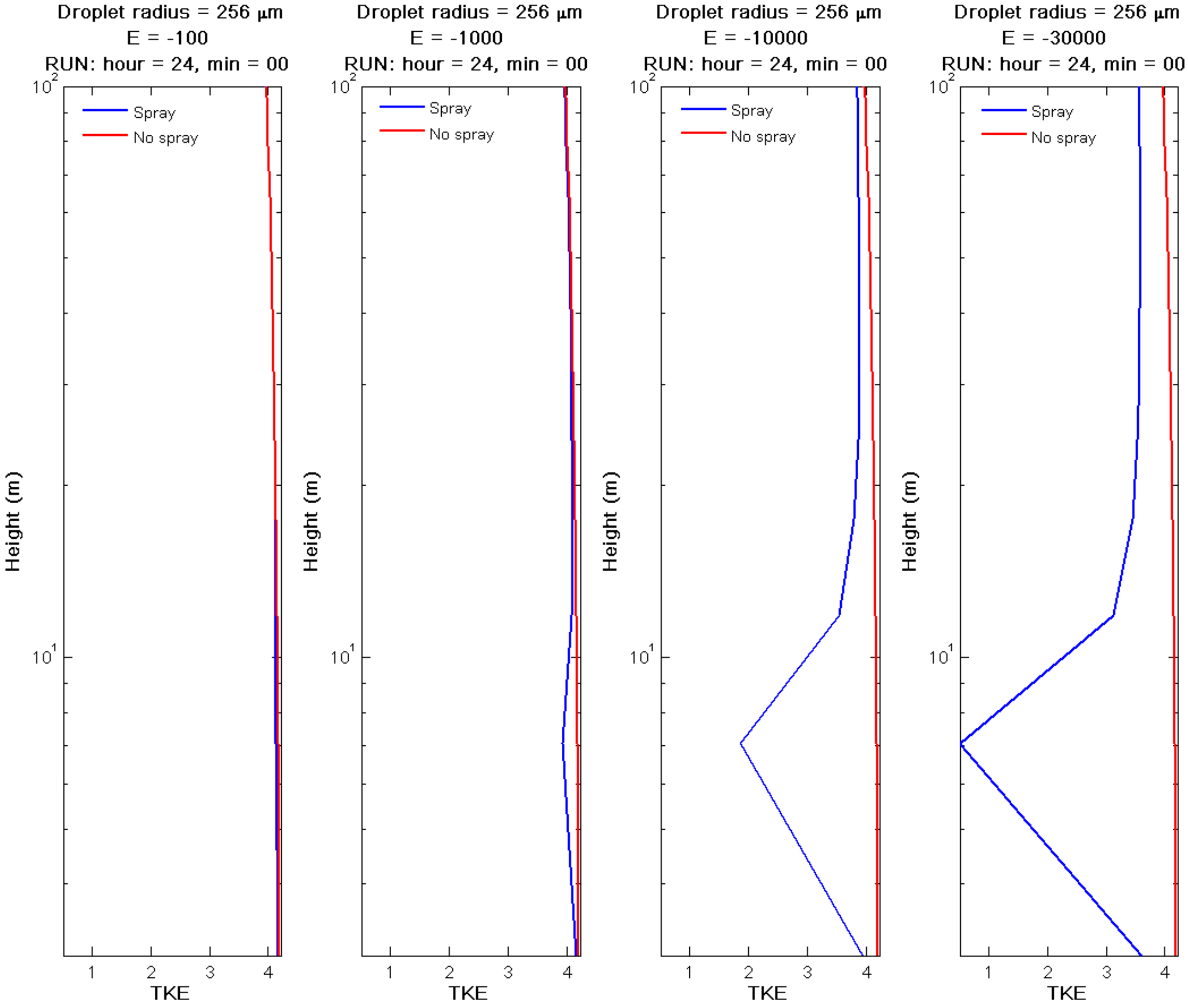


Figure 6: The change of vertical TKE distribution as the total spray mass of large spray droplets (r = 256 μm) increases. The total mass production of the droplets is indicated by the magnitude of E (in watt unit), which equals to the total mass multiplied by the latent heat.

kinematic feedback of sea spray to the momentum flux, an additional term has been included in the turbulence kinetic energy (TKE) equation to take into account the TKE dissipation due to sea-spray load. Figure 6 compares the differences in the simulated vertical TKE profiles between the runs with and without sea spray that are driven by hurricane winds. The model output is valid at 20 h into the simulation when the solution becomes quasi-steady. It is seen that as the total mass of large spray droplets (r = 256 μm) increases, the TKE within the lowest 100

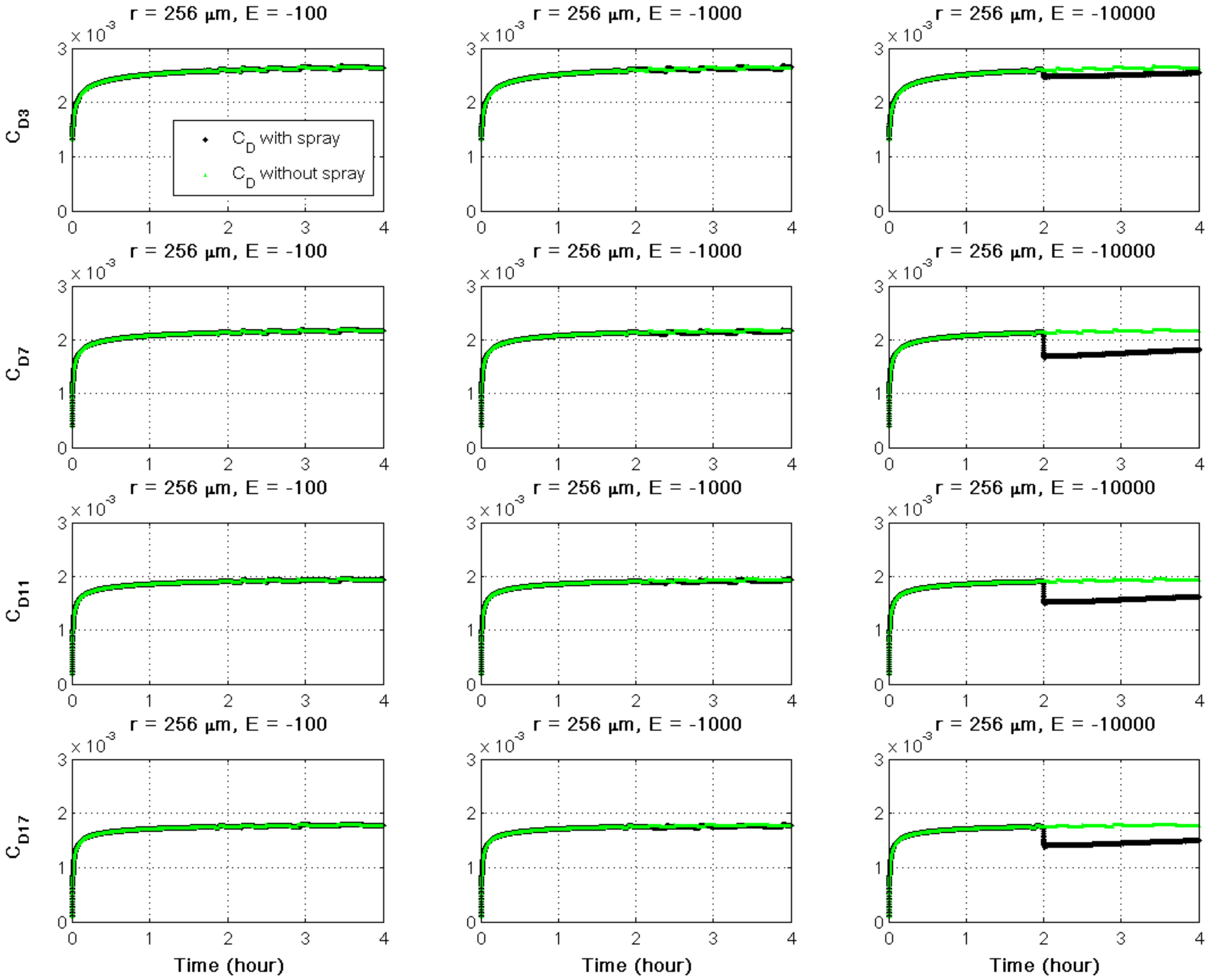


Figure 7: The drag coefficients at 3 m (1st row), 7 m (2nd row), 11 m (3rd row) and 17 m (4th row) above the surface, corresponding to the run without sea spray (black) and the runs with various total mass of large droplets (r = 256 μm) large spray droplets (green): |E| = 100 W, 1000 W, 10000W. The spray generation takes place at z = 7 m, and does not start until 2 h into the simulation. The total mass production of the droplets is indicated by the magnitude of E (in watt unit), which equals to the total mass multiplied by the latent heat.

m decreases with the minimum at the spray ejection level (~7 m). Changes in the drag coefficient at z = 3 m, 7 m, 11 m and 17 m corresponding the changes in the TKE profile are shown in Fig, 7 for |E| = 100 W, 1000 W, 10000 W. Since the spray droplets are ejected into the air at z = 7 m starting at 2 h into the simulation, the results shown in Fig. 7 indicate that the net effects of large spray droplets on the spray-filled surface layer are that the drag coefficient decreases and thus the flow within the surface layer accelerates. This is no surprise because (1) the free fall of spray suppresses turbulence and (2) the spray mass increases the effective density of the air, leading to more stable stratification within the surface layer. Consequently, the vertical momentum transport by turbulence is reduced in the surface layer by sea spray.

To parameterize the kinematic effects of spray in operational models where the spray-filled surface layer is not resolved, one must appeal to the first principles of the Monin-Obukhov similarity theory. Basically our parameterization scheme takes into account the kinematic effects of spray in the friction velocity calculation. Following the procedure summarized in Lykossov (2001), the application of the steady TKE and spray-droplet transport equations in the spray-filled surface layer leads 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. It is assumed in the derivation of the formulation that the thermal stratification is neutral, and droplets are ejected at z = 10 m above the mean sea surface. Figure 8 presents that spray-modified drag coefficient and heat exchange coefficient at z = 25 m above the mean sea surface (regarded as the lowest model level). The results shown in Fig. 8 are consistent with the results shown in Figs. 6 and 7: under the same background mean conditions the flow in the surface layer accelerates by the consumption of TKE for spray suspension. In other words, the suspended spray droplets decrease the turbulent drag. The variation of the drag coefficient with wind speed agrees well qualitatively with those revealed by previous observational and theoretical investigations such as Powell et al. (2003), Andreas (2004) and Kudryavtsev (2006).

The implementation and testing of the parameterization scheme in the HWRF model requires taking into account the thermal stratification as expressed in the Monin-Obukhov stability parameters. Figure 9 compares the best track estimate of the maximum wind speed and the minimum sea level pressure of Hurricane Katrina (2005) with those from 4 HWRF model forecast runs. The four HWRF runs shown in Fig. 9 include**:** one run with sea spray, two runs including only the thermal effects of sea spray with different values of source strength parameter (ss =1 and 10)**,** and one run including both the thermal and kinematic effects of sea spray with the source strength parameter of 1. The impact of the kinematic effects on the forecasted track is negligible.

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. Particularly, the relationship between the wave-induced drag on the spray-modified drag should be investigated.

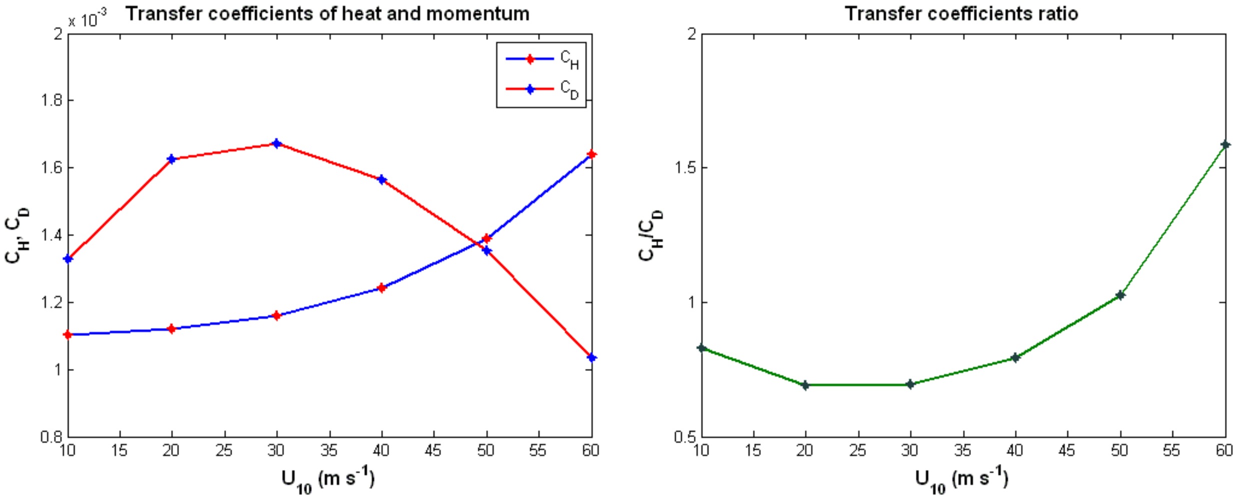


Figure 8: The left panel shows the drag coefficient (C_D) and the heat exchange coefficient (C_H) at z = 25 m above the mean sea surface. The right panel is the ratio of C_H / C_D. It is assumed that spray droplets are ejected at z = 10 m above the mean surface.

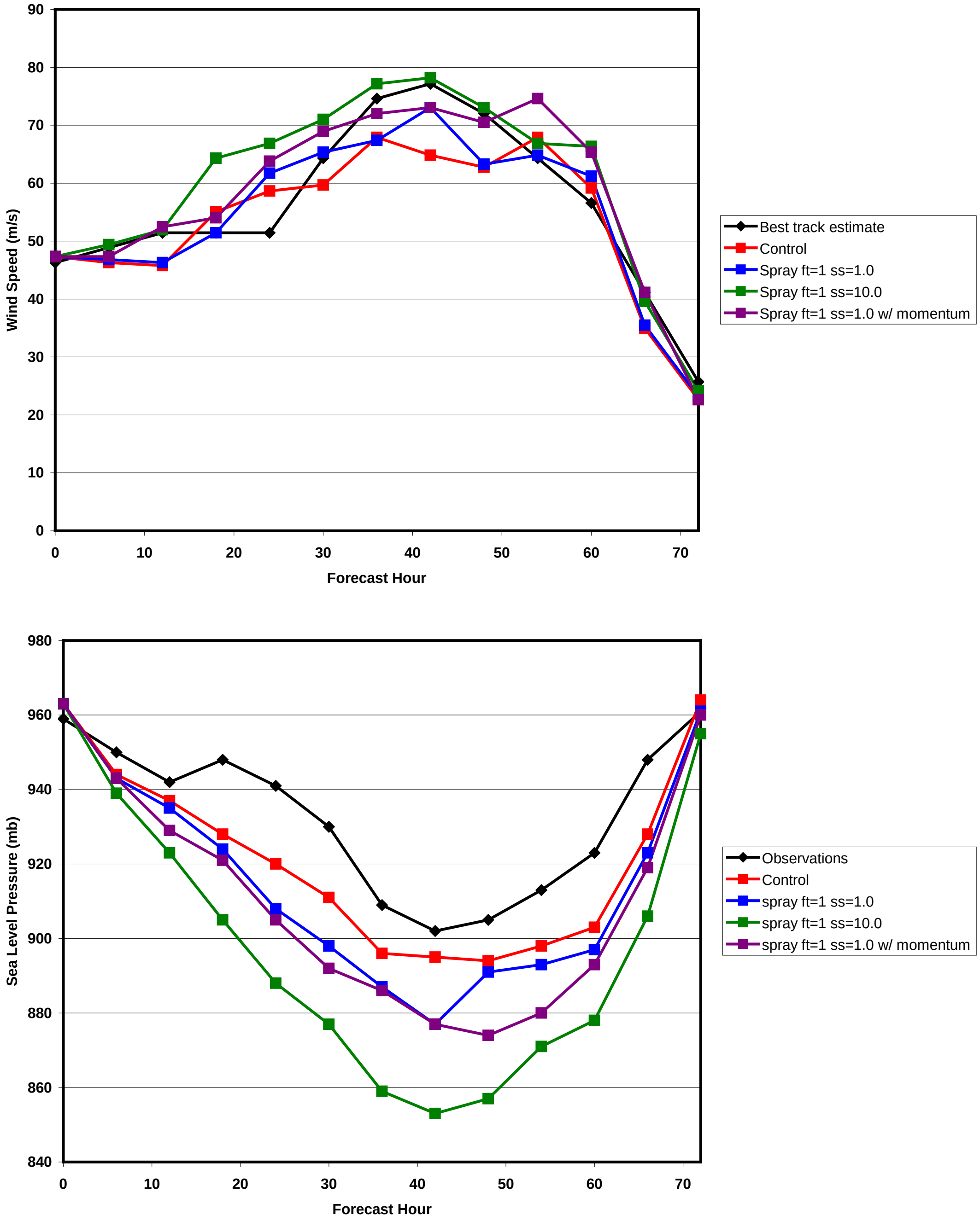


Figure 9: The maximum wind speed (top panel) and minimum sea level pressure (bottom panel) from the best track estimate (back) and four HWRF forecast runs of Hurricane Katrina (2005). The four HWRF model runs are: a run without sea spray (red) , two runs including only the thermal effects of seas spray with the source strength parameter of 1 (blue) and 10 (green) and one run including both the thermal and kinematic effects of seas pray with the source strength parameter of 1 (purple).

In summary, with the physical understanding of the kinematic effects of sea spray on the surface momentum flux, we developed a parameterizations scheme for the HWRF model that includes both the kinematic and thermal effects of sea spray on the momentum and thermal fluxes. Results from running the HWRF model with the sea-spray scheme with both kinematic and thermal feedback effects show that the scheme is a potentially promising option in operational models to improve hurricane intensity forecasts.

5.2 Evaluation of the improved sea-spray scheme

As planned with the NCEP/EMC team, a total of five benchmark historic hurricane events were chosen to run the cycled forecasts of the HWRF model to evaluate the improved scheme. Although all the runs have been completed, the diagnosis to obtain the evaluation statistics mandated at NCEP is still ongoing as the HWRF model evolves with new updates. Only some of the statistics for three of the five events are reported here: Dennis (2005), Katrina (2005), Rita (2005).

5.2a Dennis (2005)

Figure 10 shows the biases of the forecasted track and maximum surface winds from the runs with the sea-spray scheme for Dennis (2005), and compares the biases those from the forecast runs without the scheme. It is clear that the inclusion of the scheme tends to produce an intensity bias that varies around that of the runs without the scheme, while the track is degraded gradually after 72 hours.

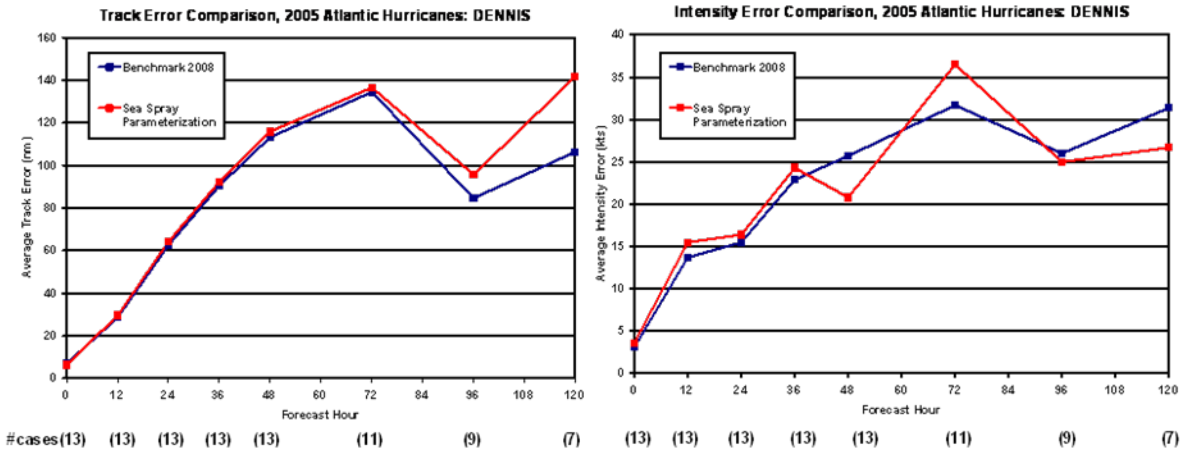


Figure 10: Biases of the forecasted track and maximum surface winds from the runs with (red) and without (blue) the sea-spray scheme for Dennis (2005). The number beneath each hour mark is the number of samples in the bias calculation for the hour.

5.2b Katrina (2005)

For this case, the accuracy of the track forecast from the runs with the sea-spray scheme is very close to that from the runs without the scheme during the first 72 hours of the forecast but becomes worse after 84 hours of the forecast. The intensity errors of the runs with the sea-spray scheme are larger than those without the scheme (see Fig. 11).

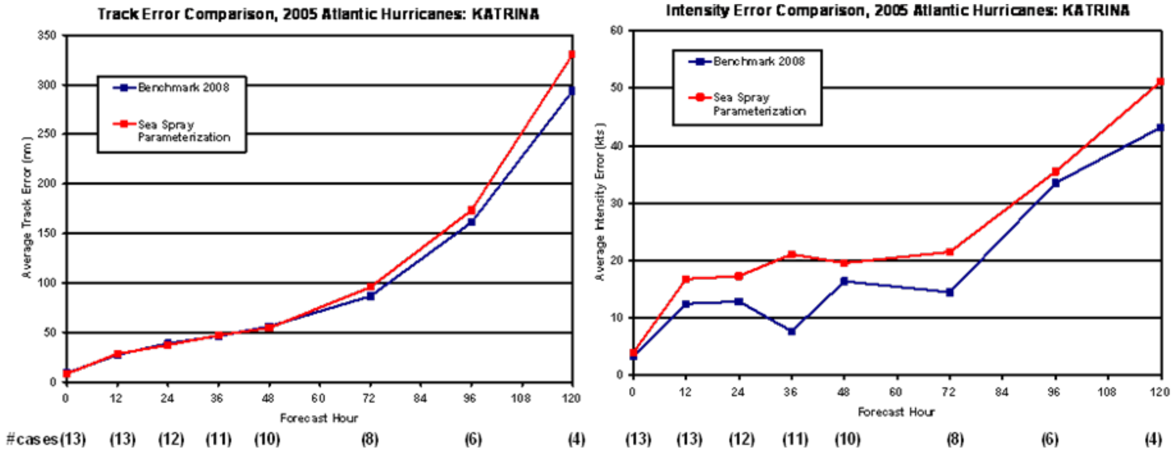


Figure 11: Biases of the forecasted track and the maximum surface winds from the runs with (red) and without (blue) the sea-spray scheme for Katrina (2005). The number beneath each hour mark is the number of samples in the bias calculation for the hour.

5.2c Rita (2005)

The biases of the forecasted track and the maximum surface winds from the runs with the sea-spray scheme for this case are shown and compared to those without the scheme in Fig. 12. It is interesting to note that for this case the impact of the sea-spray scheme on the track forecast is negligible. While the scheme overestimates the intensity during the first 72 hours of the forecast, there is an improvement at hour 96. Comparing this case with the Dennis and Katrina cases, it appears that the errors in the intensity forecast are not closely associated with those in the track forecast. It is also worth mentioning that the increase in the forecasted bias during the first 24 hours of the forecast appears to be intrinsic to the HWRF model's spin-up, possibly associated with its vortex initialization. This result has two implications. The first is that the errors in the HWRF model forecast can only be partially attributed to the errors in the surface fluxes. The second implication is that the tuning of the two parameters in the sea-spray scheme should be performed in accordance with the tuning of the vortex initialization.

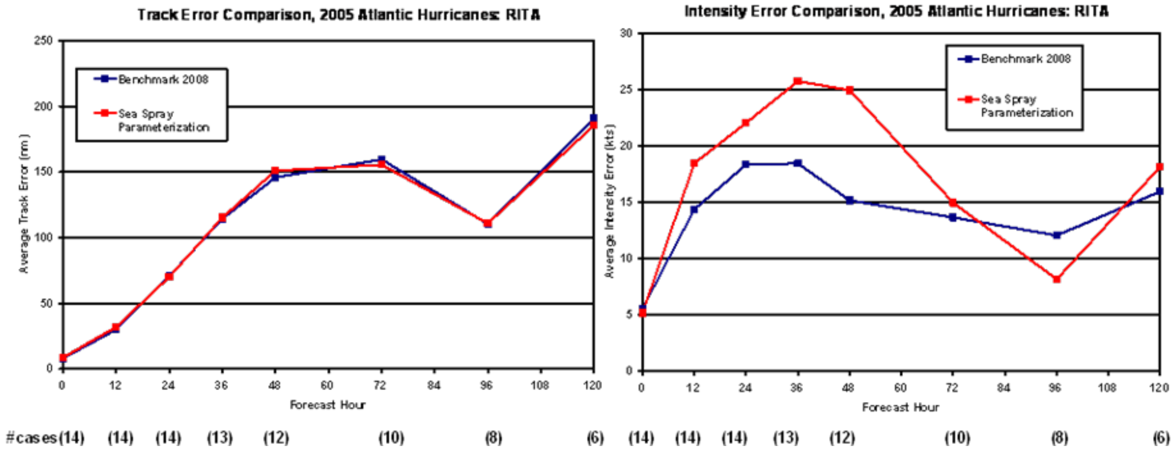


Figure 12: Biases of the forecasted track and the maximum surface winds from the runs with (red) and without (blue) the sea-spray scheme for Rita (2005). The number beneath each hour mark is the number of samples in the bias calculation for the hour.

5.2d Summary

Statistical results from the second year of this project indicate more aspects of the ESRL sea-spray scheme which did not emerge in last year's evaluation of the scheme in single-cycle cold-start runs. The major findings from all the sensitivity runs so far are:

- For strong storms (such as Katrina and Rita), the scheme tends to produce a greater positive bias of intensity during the first 48-72 hours than the control runs, while the impact on track is small.

- For weak storms (such as Dennis), the scheme tends to produce an intensity bias that varies around that of the control runs, while the track is degraded slightly after 72 hours.
- The errors in the intensity forecast are not closely associated with those in the track forecast.
- The increase in the forecast bias during the first 24 hours appears to be intrinsic to the HWRF models spin-up, possibly associated with its vortex initialization.
- The last finding has two implications. The first is that the errors in the HWRF model forecast can only be partially attributed to the errors in the surface fluxes. The second is that the tuning of the two parameters in the sea-spray scheme should be performed in accordance with the tuning of the vortex initialization.

5.3 Summary of the second-year accomplishments

In addition to the further evaluation of the sea-spray parameterization scheme in the HWRF model, the explicit sea-spray model of Kepert et al. (1999) coupled with the 1-D Mellor-Yamada turbulence mixing model was used to investigate both the thermal and kinematic feedback effects. Results from the investigation using the explicit sea spray model revealed important characteristics of the way in which evaporating droplets of various sizes modify the turbulence mixing near the surface, which in turn affects further droplet evaporation. Based on these results, a parameterization accounting for the kinematic effect of sea spray in the surface thermal and momentum fluxes was developed. The ESRL sea-spray scheme was then improved based on the results obtained from the abovementioned 1-D explicit sea-spray simulations by taking into account the feedback effect of sea spray on the momentum flux in the surface boundary layer. Testing of the scheme was conducted in the operational cycling mode in the HWRF model for five benchmark historical hurricane cases. This is the first time the ESRL sea-spray scheme was evaluated in cycled operational forecasts. The preliminary results of the evaluation statistics for three of the five benchmark cases indicate that for strong storms (such as Katrina and Rita), the scheme tends to produce a greater positive bias of intensity during the first 48-72 hours than the control runs, while the impact on the track is small. For weak storms (such as Dennis), the scheme tends to produce an intensity bias that varies around that of the control runs, while the track is degraded slightly after 72 hours.

6. SUMMARY OF DELIVERABLES AND PUBLICATIOLNS IN PREPARATION

The major outcome of this 2-year project is that the NOAA/ESRL sea-spray parameterization scheme has been added to the atmospheric boundary layer physics subroutine of the operational HWRF model and evaluated in cycled operational forecasts for some HWRF benchmark cases. Due to the sound physics in the parameterization scheme and the positive results from the evaluation, a consensus has been reached between EMC and ESRL that the scheme will be included in the future versions of the operational HWRF model as an option in the model physics configuration.

There are also two journal articles in preparation that are base on the results from this project. The first article is entitled “Impact of Sea Spray on the Surface Boundary Layer”, while the second article is entitled “Parameterizations of Sea-Spray Impact on the Air-Sea Momentum and Heat Fluxes”. The following is the abstract of the first article in preparation:

> The feedback effects of sea-spray on the heat and momentum fluxes under equilibrium conditions associated with winds of tropical cyclones is investigated using a

1-D coupled sea-spray and surface boundary layer (SBL) model. This model is capable of simulating the microphysical aspects of evaporation of saline water droplets of various sizes and their dynamic and thermal interaction with the turbulence mixing that is simulated by the Mellor-Yamada 1.5-order closure scheme. Sea-spray droplet generation is described by a state-of-the-art parameterization which predicts the size spectrum of sea-spray droplets at a given surface stress (or wind speed). The results from a series of simulations reveal salient characteristics of the way in which evaporating droplets of various sizes modify the turbulence mixing near the surface, which in turn affects further droplet evaporation. All these results are direct consequences of the effects of sea-spray on the balance of TKE in the spray-filled surface layer. In particular, the overall impact of sea-spray droplets on the mean winds depends on the wind speed at the level of sea-spray generation. When the wind is below 35 ms^{-1}, the droplets are small in size and tend to evaporate entirely and thus cool the spray-filled layer, while at winds above 50 ms^{-1}, the size of droplets is so big that they do not have enough time to evaporate that much before falling back into the sea. Effectively, the sensible heat carried by the droplets is released to the ambient air, increasing the buoyancy of the surface layer and enhancing the turbulent mixing. The suspension of sea-spray droplets reduces the buoyancy and makes the surface layer more stable, rendering the friction velocity lowered and the downward turbulent mixing of momentum reduced. The results from the numerical experiments also suggest that a displacement equal to the mean wave height should be included in the logarithmic profiles of wind and thermal fields, in order to not violate the constant flux assumption critical to the Monin-Obukhov similarity theory.

The abstract of the second article in preparation is:

Although it is widely recognized that sea spray under hurricane-strength winds is omnipresent in the marine surface boundary layer (MSBL), how to parameterize the effects of sea spray on the air-sea momentum and heat fluxes at hurricane-strength winds still remains a subject of research. This paper focuses on how the effects of sea spray on

the momentum and heat fluxes are parameterized in weather prediction models using the Monin-Obukhov similarity theory, which is a common framework for the parameterizations of air-sea fluxes. In this scheme, the effects of sea spray can be considered as an additional modification to the stratification of the near surface profiles of wind, temperature and moisture in the MSBL. The overall impact of sea-spray droplets on the mean profiles of wind, temperature and moisture depends on the wind speed at the level of sea-spray generation (or wave state if available). As the wind speed increases, the droplet size increases, rendering an increase in the spray-mediated total enthalpy flux from the sea to the air and leveling off of the surface drag. When the wind is below 35 ms^{-1}, the droplets are small in size and tend to evaporate substantially and thus cool the spray-filled layer. When the wind is above 50 ms^{-1}, the size of droplets is so big that they do not have enough time to evaporate that much before falling back into the sea. Furthermore, the scheme includes the physics of the suspended sea-spray droplets reducing the buoyancy, therefore making the surface layer more stable. Results from testing the scheme in a numerical weather prediction model are presented along with a dynamical interpretation of the impact of sea spray on the intensification of tropical cyclones.

These two articles will be submitted for publication in January 2010.

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