475 **Evaluating HWRF Modeling of Landfallling Tropical Cyclones over Florida**

Dany Tran* and Sen Chiao
Meteorology and Climate Science
San Jose State University, San Jose, California

1. Introduction

Weather model simulations have improved exponentially with the continuing advancement of computational capabilities over time. Forecasting hurricanes and tropical cyclones (TC), in particular forecasting the track of these phenomena, has improved considerably. Forecasting the structure and intensity of TCs, especially the ones that make landfall however, still remains an issue in model simulations (Davis et al. 2008).

It is difficult to predict how tropical systems will behave when they make landfall since there are cases when a storm suddenly strengthens and experience a rapid intensification (RI) event before or during landfall. The mechanisms that drive RI for landfalling TCs are still not well-known which limit the capability of current models.

Tropical cyclones that undergo RI during landfall are an important phenomenon for their social and economical impact, especially for those who reside around the North Atlantic Basin. These storms can increase within hours and bring in tremendous amounts of precipitation that cause severe property damage and deaths. One reason that may induce RI is the change in the cloud microphysics of a system as it approaches land. The cloud microphysics controls the heat transport and precipitation processes for TCs which can affect the amount of rainfall in a specific area (Fovell et al. 2009). If a tropical cyclone that makes landfall and undergoes RI is inaccurately depicted by models, this can hinder safety precautions and cause flooding and damage.

Previous studies have been conducted to look at the cloud microphysics of TCs and its significance to TC track and intensity forecasts. Clouds transport large amounts of energy through latent heating release and precipitation processes and these changes can affect the precipitation and energy transfer of TCs which then affect the structure and intensity forecasts (Fovell et al. 2009). Aerosols have also been the focus of recent studies on their potential effects on TCs. It has been observed that increased amounts of aerosols can have a negative effect on intensity (Khain et al. 2010; Rosenfeld et al. 2012). The increase of cloud condensation nuclei (CCN) aerosols in the form of pollution and dust, form smaller cloud droplets that can also hinder the precipitation processes.Therefore it is vital to be able to properly simulate these processes within the models. However since it is difficult to track every single condensate particle, current models make general assumptions with the microphysical parameterizations, and this can strongly affect how they forecast TCs in terms of track and intensity especially for storms that undergo RI (Fovell et al. 2009).

It is important to evaluate the capability of HWRF in terms of how well the precipitation and wind speeds are captured for the respective cases and consider their social and economic implications for the area. As TCs make landfall, the structure and intensity of an individual system can vary drastically (Yaukey2011). In August 2008, Tropical Storm (TS) Fay made landfall over Florida multiple times and underwent RI as it traversed over Lake Okeechobee (Figure 1a). During this time, observed winds of up to 75 knots brought heavy rainfall which caused extreme flooding (Stewart and Beven 2009). A synoptic scale weather system during the time of TS Fay has been linked to the steering and intensification processes (e.g., Washington and Chiao 2011). TS Fay was responsible for approximately $560 million in property damage. In October 2011, an unnamed system later deemed as the Florida Gale, intensified with tropical storm force winds and made landfall over Melbourne Florida within a 24 hour period (Figure 1b).Although this case may not have caused significant property damage, it does bring up the subject about the difficulty of trying to forecast a system that underwent RI within a short period of time and the problems a more intense storm may pose.

The proposed research will utilize the Hurricane Weather Research and Forecasting model (HWRF) to expand our understanding of the effects high resolution models have on TC operations and to improve the depiction of the structure and intensity for the two cases. HWRF is

* *Corresponding author address:* D. Tran, San Jose State University, San Jose, CA, 94087.
E-mail: dany.tran@sjsu.edu, trandany@gmail.com

an atmosphere-ocean coupled model that has been operational since 2007 and has been aimed to improve the structure, intensity and precipitation forecasts for TCs. TS Fay and the Florida Gale both move from the ocean to land which may not be resolved well by HWRF since the model is more suited for ocean dwelling systems. The differences in the surface energy flux between ocean and land may cause issues with HWRF accurately depicting the TCs.

The objectives of this proposed research are to evaluate the accuracy of the wind field and rain band structures of both tropical cyclones (i.e., radii of 34, 50, 64 knot wind fields) before and after rapid landfall intensification and to evaluate how the cloud microphysics of HWRF affect forecasts of intensity change in terms of rainfall distribution. The ultimate goal is to understand the effects of high resolution model simulations can have on landfalling TC operations and to improve the quality of the 48-72 hour forecasts relative to the feature locations and the overall magnitude of severity of the two storms.

2. Numerical Model and Experimental Design

In order to better quantify the uncertainty and evaluate the results from HWRF model forecasts, the latest version (HWRF v3.4a) will be utilized in the proposed research. HWRF is an ocean-atmosphere coupled model facilitated by the National Centers for Environmental Prediction (NCEP) and made operational since 2007. It offers a triple-nest grid capability, with an outer domain (27km) and two nested domains (9 and 3km) that follows the storm (Figure 2). The 27 km domain will help resolve larger scale circulations and synoptic weather conditions that may have an effect on the TCs. The 9 km and 3 km nested domains will be more focused on the TC circulation and formation, most notably the wind field and rain band structure in regards to the Intensity change of the systems.

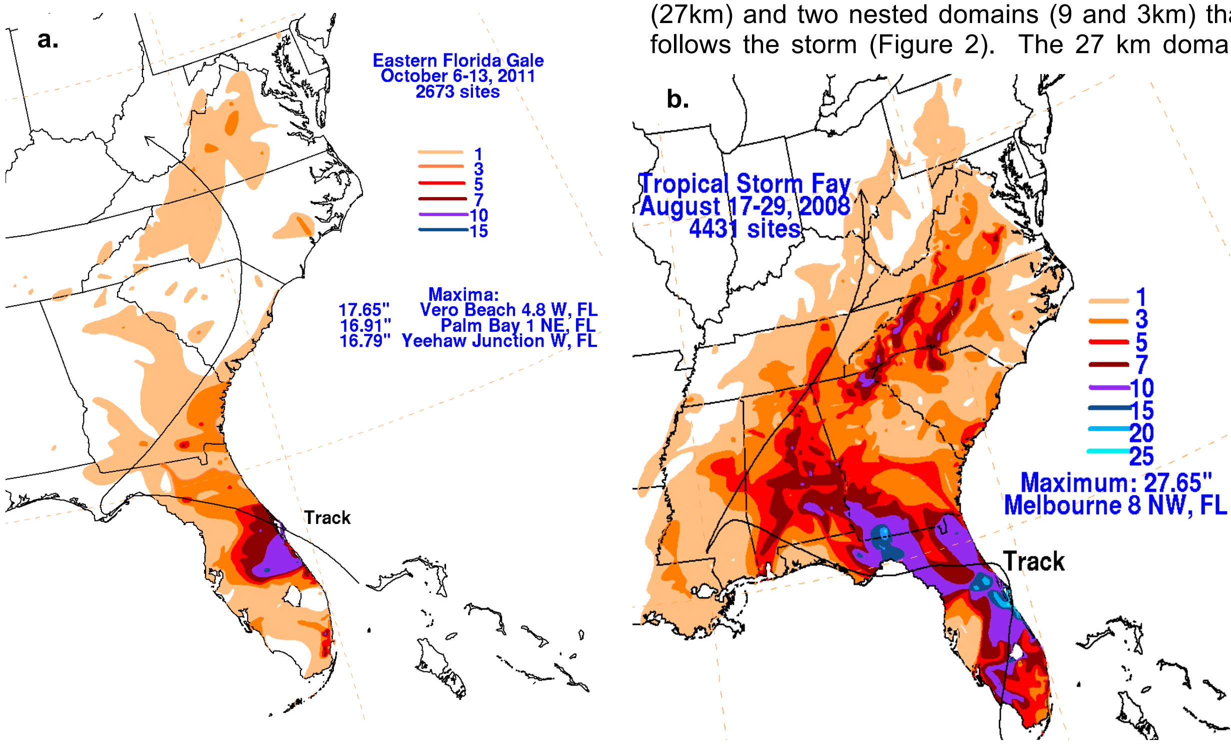

Figure 1: Observations of the track and cumulative precipitation for the Columbus Day Storm (2011) (a) and TS Fay (2008) (b).Images via The Hydrological Prediction Center (HPC).

The proposed research will focus on two events that make landfall and undergo RI, TS Fay (2008) and the Florida Gale (2011). Three simulations for each case will be conducted at least 6 hours prior to landfall each respective event. This will be done in order to capture the characteristics of the TCs before and during the period of landfall, most specifically the surface precipitation, reflectivity, winds and hydrometeor processes (e.g., Atmospheric Column Total Cloud Ice [q_i], and Cloud Water [q_c]). The main questions that will be answered with the proposed research will be: 1.) how well does the triple nested grid capability capture the structure and intensity of the two systems during landfall, and 2.) if changes in the microphysics scheme will improve the land-ocean-atmosphere coupling with rapid landfall intensification?

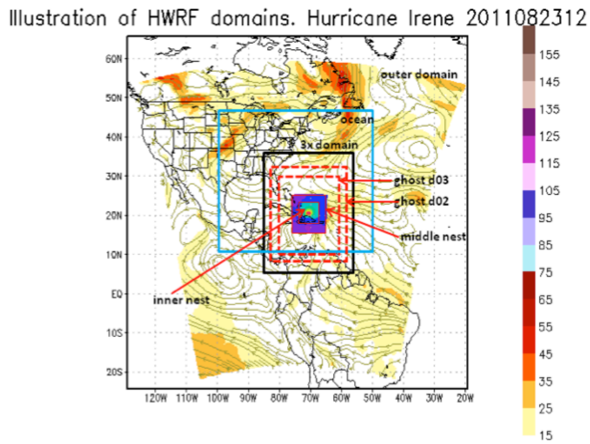

Figure 2: An example of the domains defined in the vortex initialization for HWRF v3.4a. *Image via the Developmental Testbed Center.*

The current microphysics configuration for HWRF utilizes the Ferrier Scheme. It is a single moment scheme that predicts the hydrometeor processes. Since it is difficult to manipulate the cloud microphysics scheme directly due to the current configurations of HWRF, the default value of number concentration of droplets (NCW) 250 cm^{-3}, will be changed to 100 cm^{-3} and 500 cm^{-3}. The changes in NCW and its effects on the hydrometeors processes with each case will be evaluated. Since it has been previously studied that aerosols have an effect on TC structure and intensity, changing the NCW may provide insight with the effects of aerosols on landfalling RI events. The NCW may have been affected by the landfall and intensification process for each respective case therefore, increasing and decreasing the NCW may provide insight to better forecast the structure and intensity of future storms that make landfall.

Both cases make landfall and that can change the NCW and amount of aerosols entering the system compared to when it was over the ocean. By changing the values, this may provide a better forecast for the two events. The reasons for how and why the changes in the NCW help/worsen the HWRF forecasts of TS Fay and the Florida Gale will be answered in the proposed research.

3. Results

3.1. Columbus Day Storm

Figures 3a-c show the simulated low pressure centers from the moveable 3 km domain for the three runs performed for the Columbus Day Storm. It appears that only slight changes in track (denoted by the +) for both the 100 and 500 cm^{-3} runs compared to the default simulation (250 cm^{-3}) were observed(Table 1). Minimal changes in the pressure were observed with each run indicating that the changes in NCW were not a factor to substantially change the storm's intensity in terms of pressure.

Areas of cumulative precipitation at the 3 km domain for the three simulations are provided in Figure 3d-f. According to observations, the area of the most cumulative precipitation is located over the central portion of the Florida panhandle (Figure 1a). The model simulations capture the general structure of the cumulative precipitation compared to observations fairly well. However, as shown in Figure 4a-c, the models tend to underestimate the amount of maximum rainfall compared to observations. The observations showed 15 inches of precipitation where the models only showed approximately 4 inches of rainfall at 0000 UTC.

The simulated vertical cross sections of the cloud water and cloud ice at October 10, 2011 0000 UTC are shown in Figure 5a-c. The results depict that the shape of the cloud water does indeed change with different values of NCW. It also appears that the peak values of q_i increase along with increasing NCW.However, these changes in q_i and q_c do not seems to correlate with the amount of rainfall produced for each simulation since the values of precipitation do not vary much between each simulation.

3.2. Tropical Storm Fay

Similar to the Columbus Day model runs, the changes in the values of MSLPas seen in Figure 6a-c, were not significant between each run. There are slight changes in the track and the location of the center low (Table 2), however the changes are minimal and reinforces the notion that the NCW does not have a large effect on changing the storm's intensity.

However, as shown in Figures 6d-f and 7, the regions of total rainfall did not agree as well as compared to the observations (Figure 1b). Areas of increased accumulated precipitation are present for the 100 cm^{-3} run compared to the 250 cm^{-3} and 500 cm^{-3}simulations(Figure 6 d-f).

The value of the max precipitation increases with increasing NCW 24 hours after initialization.The HWRF model runs tend to slightly overestimate amounts of precipitation compared to observations for the 3km domain with an area of maximum precipitation of 12-16 inches north of Lake Okeechobee. The observations for the same region showed values of 10 inches.

The simulated cloud water and cloud ice of the three simulations showed an increase of cloud ice with lower concentrations of NCW (Figure 8a), and an increase of cloud water tops with higher NCW (Figure 8c). Large concentrations of q_l are present at 250 hPafor the 100 cm^{-3} simulation compared to the 250 cm^{-3} and 500 cm^{-3} runs.

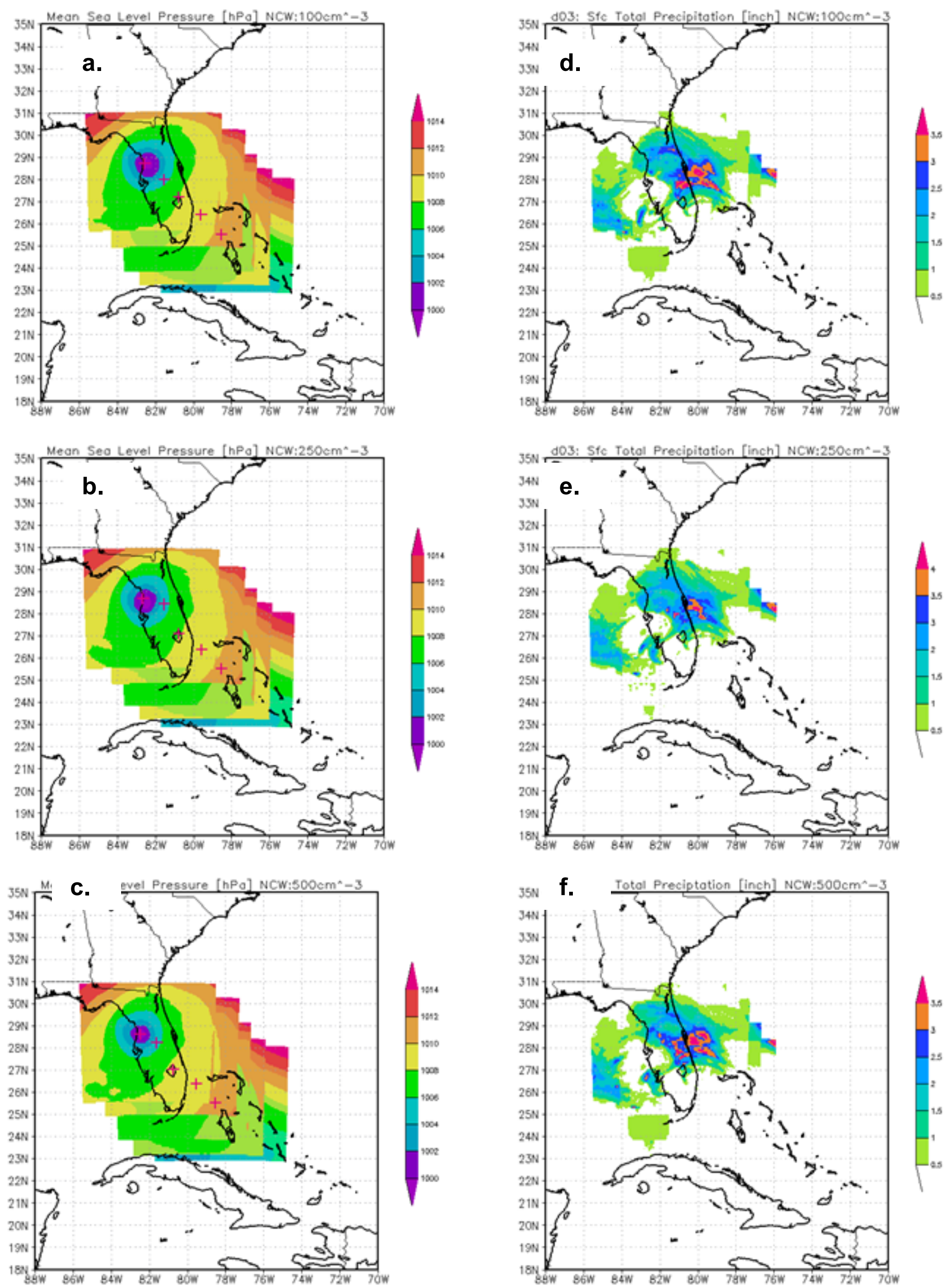

Figure 3: MSLP (left) and Cumulative Precipitation (right) for the 3 km nested domain for the Columbus Day Storm at 100 cm-3 (a, d), 250 cm-3 (b, e) and 500 cm-3 (c, f) with the storm center at 6 hour increments are denoted by the +.

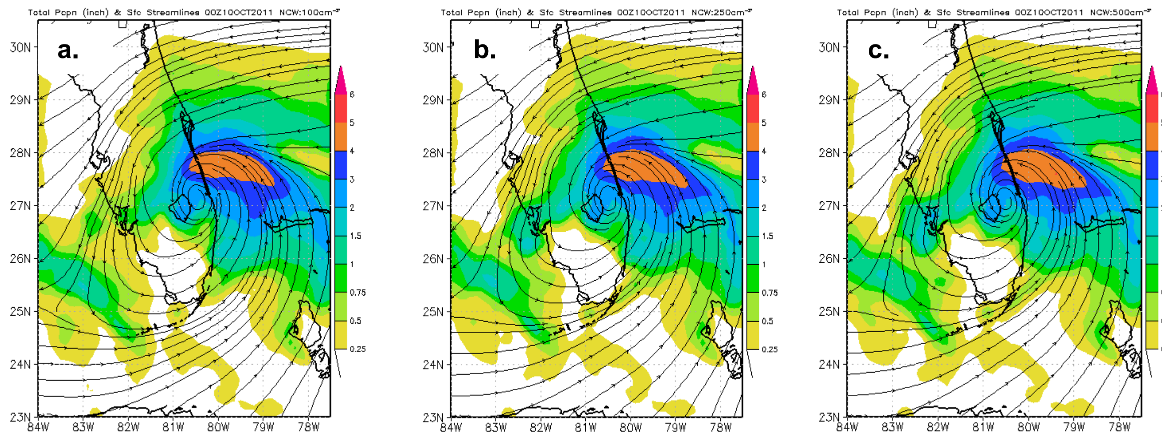

Figure 4: Plots of surface total precipitation at 0000 UTC Oct 2011 for the (a) 100 cm-3, (b) 250 cm-3, and (c) 500 cm-3 simulations.

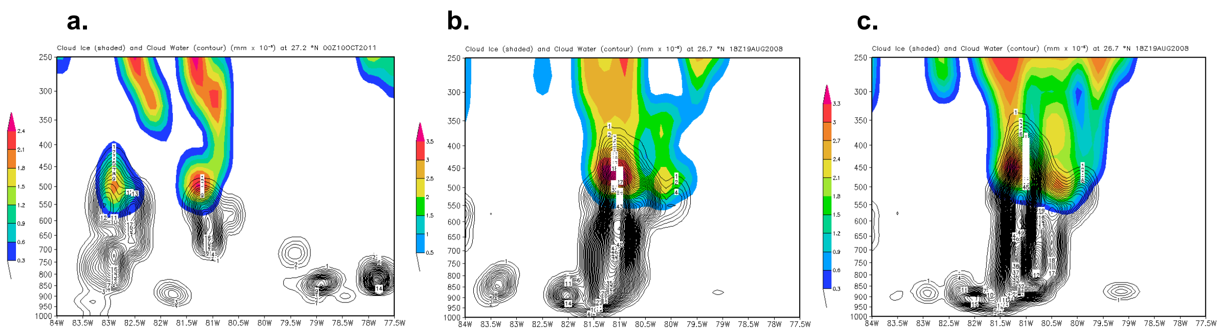

Figure 5: Vertical cross sections of cloud ice (shaded) and cloud water (contours) at the latitude of the storm center 12 hours after initial run time for the 100 cm-3 (a), 250 cm-3 (b) and 500 cm-3 (c) simulations.

Table 1: Columbus Day Storm – Storm Centers						
Date	100 cm^{-3}		250 cm^{-3}		500 cm^{-3}	
10/09	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude
12Z	-78.54	25.51	-78.54	25.51	-78.54	25.51
18Z	-79.60	26.42	-79.57	26.39	-79.55	26.39
00Z	-80.78	27.22	-80.78	27.10	-80.75	27.04
06Z	-81.54	28.01	-81.55	28.43	-81.60	28.25
12Z	-82.57	28.71	-82.65	28.69	-82.49	28.62

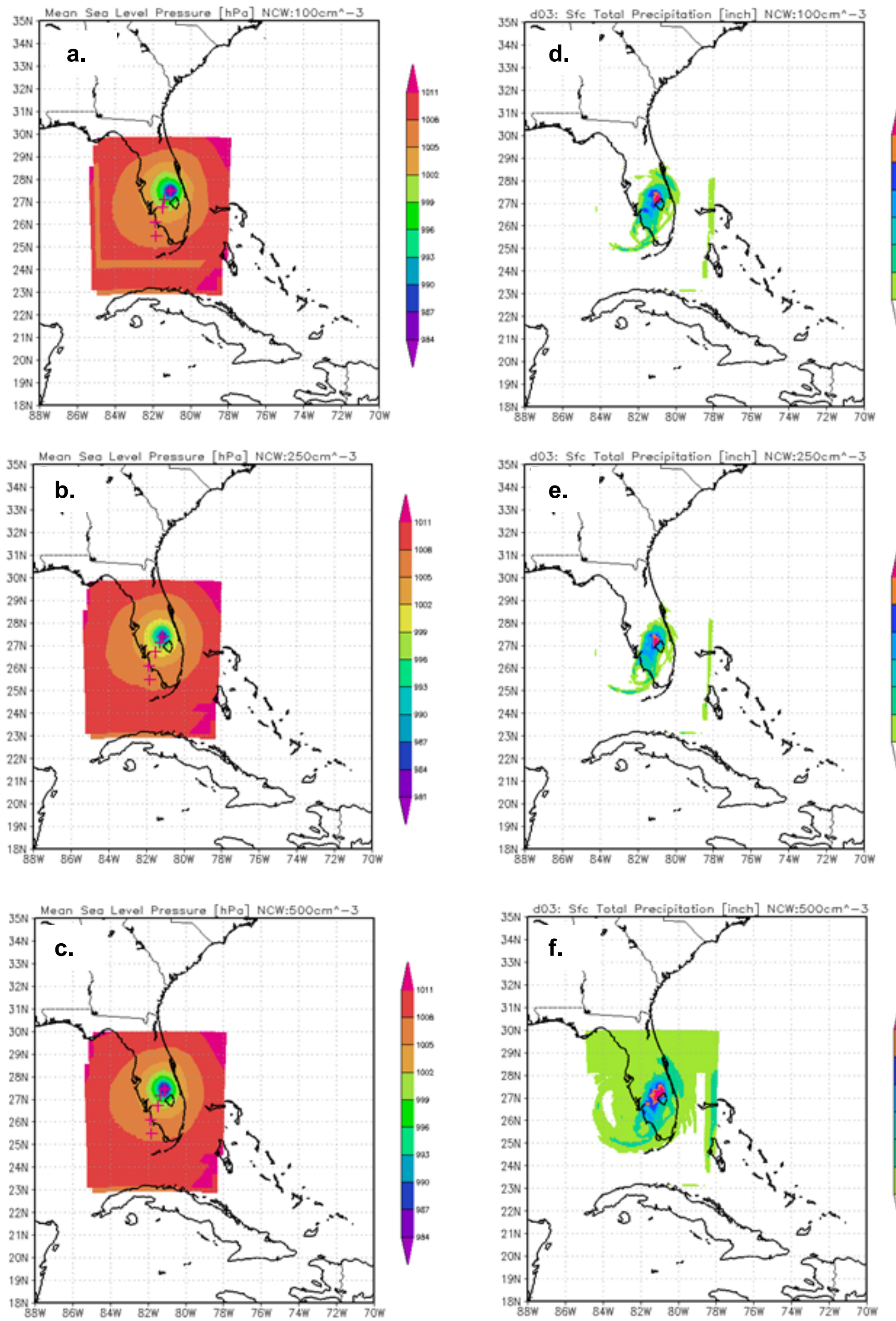

Figure 6: MSLP (left) and Cumulative Precipitation (right) for the 3 km nested domain for TS Fay at 100 cm-3 (a, d), 250 cm-3 (b, e) and 500 cm-3 (c, f) with the storm center at 6 hour increments are denoted by the +.

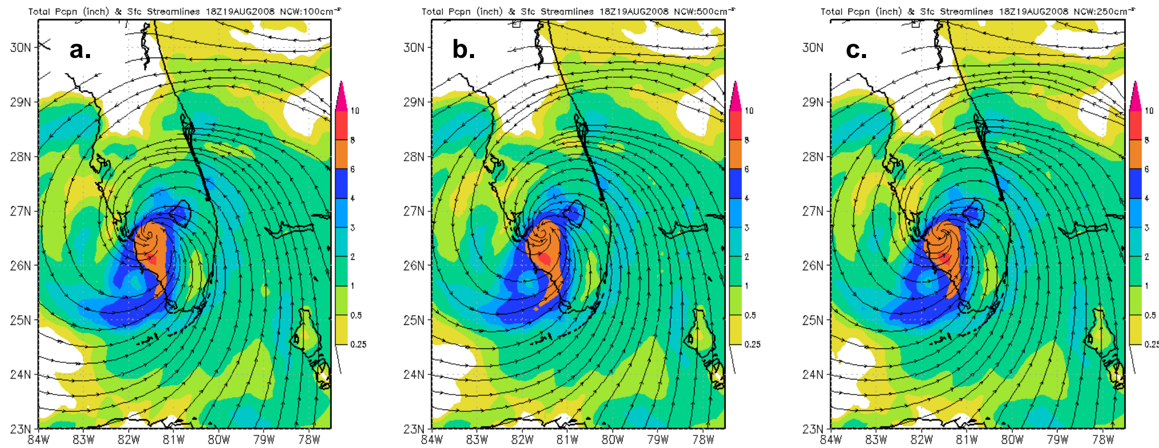

Figure 7: Plots of surface total precipitation at 1800 UTC Aug 2008 for the (a) 100 cm-3, (b) 250 cm-3, and (c) 500 cm-3 simulations.

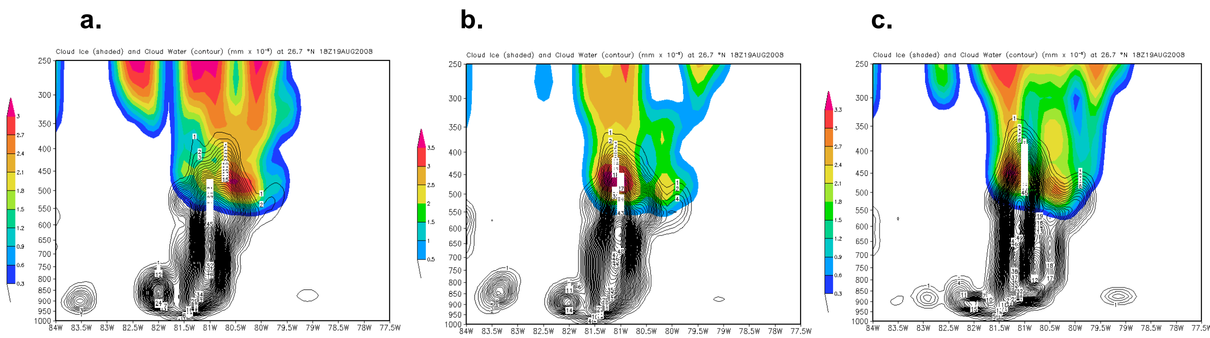

Figure 8: Vertical cross sections of cloud ice (shaded) and cloud water (contours) at the latitude of the storm center 12 hours after initial run time for the 100 cm-3 (a), 250 cm-3 (b) and 500 cm-3 (c) simulations for TS Fay.

Table 2: Tropical Storm Fay – Storm Centers						
Date	100 cm^{-3}		250 cm^{-3}		500 cm^{-3}	
08/19	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude
06Z	-81.81	25.48	-81.81	25.48	-81.81	25.48
12Z	-81.86	26.08	-81.86	26.08	-81.86	26.08
18Z	-81.48	26.74	-81.51	26.71	-81.48	26.71
00Z	-81.39	27.1	-81.27	27.13	-81.33	27.16
06Z	-81.06	27.49	-81.13	27.4	-81.12	27.46

4. Concluding Remarks

In this study, HWRF model simulations for two events were evaluated by analyzing the mean sea level pressure, precipitation, wind fields and hydrometeors as each system makes landfall. For the Columbus Day runs, the regions of precipitation seemed to agree well with observations (Figure 1a) for the most part except that all of the model simulations had a tendency to underestimate the amount of total rainfall (Figure 4 a-c). TS Fay, however, seemed to slightly overestimate precipitation (Figure 6d-f, 7) which suggests that larger values of NCW lead to an increase in the spatial distribution of the precipitation. Since changes in the NCW did not affect the cases in the same way, this suggests that the affects of NCW within HWRF may be system dependent.

It is important to understand the cloud microphysics and tendencies of storms to help improve forecasting the strength and intensity of TCs. Improved forecasts will help with risk assessment and with the planning of evacuating procedures.Future work will investigate the effects of other cloud microphysical schemes on landfalling TC structure and precipitation forecasts for HWRF. Since it is configured to use the Ferrier Scheme, some work will be required to integrate other microphysics scheme into HWRF in the future.

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