16D.4 Evaluating HWRF Forecasts of Tropical Cyclone Intensity and Structure in the North Atlantic Basin

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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 economic 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 can vary drastically from one system to the next (Yaukey 2011).

For example, an unnamed system later known as the Florida Gale, intensified with tropical storm force winds and made landfall over Melbourne Florida within a 24 hour period. The system first developed on the 6th of October and made landfall on October 10th at approximately 00Z UTC before dissipating on the 13th of October (Figure 1a). The event was not well forecasted, especially the RI period that brought most parts of Central and Eastern Florida received around 4-8 inches of precipitation within a three hour span. Although the system was a small event and did not cause significant property damage, it highlights the ongoing challenges of accurately forecasting RI events, especially ones that make landfall.

In August 2008, Tropical Storm (TS) Fay made landfall over Florida multiple times and underwent RI as it traversed over Lake Okeechobee (Figure 1b). Fay was a long lived storm that recorded sustained wind speeds of up to 75 knots and brought heavy rainfall cover Florida which caused extreme flooding (Stewart and Beven 2009). It was responsible for

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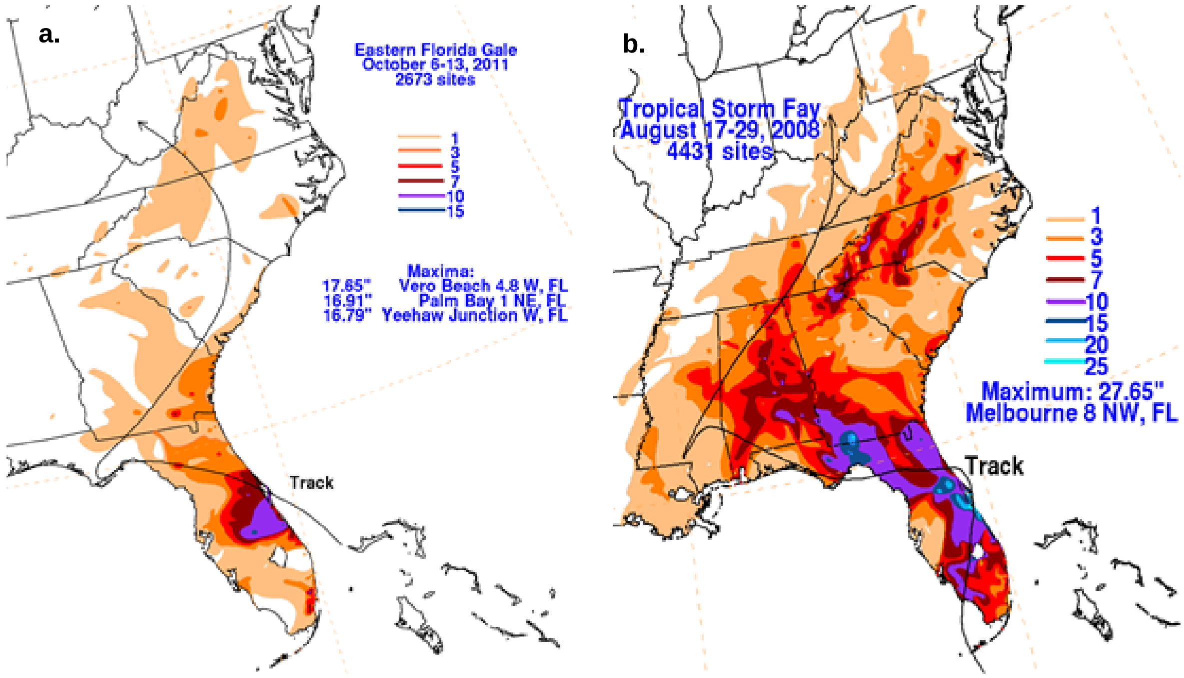

Figure 1. Observations of the track and cumulative precipitation for the Florida Gale (2011) (a) and TS Fay (2008) (b).Images via The Hydrological Prediction Center (HPC).

approximately $560 million in property damage. A synoptic scale weather system during the time of TS Fay has been linked as being an influential driving mechanism for the steering and intensification processes (e.g., Washington and Chiao 2011).

With the Florida Gale being a small, fast moving system and TS Fay being a large, persistent storm, they are great examples of storms with vastly differing driving mechanisms that underwent RI and make landfall over Florida. Both cases help reinforce the fact that there is still room for improvement with the current hurricane models to forecast for all types of situations that may induce a RI event and ultimately better prepare for potential risk.

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 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

2.1 The Hurricane Weather Research and Forecasting (HWRF) Model

In order to better quantify the uncertainty and evaluate the results of model forecasts on landfalling TCs, numerical simulations were performed using HWRF version v3.4a. HWRF is an ocean-atmosphere coupled model facilitated by the National Centers for Environmental Prediction (NCEP) that has been operational since 2007. HWRF v3.4a was the first version to introduce the three domain grid capability, with a parent grid at 27 km resolution and two movable nested grids with 9 and 3 km resolution that follow the storm (Figure 1). The 27 km domain will help resolve larger scale circulations and synoptic weather conditions that may have an effect on the TCs. Whereas the two nested domains will be more focused on the TC circulation and formation, most notably the wind field and rain band structure characteristic to the intensity changes of TCs. HWRF is currently configured to use the Global Forecast System (GFS) reanalysis data produced by NCEP to gather the initial conditions (i.e. storm center, storm wind speed) of a specific system for the model startup. Additional information about the HWRF model configuration can be found at: http://dtcenter.org/HurrWRF/users/overview/hwrf_overview.php.

Table 1: HWRF v3.4a		
Grid Configuration	Parent Domain	27 km resolution
		80° x 80° (0.18° spacing)
	Intermediate Vortex Following Domain	9 km
		11° x 10° (0.06° spacing)
	Inner Vortex Following Domain	3 km
		6° x 5.5° (0.02° spacing)
Cloud Microphysics	Modified Ferrier Scheme	
Ocean Coupling	POM	
Initial Forcing Data	GFS Analysis	

2.2 National Stage IV Precipitation Data.

The proposed research will focus on the two systems, TS Fay and the Florida Gale. Real time observations of precipitation for both storms will be analyzed using the NCEP Stage IV QPE data. The Stage IV precipitation analysis data is a mosaic of the regional hourly or 6-hourly multi-sensor precipitation analyses (MPEs) over a 4km grid which is produced by the 12 regional forecasts centers all over the nation (NOAA Environmental Modeling Center). Stage IV observations are available in three different time frames: hourly, 6 hour analysis and 24 hour analysis (12Z-12Z). Manual quality control is done and filled over time into the 6 hourly Stage IV analyses, which makes the 6-hour analyses more accurate and reliable than the one hour observations. Therefore the 6 hour accumulated precipitation Stage IV observations will be used when comparing the HWRF model simulations.

2.2 TS Fay and the Florida Gale.

The proposed research will focus on the two systems, the Florida Gale and TS Fay. As stated earlier, both storms were events that made landfall over Florida and experienced a RI event however; they differed in length and intensity. The Florida Gale was a short lived system that intensified quickly over land and produced considerable amount of precipitation. TS Fay was a long lived storm that brought tremendous amounts of rainfall over Florida and caused serious flooding. Multiple simulations using HWRF will be conducted to evaluate how well it can capture these two storms with differing characteristics. The simulations for each case will be conducted at least 6 hours prior to landfall for each respective event. This will be done in order to capture the characteristics of both cases before, during and after 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 objectives of this research are: 1.) to analyze how well the triple nested grid capability capture the structure and intensity of the two systems before and after landfall, 2.) to analyze how changes in the microphysics scheme affect the land-ocean-atmosphere coupling with rapid landfall intensification; and 3.) to observe if changes in the initial forcing mechanisms of HWRF will improve or hinder the accuracy of RI events of landfalling TCs.

The current microphysics configuration for HWRF utilizes the Ferrier Scheme. It is a single moment scheme that predicts the hydrometeor processes. Due to the current configurations of HWRF, it is difficult to manipulate the cloud microphysics scheme directly in the model. Therefore, the number concentration of droplets (NCW) will be manipulated to simulate possible changes in the cloud microphysics for TS Fay and the Florida Gale. By changing the NCW, the cloud properties should then be affected during the simulations and the differences will be recorded and analyzed for both cases. Three separate simulations with differing NCWs will be done for each case. The default NCW for HWRF is 250 cm^{-3} and will be used as the control run used throughout the research. Then simulations of 100 cm^{-3} and 500 cm^{-3} will be conducted to observe how an increase and decrease of the NCW affects the structure and intensity as well of TS Fay and the Florida Gale. 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. Both cases make landfall that may have affected the NCW and the 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 or worsen the HWRF forecasts of TS Fay and the Florida Gale will be answered in the proposed research. Therefore, altering the NCW may provide insight to better forecast the structure and intensity of future landfalling storms with similar behaviors.

2.3 GFS vs. ECM reanalysis data.

After performing the tests with the different values of NCW for both cases, changes in the HWRF initial forcing mechanisms were then analyzed to see how it will affect the intensity forecasts for both cases. The HWRF normally uses GFS reanalysis data to generate the initial conditions of the storm for the model simulation. The GFS reanalysis data was then replaced with the ERA-Interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) to observe how changes in the initial forcing data affect both cases. There have been comparisons between the European and American models before and some suggest that the European models fare better than the American counterparts when performing TC forecasts. Therefore taking this theory into account, using the ECM data reanalysis data instead of the GFS data may provide better forecasts for landfalling TCs. HWRF simulations were conducted for both TS Fay and the Florida Gale using the ECM ERA-Interim reanalysis data to analyze any significant changes in the structure and intensity compared to the runs with the default GFS reanalysis data.

The main points of interests with changing the reanalysis data will be to see if there are any significant differences with each forecast. How exactly will using ECM data affect the TC forecast in terms of structure and intensity compared to the GFS model simulations? Are the simulations with the ECM data a better interpretation of what really happened during both storms or is it worse? In addition, are these changes significant enough to merit a change for future forecasts?

3. Results

3.1. Florida Gale

Figures 2 a-c provides plots of the mean sea level pressure (MSLP) at the 3 km domain 24 hours after initialization for the three different simulations of the Florida Gale. The MSLP plots are overlapped at six hour increments with the simulated low pressure centers denoted by the plus sign. It appears that only slight changes in track for both the 100 and 500 cm^{-3} runs compared to the default (250 cm^{-3}) were observed (Table 1). Slight changes in the pressure were observed with each run indicating that the changes in NCW between each simulation were not large enough of a factor to substantially change the dynamics of the storm.

The plots from Figures 2 d-f provide the hourly precipitation at the 3 km domain for the three simulations during each six hour period. It was expected that changing values in the NCW would influence changes in the cloud structure which would then affect the rainfall distribution however, little variation between the three runs were observed. Although the overall depiction of the rainfall remains nearly identical in the three runs, there are definite changes on a smaller scale between each simulation. For example, the area of maximum precipitation over Melbourne increases as the simulations increases in NCW.

According to observations, the area of the most cumulative precipitation during the Florida Gale is located over the central Florida (Figure 1a). When comparing the HWRF simulations to observations, it appears that the simulations capture the general structure of the cumulative precipitation fairly well. However, as shown in Figure 3, the models (3b-d) tend to underestimate the amount of maximum rainfall compared to observations (3a). The Stage IV observations show over six inches of precipitation off the coast of Melbourne whereas the models simulations only depict approximately 4 inches of rainfall at 0000 UTC. As shown earlier, the structure of the precipitation barely differs between the three simulations with differing NCW values in the HWRF configurations. This indicates that the changes in NCW were either not large enough to cause any significant variation or that the microphysics may not have a direct correlation with the dynamics of the HWRF model. The thermodynamic and dynamic connection in HWRF needs to be further examined.

The simulated vertical cross sections of the cloud water and cloud ice at October 10, 2011 0000 UTC are shown in Figures 4a-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 rainfall totals does not vary as much as the cloud water and cloud ice content between each model run.

3.2. *Tropical Storm Fay*

Similar to the Columbus Day model runs, the changes in the values of MSLP as seen in Figure 5a-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 5d-f and 6, 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 5 d-f).

The value of the max precipitation increases with increasing NCW 12 hours after initialization (Figure 6 b-d). The HWRF model runs tend to overestimate the precipitation in terms of the area as the simulations tend to depict much more stratiform precipitation through the 3 km domain. However in terms of the strength of the rainfall, the model runs tend to underestimate in this regard. The area of maximum precipitation southwest of Lake Okeechobee is larger in the simulations compared to observations (Figure 6a) for the 3km domain however; the simulations fail to resolve the other local maxima located northeast of Lake Okeechobee. Although the trend is fairly resolved, the simulations still lack in depicting the strength of the precipitation compared to observations.

The simulated cloud water and cloud ice of the three simulations showed an increase of cloud ice with lower concentrations of NCW (Figure 7a), and an increase of cloud water tops with higher NCW (Figure 8c). Large concentrations of q_I are present at 250 hPa for the 100 cm^{-3} simulation compared to the 250 cm^{-3} and 500 cm^{-3} runs.

3.3. *GFS vs. ECM ERA-Interim*

a. Florida Gale

The initial assessment of the HWRF model simulations for the Florida Gale using the ECM ERA-Interim reanalysis data is that it appears to be a more accurate interpretation of actual events compared to the runs conducted with the default GFS reanalysis data. For example in terms of track, the HWRF runs using the ECM reanalysis data better follows the best track shown in observations (Figure 8). During the default run using the GFS reanalysis data, the system traverses over Lake Okeechobee. While for the model simulation using the ECM ERA-Interim data for the initial condition, the system makes landfall north of Lake Okeechobee. This more resembles the actual trajectory of the Florida Gale since it was previously noted that it made landfall over Melbourne which his more north of Lake Okeechobee (Figure 1a).

Since the track was better resolved using the ECM reanalysis data for the initial conditions, it would be fair to believe that these simulations would lead to a more accurate depiction of the intensity forecasts such as the cumulative precipitation. However in terms of the total precipitation, the HWRF runs using the ECM ERA-Interim data did not prove to be a better replacement of the initial forcing mechanisms than the GFS reanalysis data. Figure 9 shows the cumulative precipitation 12 hours after initialization (October 10, 2011 00Z) for the Stage IV observations (a), and the two HWRF simulations (b and c). It is apparent that the two model runs tend to overestimate the precipitation in terms of surface area. This suggests that the models tend to create more stratiform rainfall compared to observations. However in terms of the maximum precipitation, the models tend to underestimate in this regard. Figure 10a shows that as the Florida Gale makes landfall, over six inches of rainfall just off the coast of Melbourne have been accumulated during a 12 hour period. The default run resolves the general location of the precipitation max similar to what was shown in observations. However, it underestimates the amount as it simulates no less than five inches of total rainfall during this period (Figure 9b). The ECM run actually underestimates the rainfall even less than the default GFS run with a smaller cell with a maximum of four inches of precipitation off the coast of Melbourne. This is nearly one third and for some parts one half less of precipitation compared to the observations. Although the track was improved using the ECM ERA-Interim reanalysis data for HWRF, this did not translate to a better representation of the precipitation.

b. TS Fay

The results for TS Fay were similar to the Florida Gale runs as it appears that changing the initial forcing data to ECM ERA-Interim reanalysis data actually fared better than the default HWRF runs. In terms of simulating the track for the first 24 hours, the simulation using the ECM reanalysis data for the initial forcing conditions was a better representation of the best track compared to the default HWRF run using GFS analysis data (Figure 10). The default run moves over Florida at a slower rate than what was observed (Figure 10 b).

Similar to the Florida Gale simulations, the improvement in track shown in the runs using the ECM ERA-Interim reanalysis data for the initial forcing conditions did not lead to an improvement the cumulative precipitation. The 12 hour analysis of total rainfall for TS Fay showed that the simulations with the default initial conditions resemble the observations better than the runs replaced with the ECM reanalysis data (Figure 11).Both runs tend to simulate more stratiform precipitation than what was observed for TS Fay with the default run (Figure 11b) depicting rainfall totals that resemble observations better than the ECM reanalysis run (Figure 11c). The location of the precipitation maximum southwest of Lake Okeechobee is better depicted during the model run using the initial conditions compared to the ECM simulation. The default HWRF run overestimates the amount of rainfall compared to observations but gets the general location better than the run using the ECM reanalysis data. The latter places the most amount of rainfall more directly west of Lake Okeechobee. Overall, both cases failed to accurately depict TS Fay's rainfall distribution 12 hours after initialization.

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. Although both the Florida Gale and TS Fay had contrasting characteristics, HWRF was able to recapture the two systems fairly well in terms of track. However in terms of precipitation, HWRF is still lacking and failed to accurately depict both cases. HWRF tended to underestimate the precipitation for both the Florida Gale and TS Fay. Although an increase in NCW did not dramatically alter the overall distribution of precipitation between each simulation for both cases, there were definite changes at a smaller scale. The area of maximum rainfall increased for both cases with increasing values of NCW for both cases.

The replacement of the reanalysis data used for the initial conditions provided favorable results towards improving the track for both the Florida Gale and TS Fay. However, this did not lead towards improving the cumulative precipitation and strength of each respective system. Both cases tended to over forecast the amount of stratiform precipitation 12 hours after initialization and underestimate the intensity of local maxima for both cases.

The need to further examine the connection between the thermodynamic and dynamic fields for HWRF is necessary considering that there was not much variation between the track and intensity when the NCW was changed for both the Florida Gale and TS Fay. 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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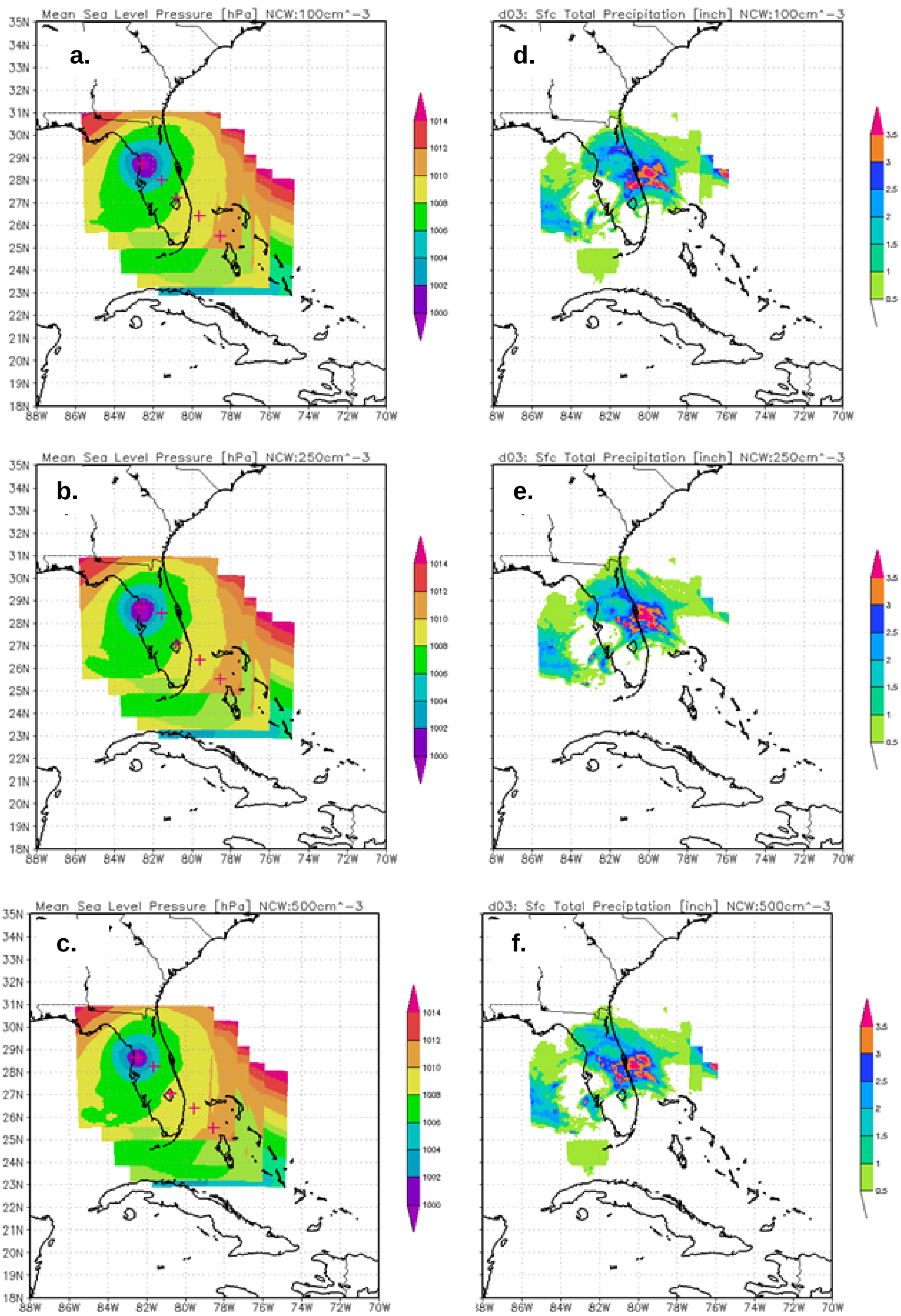

Figure 2. MSLP (left) and Cumulative Precipitation (right) for the 3 km nested domain for the Columbus Day Storm at 100 cm-3 (a, d), 250 cm-3 (b, e) and 500 cm-3 (c, f) with the storm center at 6 hour increments are denoted by the +.

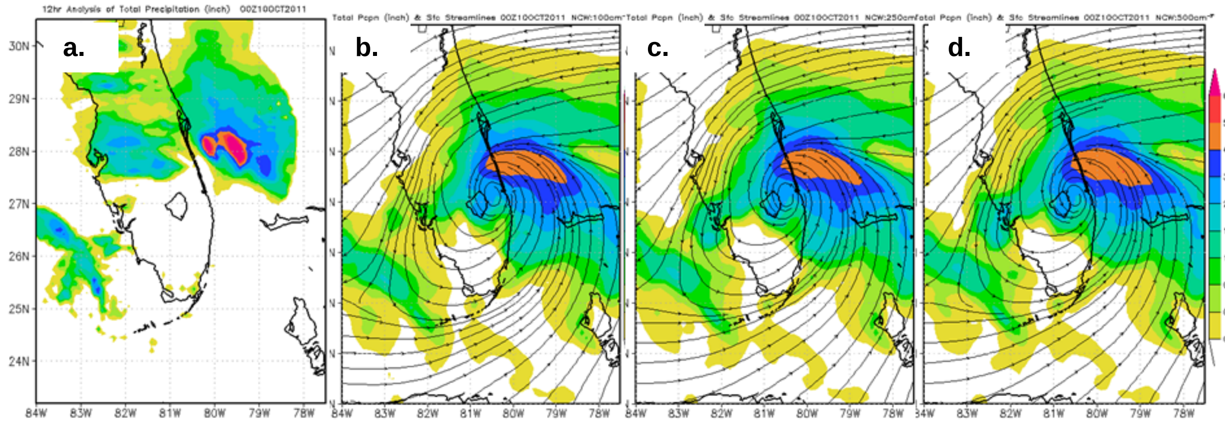

Figure 3. Plots of the cumulative precipitation at 0000 UTC October 2011 for the (a) Stage IV Observations, (b) 100 cm^{-3}, (c) 250 cm^{-3}, and (d) 500 cm^{-3} model simulations.

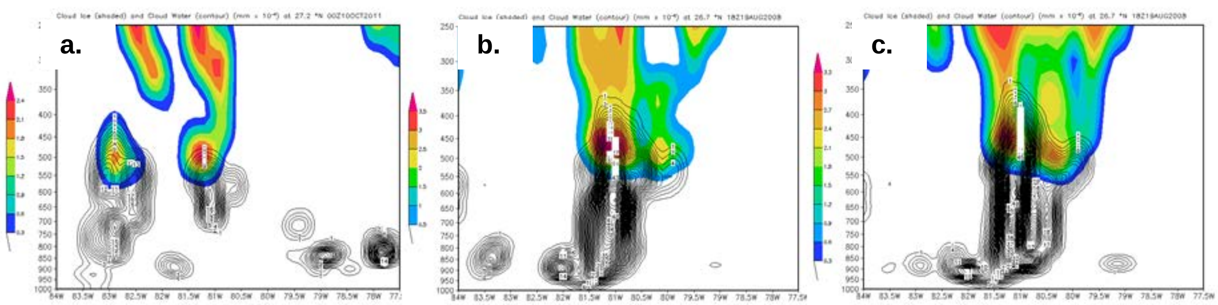

Figure 4. Vertical cross sections of cloud ice (shaded) and cloud water (contours) at the latitude of the storm center 12 hours after initial run time for the 100 cm-3 (a), 250 cm-3 (b) and 500 cm-3 (c) simulations.

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Table 2: Columbus Day Storm – Storm Centers - GFS						
Date	100 cm^{-3}		250 cm^{-3}		500 cm^{-3}	
9-Oct	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude
12Z	-78.54	25.51	-78.54	25.51	-78.54	25.51
18Z	-79.6	26.42	-79.57	26.39	-79.55	26.39
00Z	-80.78	27.22	-80.78	27.1	-80.75	27.04
06Z	-81.54	28.01	-81.55	28.43	-81.6	28.25
12Z	-82.57	28.71	-82.65	28.69	-82.49	28.62
Columbus Day Storm – Storm Centers - ECM						
Date	100 cm^{-3}		250 cm^{-3}		500 cm^{-3}	
9-Oct	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude
12Z	-78.57	25.54	-78.57	25.54	-78.57	25.54
18Z	-79.7	26.49	-79.7	26.49	-79.72	26.45
00Z	-80.96	27.37	-80.99	27.46	-80.96	27.46
06Z	-81.87	28.95	-81.68	28.62	-81.8	28.71
12Z	-83.11	29.74	-82.92	29.86	-82.88	29.71

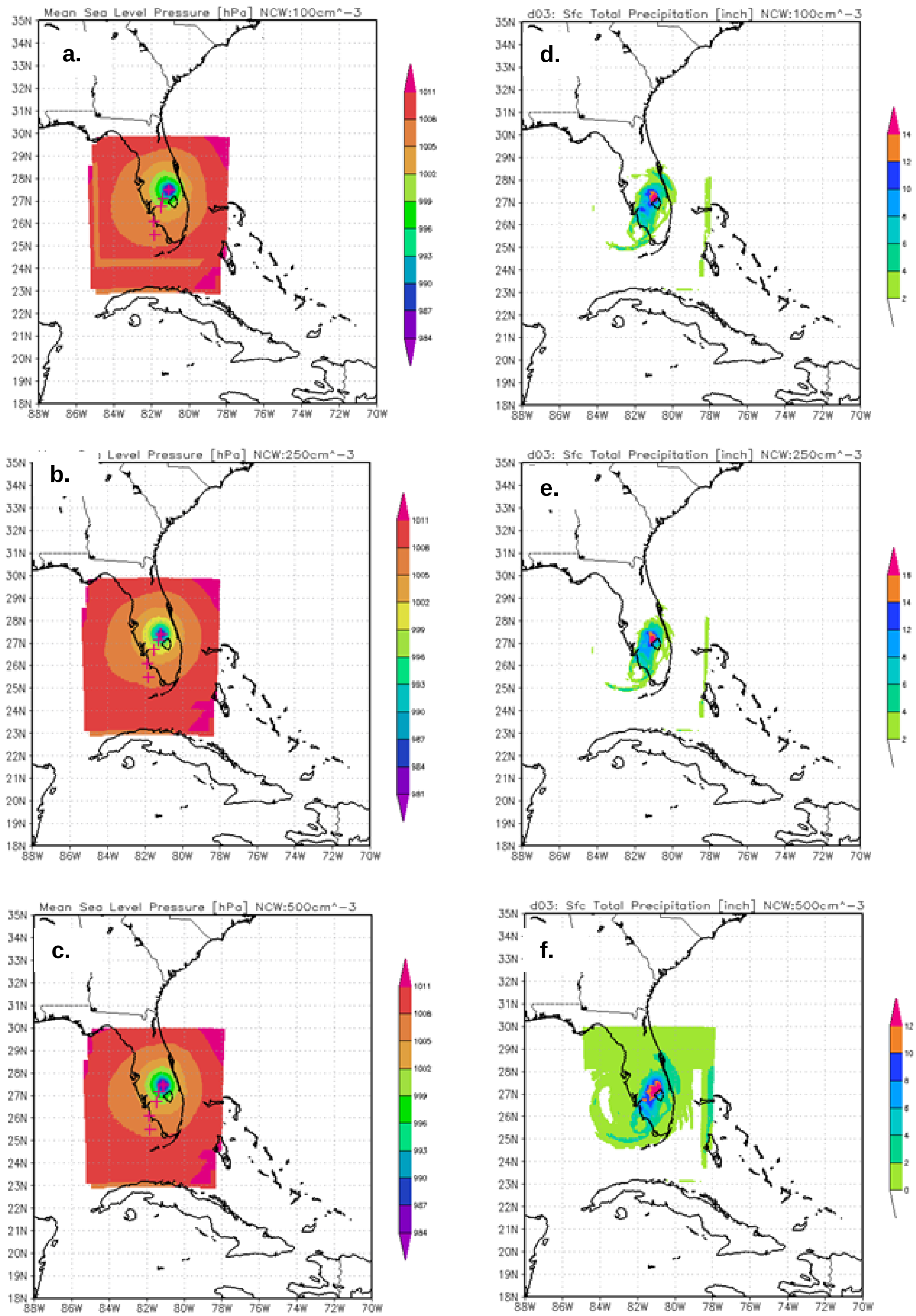

Figure 5. MSLP (left) and Cumulative Precipitation (right) for the 3 km nested domain for TS Fay at 100 cm-3 (a, d), 250 cm-3 (b, e) and 500 cm-3 (c, f) with the storm center at 6 hour increments are denoted by the +.

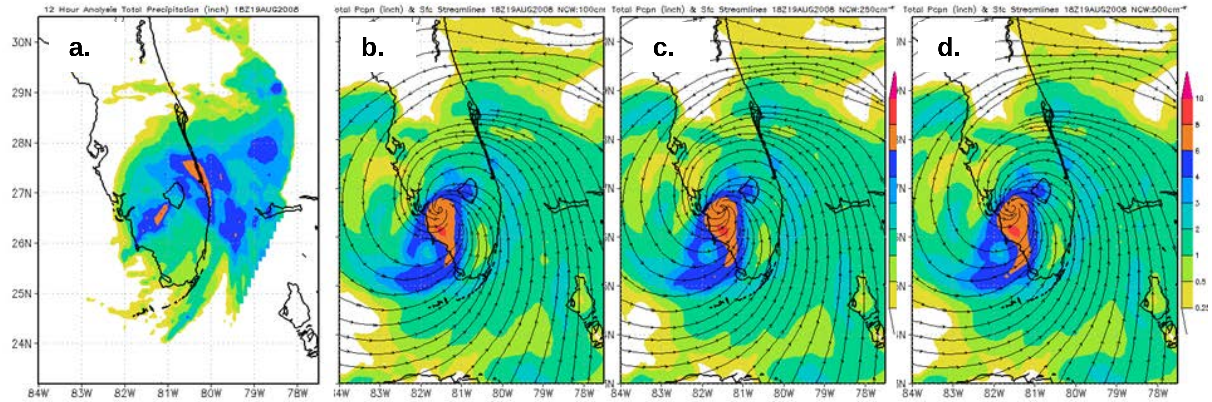

Figure 6. Plots of the cumulative precipitation at 0018 UTC August 2008 for the (a) Stage IV Observations, (b) 100 cm^{-3}, (c) 250 cm^{-3}, and (d) 500 cm^{-3} model simulations.

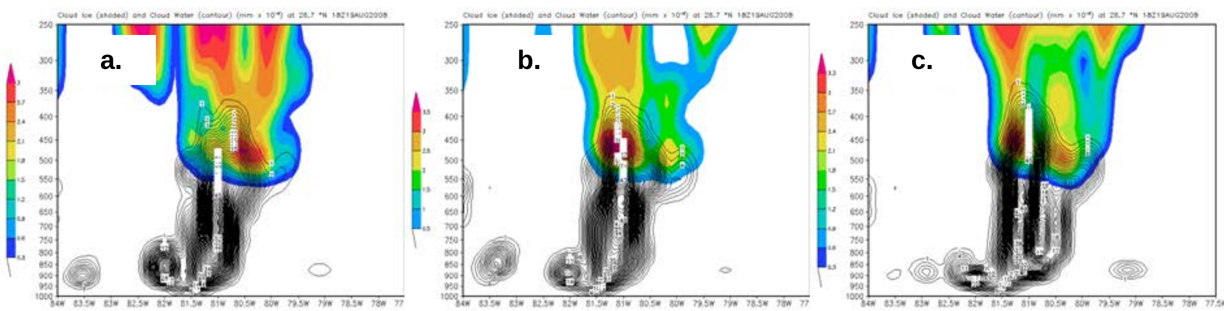

Figure 7. Vertical cross sections of cloud ice (shaded) and cloud water (contours) at the latitude of the storm center 12 hours after initial run time for the 100 cm-3 (a), 250 cm-3 (b) and 500 cm-3 (c) simulations for TS Fay.

Table 1: Columbus Day Storm – Storm Centers - GFS						
Date	100 cm^{-3}		250 cm^{-3}		500 cm^{-3}	
9-Oct	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude
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18Z	-79.6	26.42	-79.57	26.39	-79.55	26.39
00Z	-80.78	27.22	-80.78	27.1	-80.75	27.04
06Z	-81.54	28.01	-81.55	28.43	-81.6	28.25
12Z	-82.57	28.71	-82.65	28.69	-82.49	28.62
Columbus Day Storm – Storm Centers - ECM - 2014						
Date	100 cm^{-3}		250 cm^{-3}		500 cm^{-3}	
9-Oct	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude
12Z	-78.57	25.54	-78.57	25.54	-78.57	25.54
18Z	-79.7	26.49	-79.7	26.49	-79.72	26.45
00Z	-80.96	27.37	-80.99	27.46	-80.96	27.46
06Z	-81.87	28.95	-81.68	28.62	-81.8	28.71
12Z	-83.11	29.74	-82.92	29.86	-82.88	29.71

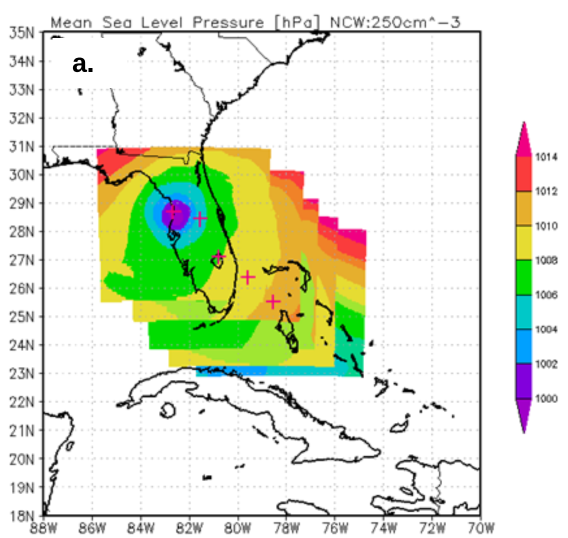

Figure 8. Comparisons of the MSLP between the two model simulations for the Florida Gale using the (a) GFS Analysis (HWRF default), (b) ECM ERA-Interim data as the initial forcing data for HWRF

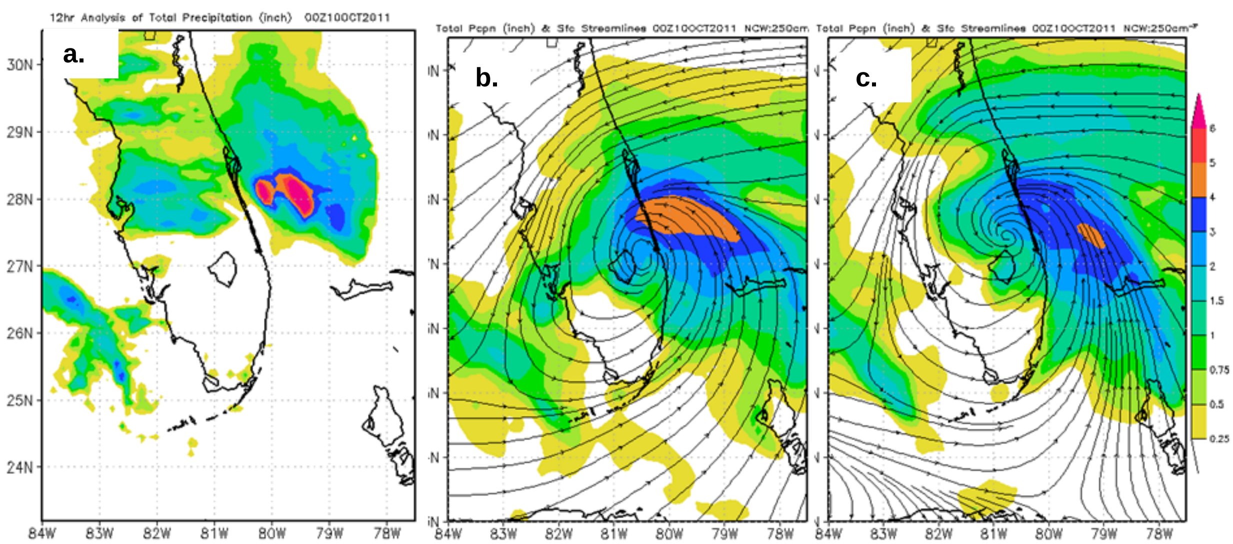

Figure 9. Plots of the cumulative precipitation 12 hours after the initial run for the Florida Gale (10/10/2012 00Z) for (a) Stage IV Observation data, (b) GFS Analysis run and (c) ECM ERA-Interim reanalysis run

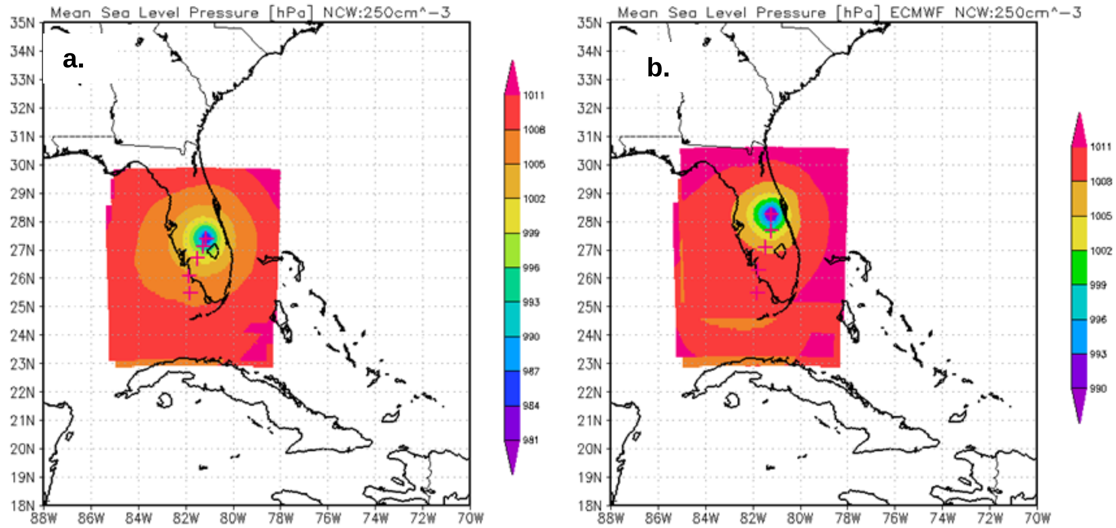

Figure 10. Comparisons of the MSLP between the two model simulations for TS Fay using the (a) GFS Analysis (HWRF default), (b) ECM ERA-Interim data as the initial forcing data for HWRF

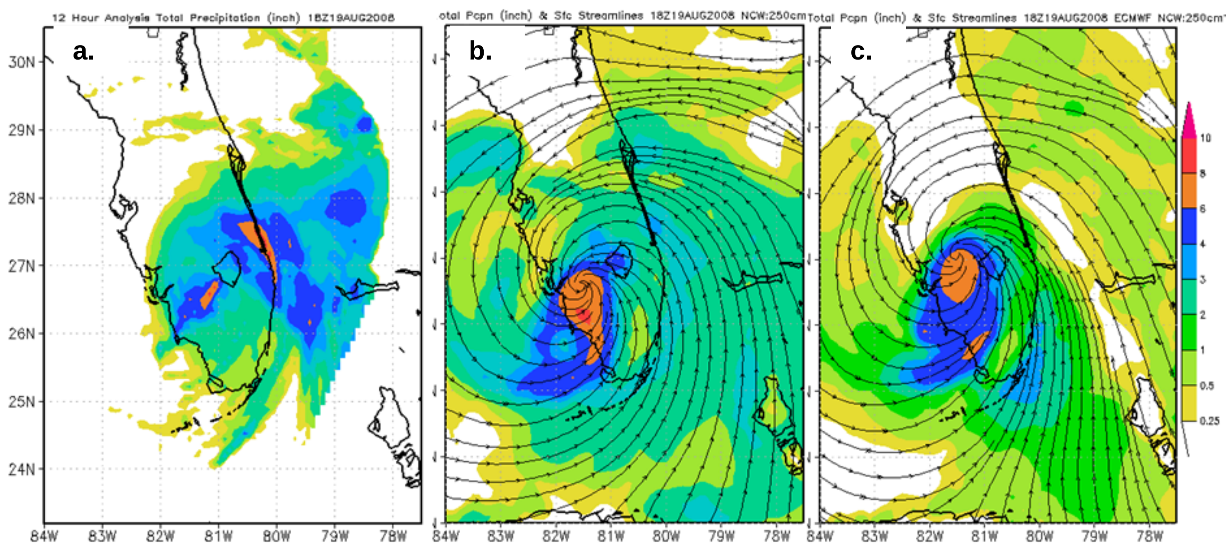

Figure 11. Plots of the cumulative precipitation 12 hours after the initial run for TS Fay (10/10/2012 00Z) for (a) Stage IV Observation data, (b) GFS Analysis run and (c) ECM ERA-Interim reanalysis run