6.7 WRF-CHEM ON TROPICAL CYCLOGENESIS

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1. INTRODUCTION

The dynamics of tropical cyclone formation, the rapid intensification or the lifespan until dissipation or landfall have been studied extensively. Nevertheless, the impact of the Saharan Air Layer (SAL) associated with dust particles on tropical cyclone (TC) formation remains a main interest for the scientific community. The SAL is a dry layer that extends to approximately 500 hPa (~5500 m) over Africa in the summer months (Prospero and Carlson 1972; Carlson and Prospero 1972). This elevated layer of Saharan air and mineral dust can transcend to other regions beyond the West African area. It can cover areas of the North Atlantic, western Caribbean Sea and Gulf of Mexico (Dunion and Velden 2004). Its impact is, therefore, of great importance to a large amount of scientific and civil communities. It has been shown that the SAL affects the African Easterly Waves (AEWs), which is of great importance since these waves have been found to be a clear structure of the major hurricanes that affect the Atlantic. These wavelike disturbances (Riehl 1954; Zipser et al. 2009) originate in the Saharan desert, from a temperature gradient between warmer air to the north and colder air to the south. The SAL is important in the initial development of AEWs and in the genesis of tropical storms by increasing baroclinic instability (Karyampudi and Carlson 1988; Karyampudi and Pierce 2002). During the past several years various hypothesis and theories have been develop over the positive or negative impact of the SAL on the AEWs and on tropical cyclone formation. Jenkins et al. (2008) suggested that aerosol-cloud interactions invigorate convective rain bands via an entrainment of dust particles at altitudes greater than 825 hPa level due to the strong midlevel jet associated with the SAL. On the other hand, Dunion and Velden (2004) proposed that the SAL can inhibit the growth of systems that can develop into tropical cyclones by introducing dry, stable air and enhancing vertical wind shear by the African Easterly Jet (AEJ).

On a broader scale, the SAL could have impacts on ocean temperatures, air quality, as well as on other weather events (Lau et al. 2007a,b,c; Evan et al. 2008; Wong et al. 2008; Prospero and Mayol-Bracero 2013). Although many observational and modeling studies have investigated on the effect of the SAL dust on precipitation, tropical cyclone activity, and sea surface temperatures, not many have analyzed the microphysics involved in the TC genesis processes. Clouds microphysics might reduce precipitation due to the dry nature of the SAL (Rosenfeld et al. 2001). Khain et al. (2005) and Jenkins et al. (2008) proposed that enhancing convective intensity could affect microphysics in the systems. These dust particles acting as cloud condensation nuclei (CCN) may cause changes in the formation and distribution of precipitation, redistribution of latent heat (Rosenfeld et al. 2008; Rosenfeld et al. 2012), and could impact the intensity of the storm (e.g., Braun et al. 2013). Centeno and Chiao (2014) suggested a time-lag connection between dust outbreak and lightning in association with the TC genesis. They further suggested that Saharan dust would not suppress TC genesis, especially in the early formation stage. Nevertheless, it is not clear to what degree these changes in microphysics or CCN would affect tropical cyclogenesis. The goal of this research is aimed to advance our understanding of the extent at which the Saharan dust affects the microphysics of tropical cyclones genesis over Eastern Atlantic. A subject that is of great concern for habitants of the Caribbean, Mexico, part of Central America and east and southeast of the United States. Furthermore, we want to evaluate the differences between the Weather Research and Forecasting – Advanced Research WRF (WRF-ARW) and the WRF-Chemistry (WRF-CHEM) models, as well as to analyze the sensitivity of WRF-CHEM to model the effects from the Saharan dust.

Our working hypothesis is that the intrusion of dust particles associated with SAL during the genesis stage of TCs, which invigorates the system by increasing the number of cloud droplets. As a result, the entire TC genesis processes may be delayed or diminished. This research aims to answer the questions left by the studies mentioned above in addition to new unknowns that are discovered on the course of it. Four different TC genesis related events are investigated to study the genesis as well as early evolution of tropical systems.

2. DATA AND ANALYSIS METHODS

2.1 *Numerical Models Configuration and data gathering*

The WRF-ARW model version 3.4 and the WRF-Chem model version 3.4.1 were employed for the four case studies. Both models were used to evaluate the differences in the environmental conditions prior, during, and post TC genesis. The initial and time-dependent lateral boundary conditions are supplied from National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) 3-hourly global analysis at 0.5º horizontal resolution.

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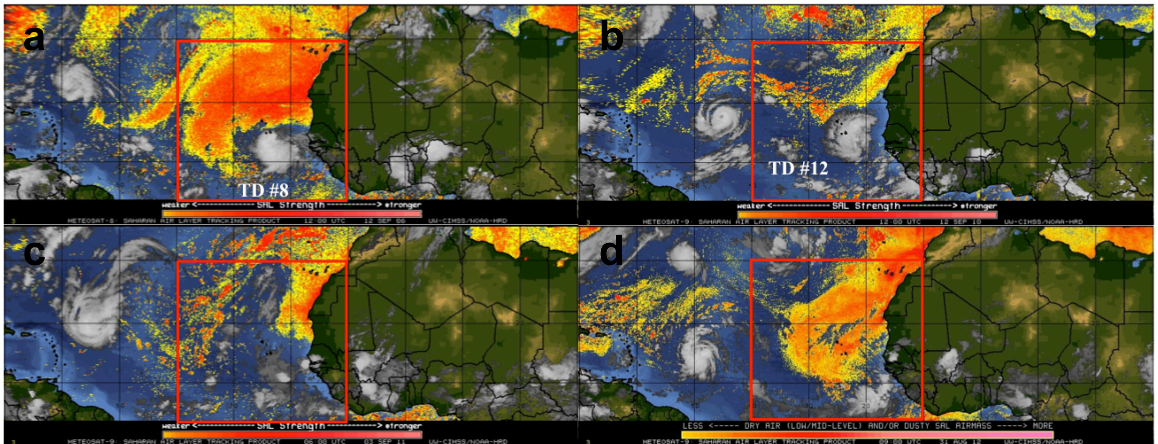

Figure 1. Meteosat-8 SAL Product Analysis of (a) Case #1 Helene 2006, (b) Case #2 Julia 2010, (c) Case #3 Non- Developed 2011, and (d) Case #4 Non-Developed 2012 (available at the University of Wisconsin – CIMSS http://tropic.ssec.wisc.edu/tropic.php).

The configuration of the models was the same, except for the chemistry module used in WRF-CHEM. The horizontal grid spacing selected was 15 km with 61 vertical levels. The microphysics scheme used was the WRF Single-Moment 5-class (WSM5) scheme. Other physic schemes used include the Yonsei University (YSU) scheme for the planetary boundary layer, the NOAH scheme for the land surface physics, the Goddard scheme for the shortwave radiation physics, Rapid Radiative Transfer Model (RRTM) scheme for the longwave radiation physics, and the GOCART simple aerosol scheme (no ozone chemistry) for the chemistry option in WRF-CHEM. The WRF-CHEM model also incorporates an emissions-input data to add (i.e., PREP CHEM SOURCES) anthropogenic emissions and GOCART background information to the simulations.

2.2 *Case Descriptions*

The cases were selected to represent different environmental (background) conditions, strong dust outbreak or weak dust outbreak, and to represent different tropical cyclogenesis outcomes, developed or non-developed. Imagery from the 12.0 and 10.8m infrared channels on the Meteosat satellite is obtained to observe the position and movement of the SAL dust particles (Fig. 1). Case #1, Helene (2006), developed from AEW #7 and was named as tropical depression (TD) #8 on September 12, 2006 at 1200 UTC. As shown in Fig. 1a, TD 8 developed under a moderate dust outbreak covering the north and northwestern parts of this system.

Case #2, Julia (2010), was declared a TD#12 on September 12, 2010 at 0600 UTC. Julia formed after a higher dust outbreak, but by the time of its formation most of the dust particles had scattered. Still, the north and northwestern regions of Julia were in contact with small clusters of dust layer (Fig. 1b).

Case #3, a non-developed event in 2011, initiated its transition from the African continent towards the Atlantic basin on September 2, 2011 at 0000 UTC. The background environment was characterized by scattered dust particles towards the northern region of the cloud cluster (Fig. 1c). Even thought it showed signs of early stage development along the coast of Senegal, it started to dissipate 12 hours later until the cloud structure completely broke down by September 4, 2011 at 0000 UTC.

Case #4, another non-developed event in 2012, initiated its transition from the African continent towards the Atlantic basin on August 30, 2012 at 2100 UTC under a strong dust outbreak located towards the north, northwest of its cloud cluster (Fig. 1d). Similarly to Case #3, this event showed signs of early stage development. However, the cloud cluster weakened until it completely dissipated by September 01, 2012 at 1200 UTC.

3. NUMERICAL ANALYSES OF THE EVOLUTION OF SAL DUST OUTBREAKS AND TC GENESIS

The uncertainty of the tropical cyclogenesis under the influence of the SAL that still remains serves as an inspiration to target the variables and characteristics of the environment, which contains the appropriate conditions for tropical cyclone formation. Any improvement in our understanding of these variables and characteristics will benefit the forecasts of such severe weather phenomena, as well as improving the physics in numerical models. This research selected our four cases around the same time frame in hurricane season, but in different years. The benefit of analyzing these cases around the same time frame is that their background conditions are similar; the SAL is most active from mid June to late July (Carlson and Prospero 1972; Dunion and Marron 2008; Dunion 2011). Therefore key similarities and differences in their environment can be identified. Cases chosen from different months for comparison (e.g., July against September) will be affected differently by the SAL, which would affect the values of the parameters and the purpose of this study. The simulations created with the WRF-ARW model are treated as the control experiments and the ones created with WRF-CHEM are the sensitivity experiments with Saharan dust involved.

The relative vorticity and the wind field at 850 hPa are analyzed for the 4 cases to observe the structure of the vortex (Fig. 2). The simulation results demonstrate high values of relative vorticity in Case #1, Hurricane Helene (2006) and Case #3 Non-Developed (2011), with values greater than 40 x 10^{-5} s^{-1} and 50 x 10^{-5} s^{-1}, respectively. The cyclonic circulations and defined vortex can be expected from the developing Case #1 (Fig. 2a). Also, the highest values of relative vorticity in the areas near the center of the developing system (Fig. 2a). Case #2, Hurricane Julia (2010), shows intermediate values of relative vorticity and the cyclonic rotation with the defined vortex characteristic of a developing system (Fig. 2b). Unlike Case #1, Case #3, does not show the defined rotation and vortex structure expected from a developing system. Instead, the center of rotation appears to be elongated towards the northeast (Fig. 2c). On the other hand, Case #4, Non-Developed (2012), does not show any significant sign of potential development as a tropical depression.

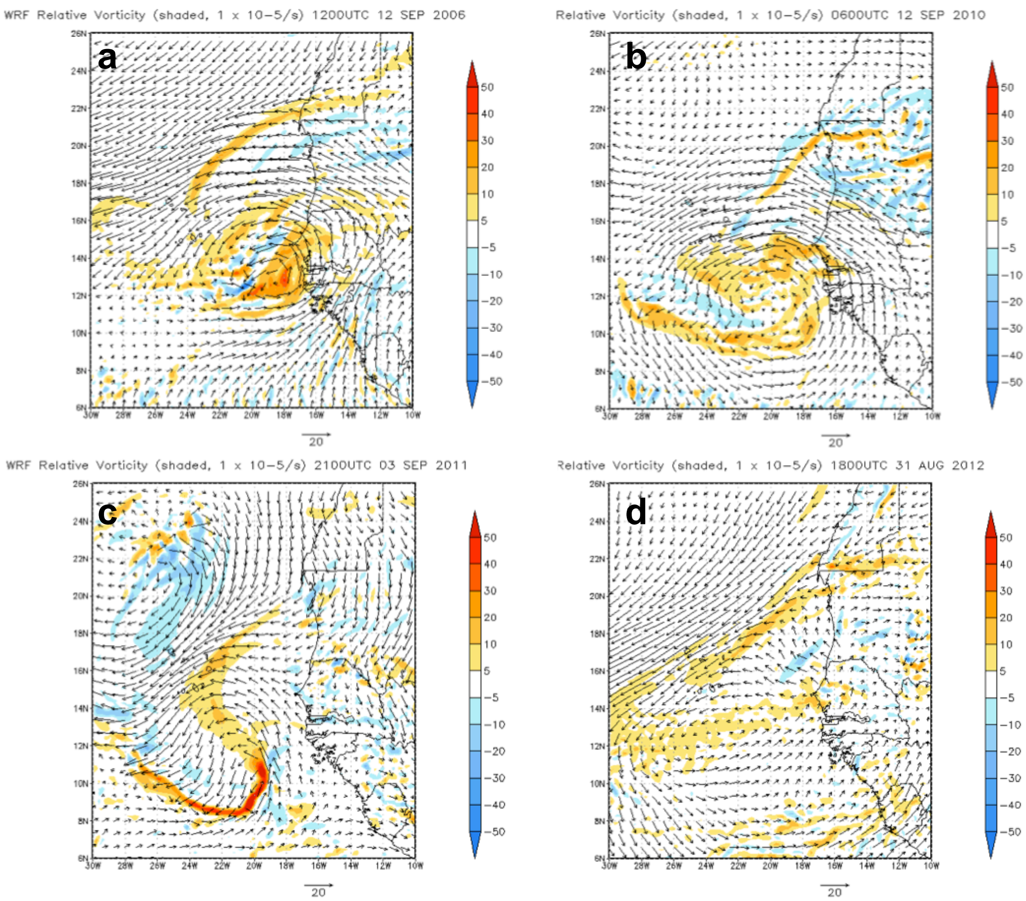

Figure 2. WRF 850 hPa relative vorticity and wind vectors for (a) Case #1 Helene 2006, (b) Case #2 Julia 2010, (c) Case #3 Non- Developed 2011, and (d) Case #4 Non-Developed 2012.

In the simulated radar reflectivity, as shown in Fig.3, a similar pattern than in the relative vorticity is depicted. Case #1 and Case #3 have the highest values, 46.68 dbz and 44.84 dbz, respectively. Case #2, also shows areas of high reflectivity as expected from a developing system and Case #4 does not show any signs of organization or development.

A slight improvement in the representation of the vortex and the structures of the cloud clusters is shown in the sensitivity experiments created with WRF-CHEM. It can be seen that the highest values of relative vorticity still exist in Case #1 and Case #3 (Fig. 4). However, Case #1 appears to have additional areas of high relative vorticity and shows a slight increase in the maximum value (69.19 x 10^{-5} s^{-1}) in comparison to the one observed from the regular WRF simulation (42.87 x 10^{-5} s^{-1}). In contrast, Case #3 appears to have a slight decrease in the maximum value of relative vorticity than the one observed in the control run. Figure 5 demonstrates the simulated radar reflectivity and the available dust particles from the WRF-CHEM model. In Case #1 (Fig. 5a) the dust outbreak can be easily identified (black dotted contours), and the transition from the continental environment towards the Atlantic basin. This result is in agreement with the satellite observation analyses shown in Fig.1a. Additionally, an intrusion of dust particles (2 µg kg^{-1} dry air) into the north and west regions of this developing system is well simulated, which cannot be clearly observed in Fig.1a. Even if Case #2, Case #3, and Case #4 (Figs. 5a, 5c, and 5d), show the transition of the dust particles from the continental sources towards the Atlantic basin, the evidence of dust intrusion into the cloud clusters are not significant. A difference between the extension of the distribution of the dust from the Meteosat satellite imagery and the WRF-CHEM results can be observed in Fig. 5d. The Meteosat imagery shows a larger area of coverage, while the WRF-CHEM results show a more conservative and concentrated distribution for Case #4.

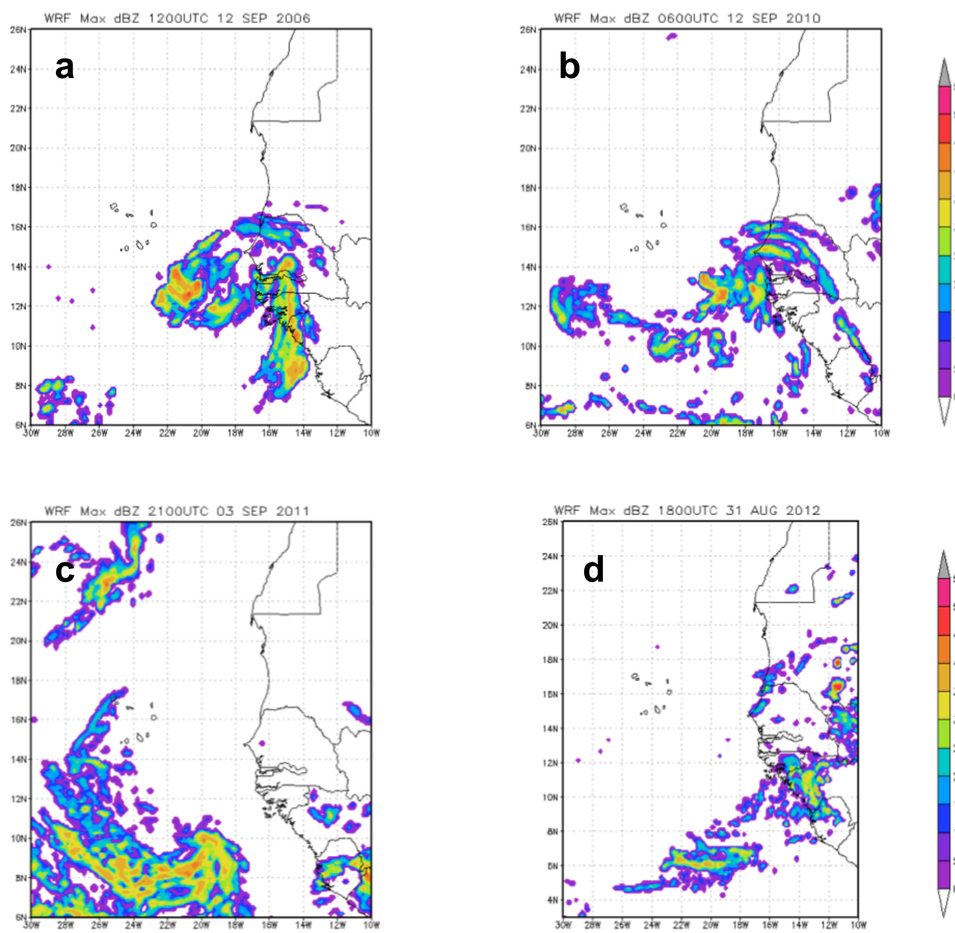

Figure 3. WRF radar reflectivity (dbz) for (a) Case #1 Helene 2006, (b) Case #2 Julia 2010, (c) Case #3 Non- Developed 2011, and (d) Case #4 Non-Developed 2012.

From the cases that developed, cross sections were conducted to analyze the vertical distribution of the moisture variables (vapor, cloud water, ice, and rain) and their interactions with the dust particles. Figures 6a and 6c show slightly similar conditions, but with differences in the coverage and the maximum value of the moisture variables. The vertical distribution of the dust particles throughout the cloud band demonstrates to have amounts as high as 6.36 μg kg^{-1} dry air (Fig.6c). In contrast, an intrusion of dust particles cannot be found for the WRF-CHEM simulation of Case #2 (Fig. 6d). Furthermore, in comparison to the regular WRF results (Fig. 6b), the WRF-CHEM results (Fig. 6d) present evidence of the impact of the aerosol and chemistry calculations included in the model in the difference of the location and amounts of the moisture variables. Even though there is no sign of dust particles acting as CCN

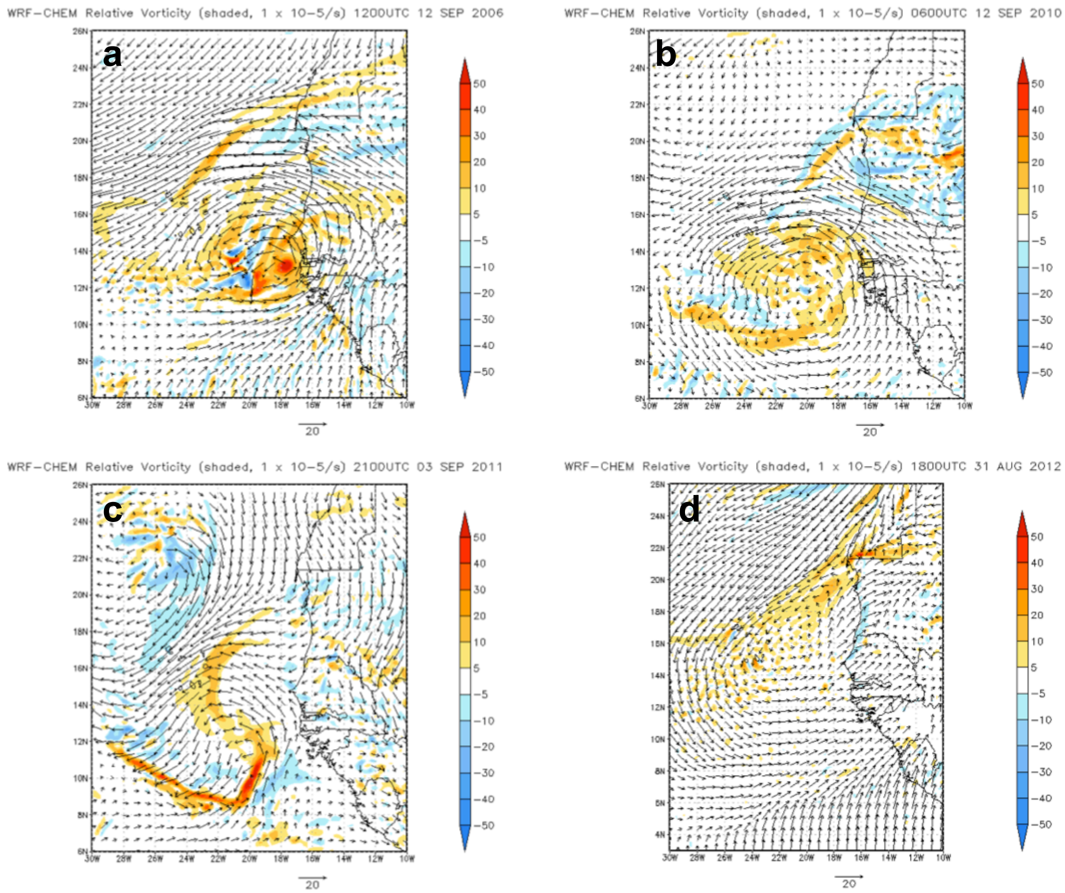

Figure 4. WRF-CHEM 850 hPa relative vorticity and wind vectors for (a) Case #1 Helene 2006, (b) Case #2 Julia 2010, (c) Case #3 Non- Developed 2011, and (d) Case #4 Non-Developed 2012.

(Fig. 6d), amounts of rain water distributed from surface to approximately 550 hPa and horizontally from 17.5º W to 19º W were simulated that were not modeled from the WRF-ARW experiment.

The total amounts of the moisture variables are presented in Table 1. From the two developed cases, Case #1 (strong dust outbreak conditions) has the highest total values of rainwater from both models (i.e., 16.28 g kg^{-1} and 63.62 g kg^{-1} for the WRF and WRF-CHEM models, respectively) in comparison to the values of Case #2 (15.44 g kg^{-1} and 15.58 g kg^{-1} for the WRF and WRF-CHEM models, respectively). The maximum value from the WRF-CHEM simulation is almost four times the total value for the regular WRF result, which suggests the participation of dust particles as CCN in rain production. Even if Case #3 and Case #4 did not develop, they show high values of total rain water (Table 1) from the cloud bands that did develop but dissipated soon after.

5. CONCLUSION AND REMARKS

Analyses of numerical simulations and satellite imagery are presented in this work to gain a better understanding of the SAL in terms of the microphysics of TC formation. Tropical depression #8 (Hurricane Helene 2006) developed in September 12, 2006 at 1200 UTC under a moderate dust outbreak in contrast to TD #12 (Hurricane Julia 2010) that developed in September 12, 2010 at 0600 UTC under a weaker dust outbreak. The use of two study cases that developed under different environmental conditions (strong/weaker dust outbreak), but around the same spatial location and temporal frame, provided a good insight of the differences in the behavior of the parameters during the different development stages. Additionally, two cases that did not developed under different environmental conditions were analyzed, Case #3 in 2011 dissipated under weak dust outbreak conditions

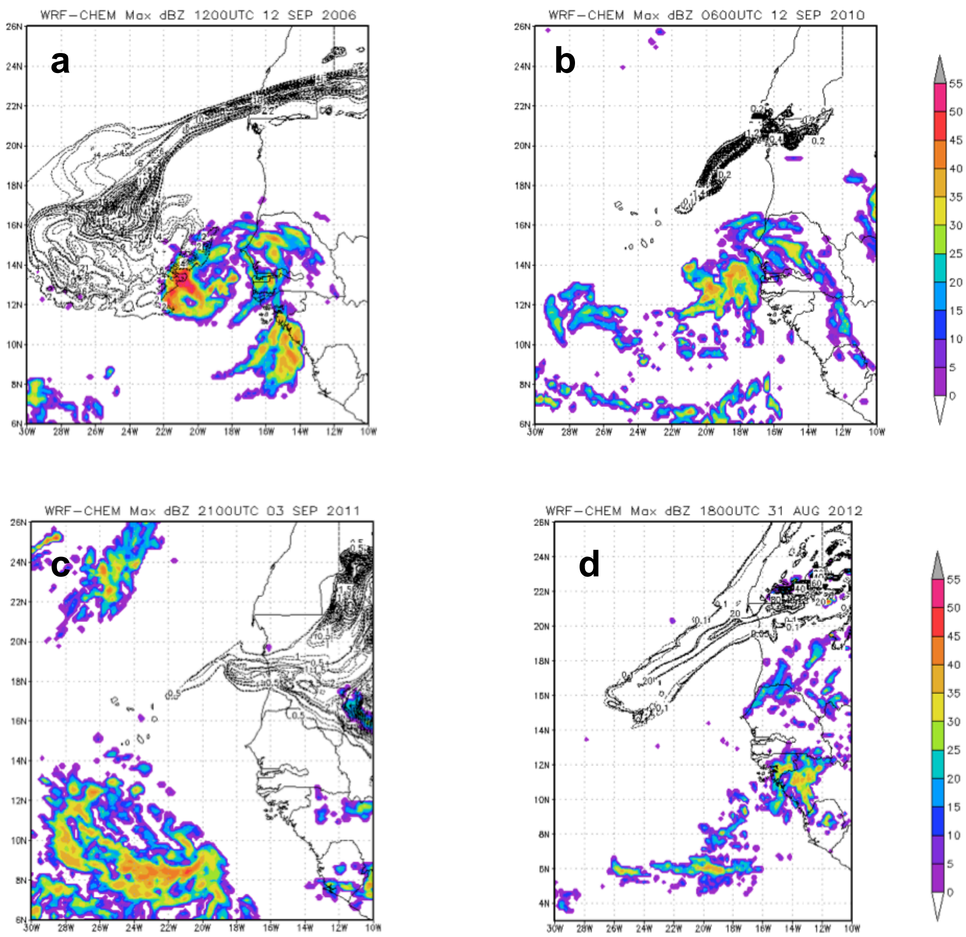

Figure 5. WRF-CHEM radar reflectivity (shaded, dbz) for (a) Case #1 Helene 2006, (b) Case #2 Julia 2010, (c) Case #3 Non- Developed 2011, and (d) Case #4 Non-Developed 2012. Dust particles (μg kg^{-1} dry air) are represented by the black dotted contours.

and Case #4 in 2012 dissipated under strong dust outbreak conditions. Furthermore, the high values of total rain observed on the day of formation of Case #1 Hurricane Helene (2006) suggest that the SAL dust particles are acting as CCN and contributing in the rain production in the system. This result suggests that the WRF-CHEM model offers the benefit of showing the presence of dust inside of the cloud, or storm structure, which usually cannot be observed with satellite imagery. The WRF-CHEM model will help identify the real location of the dust in areas that are misidentified as dust-laden regions in the satellite imagery, which are instead dominated just by dry air. Additionally, the WRF-CHEM model seems to recreate a more defined structure of the systems (or cloud clusters) than the regular WRF model. Overall, the results in this study suggest that dust is a contributor. Nevertheless, more analyses need to be done to identify it as a factor that affects the formation of tropical cyclones negatively or vice versa. Future work will involve the repetition of this analysis using different resolutions and microphysics schemes and use the WRF-CHEM to assimilate MODIS Aerosol Optical Depth (AOD) into the simulations. The AOD will also be used to calculate the mass inside of the domain and compare it with the WRF-CHEM results. Furthermore, an additional part of this study will consist in the creation of an idealized simulation to manipulate key variables that will help to improve our understanding of the impact of dust (aerosols) on tropical cyclones formation.

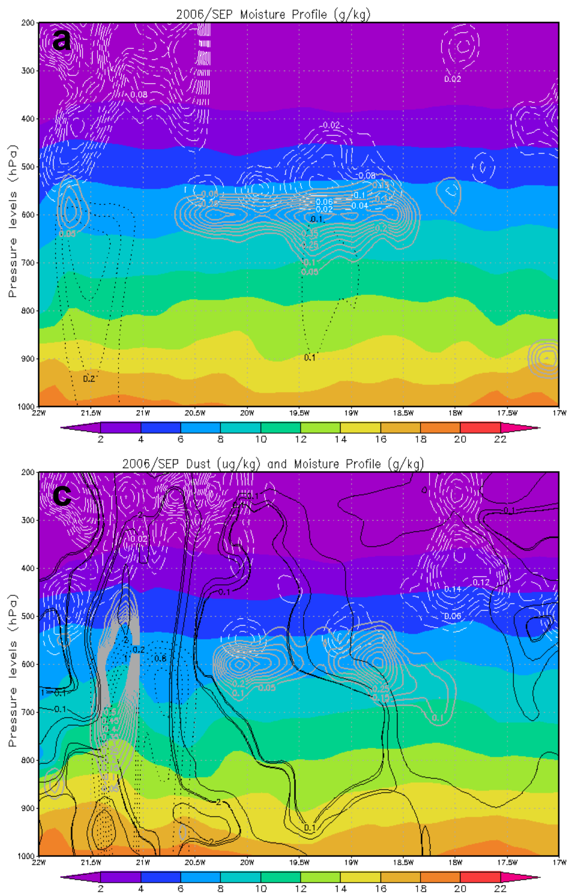

Figure 6. Moisture profiles for Case #1 Helene 2006 (left column), and Case #2 Julia 2010 (right column), from the WRF (a and b) and WRF-CHEM (c and d) models. The moisture variables (g kg^{-1}) included are: water vapor mixing ratio (shaded), rain water (black dotted line), ice (white long dash-short dash line), and cloud water (gray solid). Dust particles (μg kg^{-1} dry air) from the bins are represented with the black solid line.

Table 1. Total amounts of the moisture variables (g kg^{-1})

	Helene 2006		Julia 2010		Non-Dev 2011		Non-Dev 2012	
	WRF	WRF-CHEM	WRF	WRF-CHEM	WRF	WRF-CHEM	WRF	WRF-CHEM
Qvapor	5101.97	5149.21	5164.07	5180.91	4814.53	4736.89	4911.64	4860.38
Qrain	16.28	63.62	15.44	15.58	52.49	49.22	35.94	28.24
Qcloud	10.10	13.76	8.16	4.13	29.53	18.01	11.14	9.44
Qice	10.45	10.04	9.04	13.34	13.54	15.75	19.08	13.02

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