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INFLUENCE OF SAL ON TROPICAL CYCLOGENESIS: COMPARATIVE STUDIES OF HELENE (2006) AND JULIA (2010)

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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). Therefore, its impact is 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).

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. Still, it is not clear how these changes in microphysics 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.

Our working hypothesis is that there exits the possibility of a lag between the observations of high values of AOD (large amount of dust particles) and the observations of high amounts of lightning over an area. The high amount of lightning is suspected to be due to the increase in dust particles acting as cloud condensation nuclei (CCN), which will cause large electrical unbalance. Another impact of the SAL has been suggested by studies showing a strong relationship between the amount of dust covering the region of development (more dust, less dust) and the tropical cyclone activity in the Atlantic (less development, more development; Evan et al. 2006; Zhang et al. 2007; Evan et al. 2008; Wong et al. 2008). High amounts of dust in the North Atlantic may decrease temperatures causing a decrease in cyclone activity (Lau and Kim 2007a,b and c).

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. We plan to use data from different field campaigns designed to study the genesis and evolution of tropical systems. The uncertainty of the connection between the AEWs, the SAL and the tropical cyclogenesis motivated NASA to expand research into the Eastern Atlantic with the NASA- AMMA (NAMMA) project (Zipser et al. 2009). Siting the campaign base at the Cape Verde Islands, Africa, and Barbados, provided insight into the evolution from the continental to the oceanic environment of the AEWs. Three aircrafts (DC-8, NOAA G-IV and NOAA P-3 Orion) participated in NAMMA with instruments that obtained measurements as they flew into the developed systems (tropical depressions, storms and hurricanes) to observe the inner structure (winds, pressure, temperature, etc.). The campaign successfully collected data from AEWs that developed into tropical cyclones and others that did not when SAL was present. The field campaign also obtained samples of the SAL dust to analyze its chemical characteristics. Analyses and computer models using these data are ongoing.

Four years later (2010), a combined effort from NASA, the National Oceanic and Atmospheric Administration (NOAA), and the National Science Foundation (NSF), three field campaigns were organized to investigate the tropical cyclogenesis and intensification of the systems in the Caribbean and West

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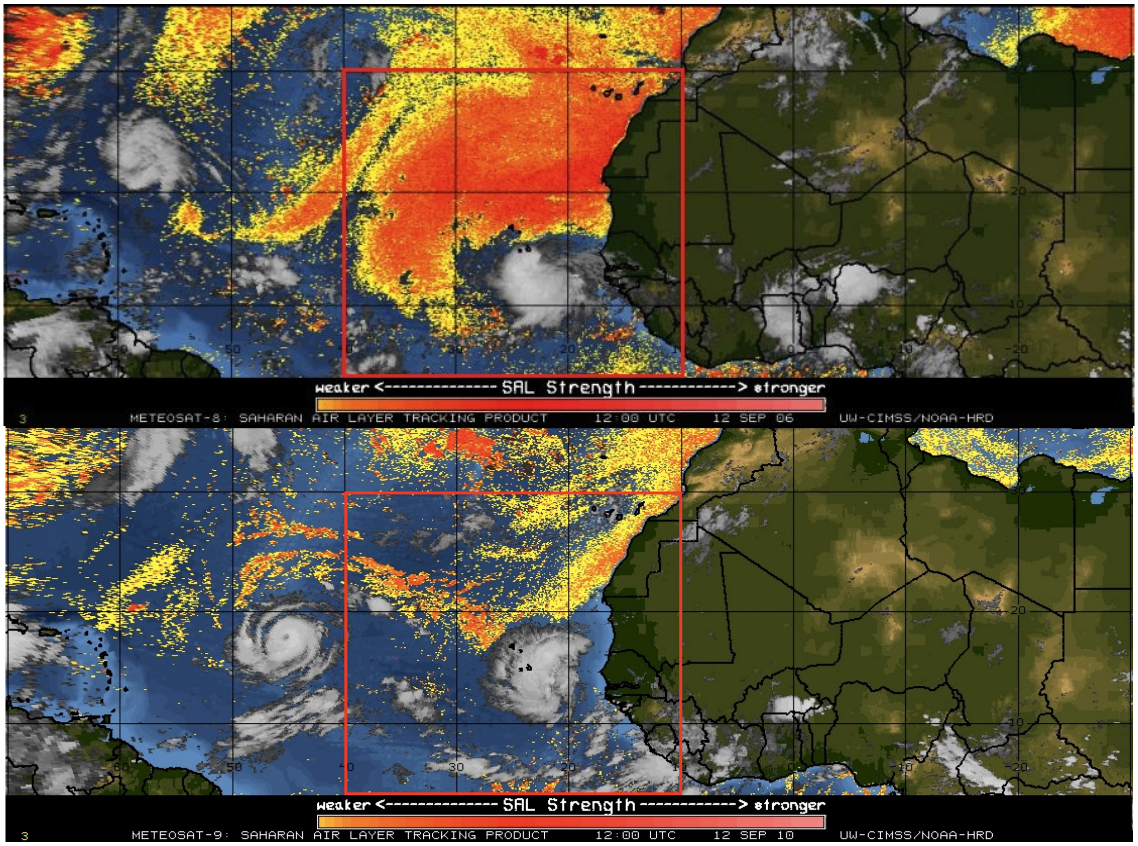

Figure 1. Meteosat-8 SAL Product Analysis of tropical cyclones Helene 2006 (top) and Julia 2010 (bottom).

Atlantic. From these campaigns, only one, PREDICT, would focus on the study of the genesis of these systems. But PREDICT campaign's domain focused on the West Atlantic and the Caribbean, which is a region out of this work's domain. The Genesis and Rapid Intensification Processes (GRIP) experiment, also conducted in 2010, focused on the internal structure and environment as the systems intensify (Braun et al. 2012). Even if most of the data collected for the GRIP 2010 experiment was obtained inside the same domain than PREDICT 2010, the data used from this experiment in the current paper was collected from radiosondes launched from the Cape Verde Islands (available online at http://ghrc.nsstc.nasa.gov/hydro/).

2. DATA AND ANALYSIS METHODS

Data from different meteorological parameters from ground observations and remote sensing are used for the study of the environmental conditions (background environment). National Centers for Environmental Prediction (NCEP) reanalysis data is used to identify the transition of African easterly waves (AEW) leaving the West African coast and to identify any influence from the African Easterly Jet (AEJ; NCEP Reanalysis data provided by the NOAA/ESRL Physical Sciences Division, Boulder, Colorado, USA, from their web site at http://www.esrl.noaa.gov/psd/). Vertical temperature, moisture and wind profiles are created using data from radiosondes launched from Praia and Senegal, and from DC-8 dropsondes from the NAMMA 2006 data and from radiosondes launched from Cape Verde from the GRIP 2010 data (available online at http://ghrc.nsstc.nasa.gov/hydro/). Satellite imagery for variables such as sea surface temperature, water vapor, rain rate, and cloud liquid water from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) radiometer is collected for comparison against ground observations (TMI data are produced by Remote Sensing Systems and sponsored by the NASA Earth Science MEaSUREs DISCOVER Project. Data are available at www.remss.com). 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 (available at the University of Wisconsin – CIMSS website http://tropic.ssec.wisc.edu/tropic.php).

Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Model backward trajectories are used to verify the source of the dust particles (model access via NOAA ARL READY website http://ready.arl.noaa.gov/HYSPLIT.php) and exclude any possibilities of an influencing source different than the Saharan Desert. Moderate Resolution Imaging Spectroradiometer (MODIS) daytime AOD at 550 nm fine mode fraction data was obtained from the National Aeronautics and Space Administration

(NASA) Goddard Space Flight Center (GSFC) Data and Information Services Center (DISC) Giovanni (Acker and Leptoukh 2007) MODIS Online Visualization and Analysis System (MOVAS) to analyze the amount dust particles that could have influenced the tropical systems (available at http://disc.sci.gsfc.nasa.gov/giovanni/overview/index.html). Also, aerosol data corresponding to the day of formation of both hurricanes (September, 12 2006 and September 12, 2010) is obtained from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite (These data is obtained from the NASA Langley Research Center Atmospheric Science Data Center http://www.calipso.larc.nasa.gov/products/lidar/ browse_images/production/). These data give us a better understanding of the aerosol type at the time of the formation of the tropical cyclones.

Arrival Time Difference (ATD) lightning data for the month of September was obtained for both 2006 and 2010 years (available online at http://www.metoffice.gov.uk) to find correlations between the amount of the dust particles and the amount of lightning.

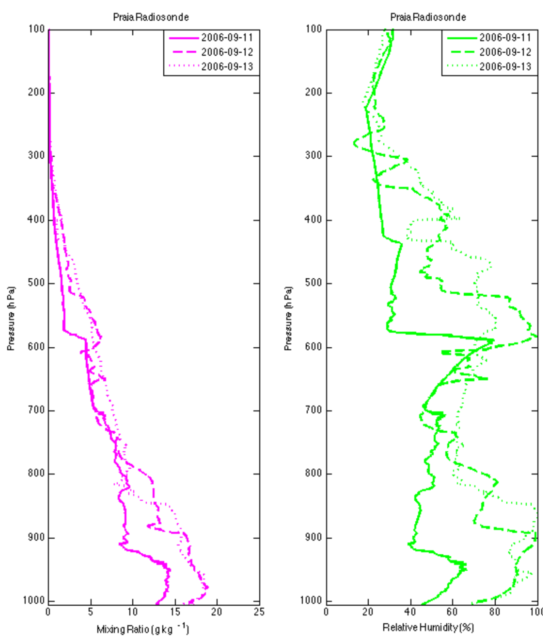

Figure 2. Mixing ratio (magenta) and relative humidity profiles (green) from radiosonde data from NAMMA 2006.

3. EVOLUTION OF SAL OUTBREAK AND TC GENESIS (OVER VIEW)

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. To better visualize these characteristics hurricane Helene (2006) and hurricane Julia (2010) were selected since both systems developed around the same time frame and spatial location (September 12, 2006 and September 12, 2010 respectively). The benefit of analyzing the same date for both seasons is that their background conditions should be similar; therefore key similarities and differences in their environment will be easier to identify. Another factor that influenced our decision in selecting these two systems was that the SAL is most active from mid June to late July (Carlson and Prospero 1972; Dunion and Marron 2008; Dunion 2011). Therefore, dates chosen from different months for comparison (like July against September) will be affected differently by the SAL. Which would affect the values of the parameters and the purpose of this study.

In terms of location, the Cape Verde Islands give a good insight of the conditions north of the formation of the systems near the area where the SAL outbreaks take place. In this analysis we use data obtained from these islands to look for features from the SAL that can be seen from vertical profiles of temperature, dew point and relative humidity (Zipser et al. 2009; Jenkins et al. 2010; Drame et al. 2011) from radiosondes launches. In the following sections we will be describing the conditions of the environment at the Cape Verde Islands on the day prior the formation, during the formation and after the tropical depression is formed.

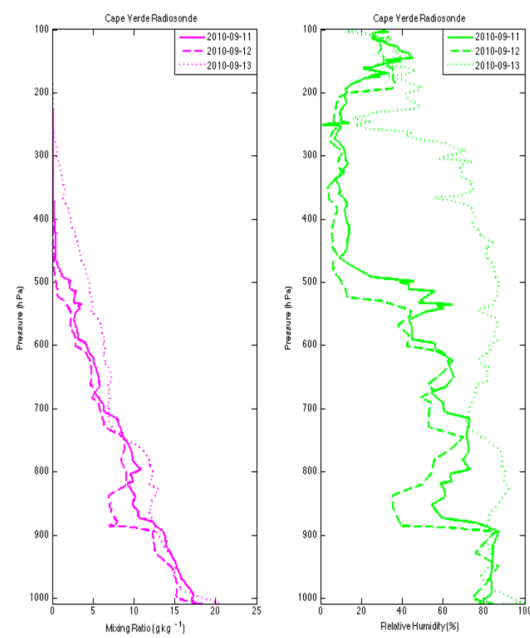

Figure 3. Mixing ratio (magenta) and relative humidity profiles (green) from radiosonde data from GRIP 2010**.**

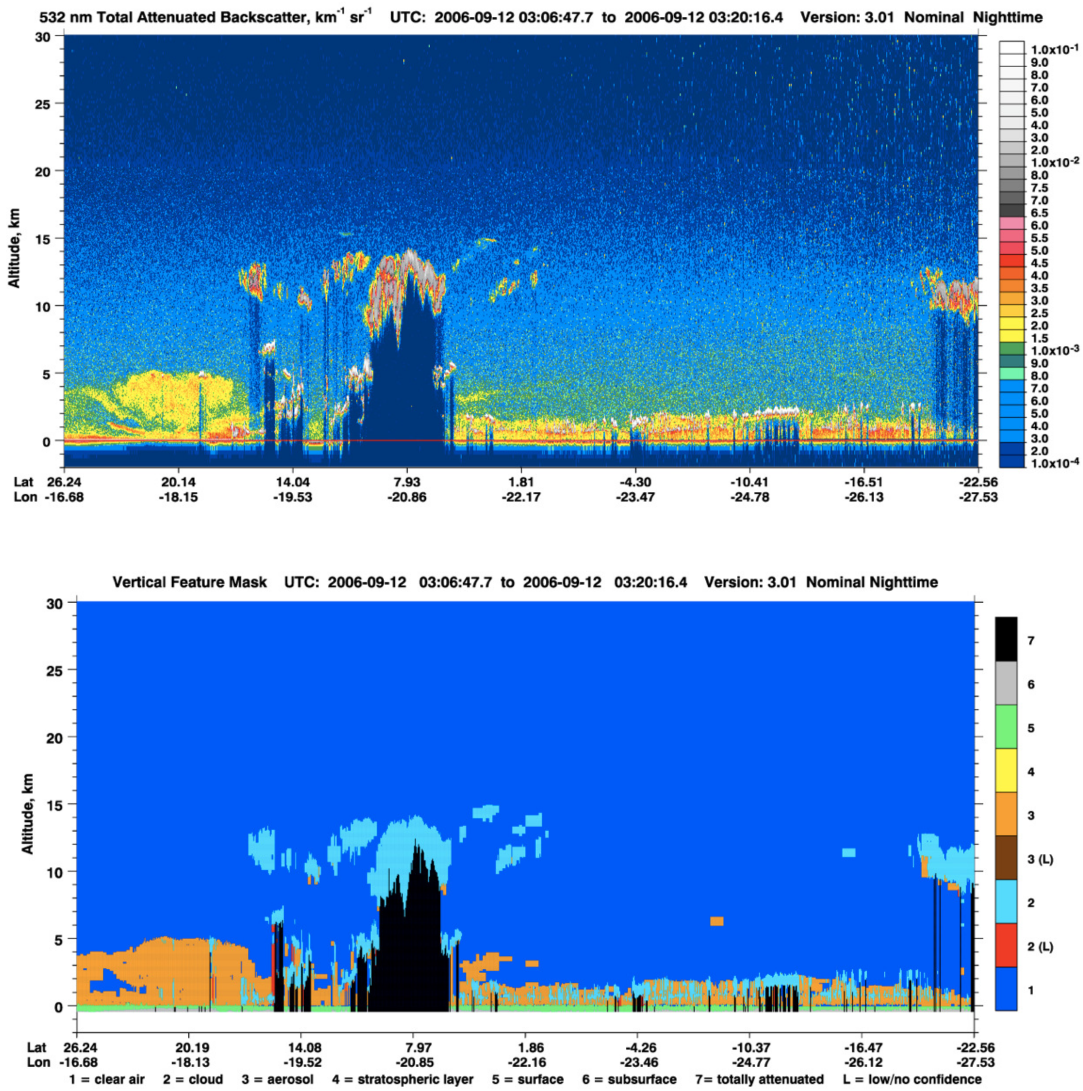

Figure 4. Aerosol data (aerosol backscatter and vertical feature mask) obtained from the CALIPSO satellite for September 12, 2006.

3.1 *Case study #1: Helene 2006*

Helene (2006) developed from AEW #7 and was declared a tropical depression (TD) #8 on September 12, 2006 at 1200 UTC at latitude of 11.9ºN and a longitude of 22ºW with a 1007 hPa pressure and maximum sustained winds of 12.9 m s^{-1}. From Fig. 1 (top) we can observe how the system developed under a moderate dust outbreak covering the north and northwestern areas of the system. Relative humidity data for the 850 hPa and 700 hPa pressure level from radiosondes launched at the Cape Verde Islands (Figure 2 and Table 1) illustrate the increase in humidity from the day prior to the storm, during the formation and after. At the 850 hPa level we can observe the increase starting at 44.5% (prior to formation), to 74.1% (day of formation), and then to 98% (after the formation). This daily increase was not observed at the 700 hPa level, values decreased from 48.5% to 47.1%, and then increased to 63.0%. Low value for vertical wind shear from the day prior the day of formation, -5.8 m s^{-1} provided the conditions necessary for the system to develop. There is a significant increase in the wind shear on the day of formation of the system to 11.7 m s^{-1} followed by a slightly significant decrease on the day after (3.5 m s^{-1}). This increase could be due to the fact that by the time that the radiosonde was launched (1137 UTC), the convection on the inner part of the storm was affecting the wind shear on the region.

3.2 *Case study #2: Julia 2010*

Julia (2010) was declared a TD#12 on September 12, 2010 at 0600 UTC at latitude of 12.9ºN and a longitude of 20.5ºW with a 1007 hPa pressure and maximum sustained winds of 14.9 m s^{-1}. Julia formed after a higher dust outbreak, but by the

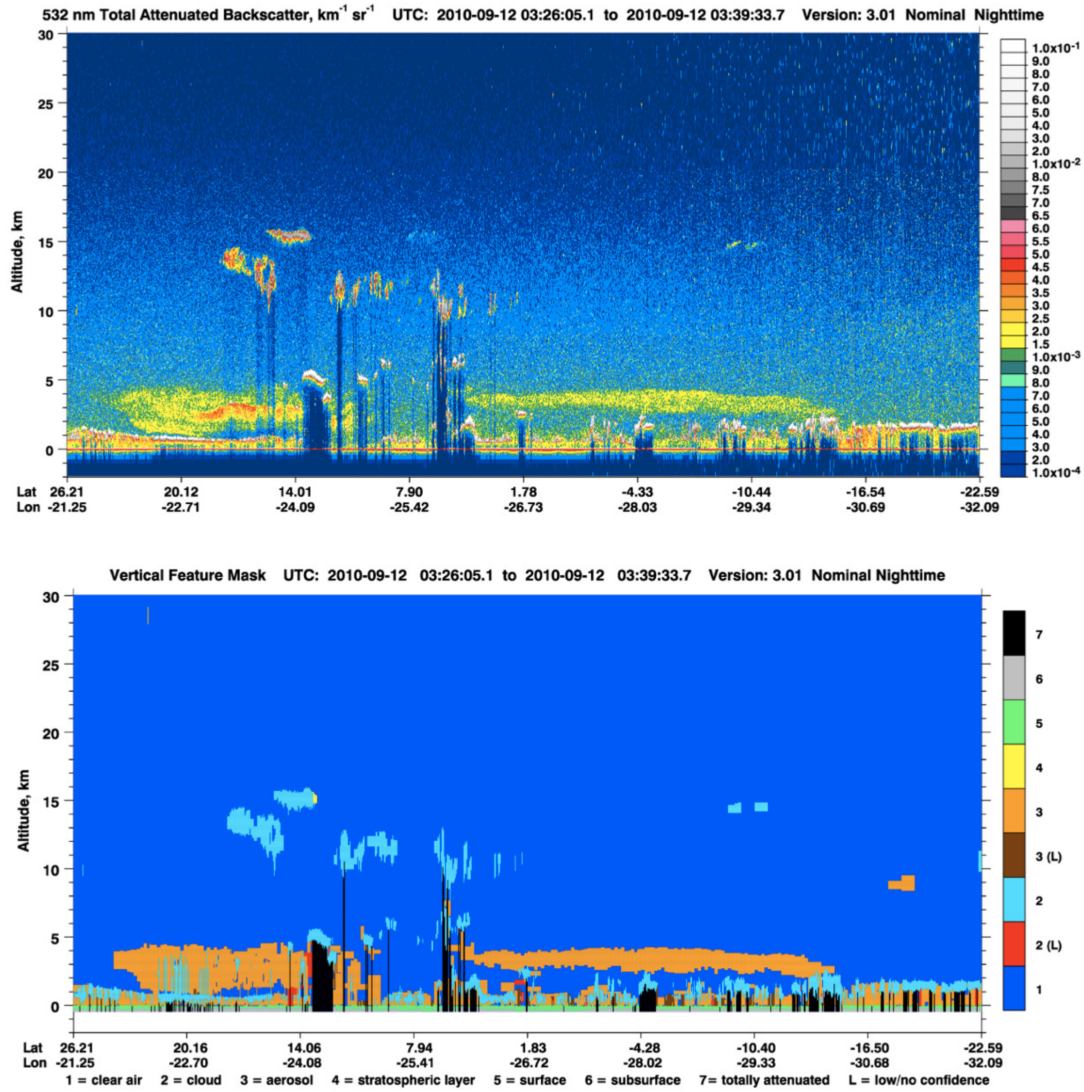

Figure 5. Aerosol data (aerosol backscatter and vertical feature mask) obtained from the CALIPSO satellite for September 12, 2010.

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 particles (Figure 1, bottom). Relative humidity values for the 850 hPa and 700 hPa level show the same behavior: a decrease in relative humidity from the day prior of formation and then an increase in humidity towards the day after the system had reach TD status. At the 850 hPa the values fluctuated from 55.3%, to 35.4% and then to 87.4%. For the 700 hPa the values varied from 60.4%, to 53.5%, and then they increased to 72.8%. From 800 to 600 hPa we observed drier conditions in the radiosonde data in Fig. 3 that could have been due as a result of the system encountering a “secondary” SAL layer observed in the CALIPSO image in Fig. 5. Wind shear values decreased from the day prior to formation, -0.4 m s^{-1} to -1.7 m s^{-1} on the day of TD formation and then increased to 2.5 m s^{-1} the day after. The low values of wind shear observed could have been one of the factors that promoted the system’s formation and intensification.

3.3 *Helene (2006) vs. Julia (2010)*

Both of these systems were able to developed into hurricanes even if the amount of dust particles was different for each. From the satellite images of Fig. 1 we can clearly observe how there is a higher amount of dust particles surrounding Helene (2006) than the amount around Julia (2010). Vertical development can be observed on the profiles in Figs. 2 and 3 as the system progresses through the Cape Verde Islands. Still, at the 850 hPa Helene showed

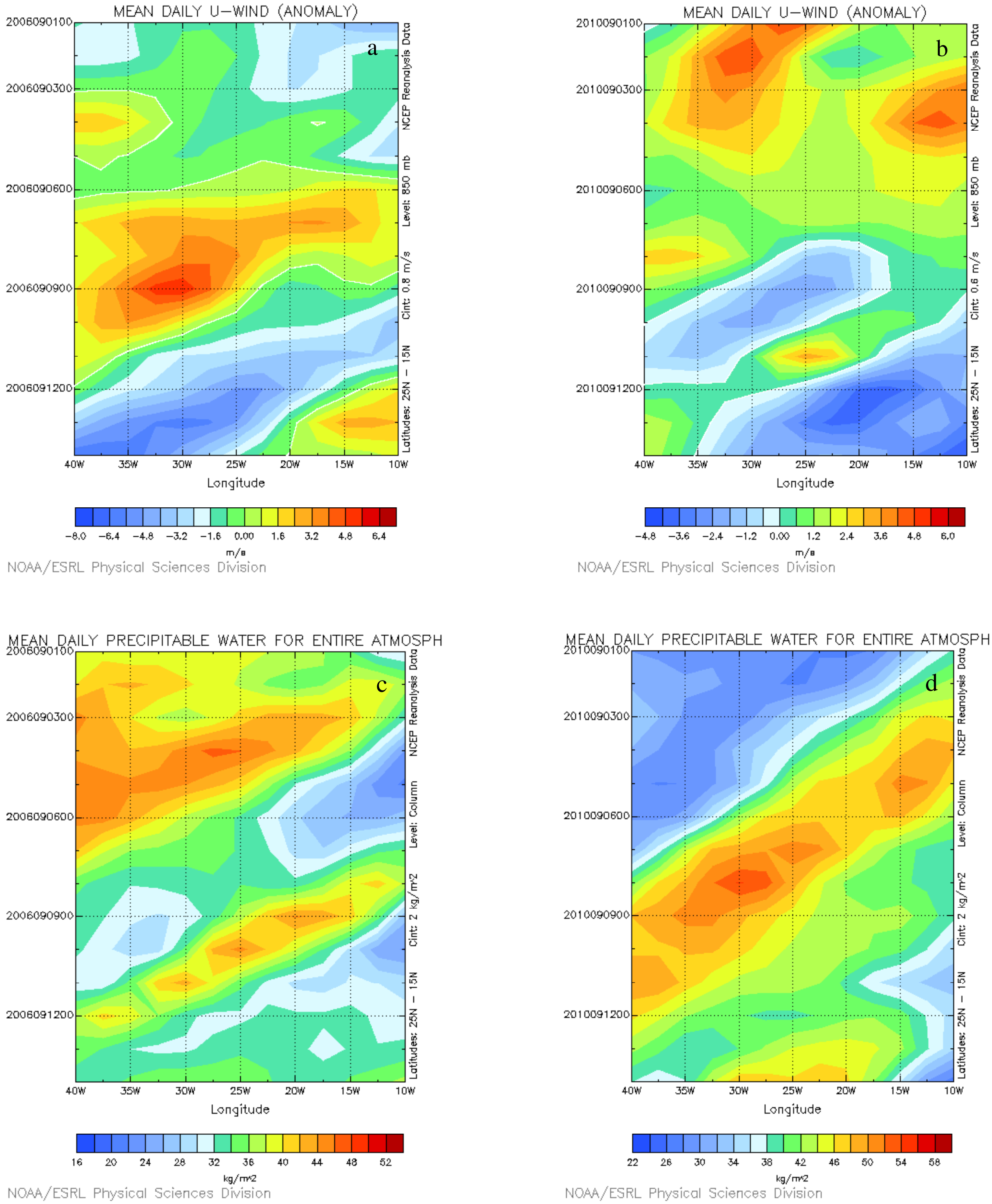

Figure 6. Mean daily precipitable water and zonal wind anomaly from NCEP Reanalysis data for September 2006 (left) and September 2010 (right).

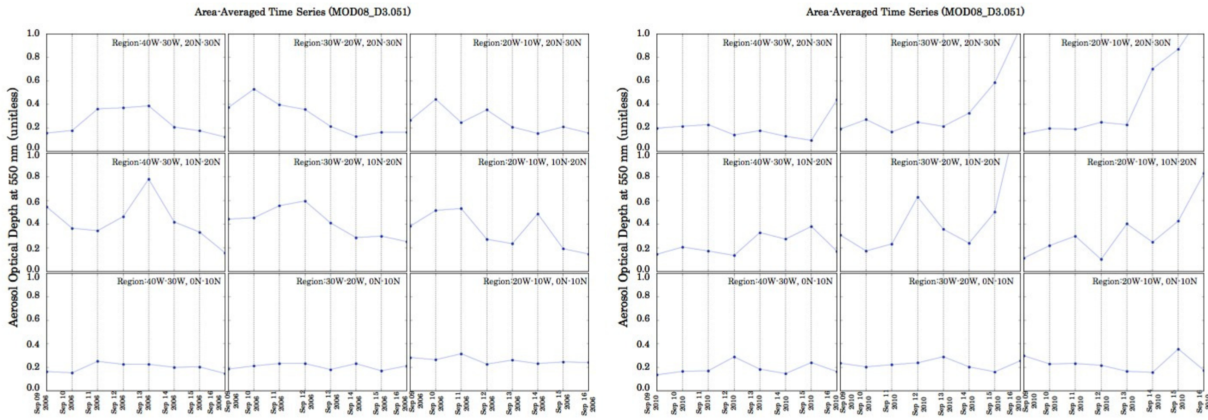

Figure 7. AOD measurements from MODIS for September 2006 (left) and September 2010 (right).

higher values of relative humidity (more moisture) than Julia. On the other hand, at the 700 hPa Julia shows higher values of relative humidity. This could possibly indicate that the SAL affects more the elevation located at 700 hPa (approximately 3010.9 m), which is the altitude at which the SAL is more evident as shown in the satellite images of CALIPSO (Figures 4 and 5). Even if Helene 2006 shows higher moisture content on the day of formation (Figure 2, dashed line), its dust-laden environment observed in Fig. 1(top) appears to have suppressed the vertical development of the system. Figure 3 implies lighter dust covered conditions that were suitable for the development of Julia 2010, which had the highest vertical development of the moist layer reaching an altitude of ~250 hPa (~10358.5 m).

The progression of the waves can be observed in the NCEP reanalysis data shown for precipitation and zonal wind anomaly in Fig. 6. The tropical system Julia (2010) showed a more organized structure since its formation throughout its movement across the eastern Atlantic as seen in Fig. 6b and 6d. From the analysis of the zonal wind data (Figure 6a and 6b) we can hypothesize that a stronger jet contributes to a stronger dust outbreak. The AEJ was stronger for the 2006 case, -8.0 m s^{-1}, as observed in Fig. 6a represented by the blue contours in comparison to the 2010 (Figure 6b) that had zonal wind value of -4.8 m s^{-1}. The low vertical wind shear and the weaker dust outbreak seemed to have helped create the ideal conditions for the development of Julia 2010.

4. CLOUD PROPERTIES COMPARISONS

Comparing Aerosol Optical Depth (AOD) from MODIS and lightning data from Met Office (Figures 7 and 8) suggest that the day before the formation of TD #8 (Hurricane Helene), the system had more Cloud Condensation Nuclei (CCN) to help formation and development (Figure 8a). The higher amounts of lightning data observed on the following day (Figure 8b), suggest that the dust particles acted as CCN source, invigorating the rain bands of the system. On the other hand, TD #12 (Hurricane Julia) did not have much CCN available due to a lower amount of dust particles, in the environment (Figure 8d). The fact that TD#12 also developed in the absence of large amounts of dust could be the result of a more organized wave (Figure 6d) and better vertical structure (Figure 3) than the ones observed in TD #8. Still, we cannot identify a threshold value of AOD that would indicate a boundary limit between suppression due to dust particles and CCN production.

5. CONCLUSION AND REMARKS

Analyses of ground and remote data sets are presented in this work to gain a better understanding of the SAL in terms of the microphysics of tropical cyclones' formation. Also, this works aimed to find a correlation between AOD, lightning, and wind shear at the genesis stage. 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 us with a good insight of the differences in the behavior of the parameters during the different development stages. 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 AOD and lightning data from MODIS and Met Office, respectively, suggest that higher amounts of dust particles in the background environment could increase CCN helping the development of the system by invigorating the rain bands as suggested by Jenkins et al. (2008). This behavior of the dust as CCN source was observed in the day prior formation of Helene 2006 but not on the day prior formation of Julia 2010. Instead, lower vertical wind shear (< ~2.6 m s^{-1}) and lighter dust covered conditions in 2010 seemed to have contributed to the vertical development of Julia. The results of the combination of data in this study support the fact that both systems develop under either stronger or weaker dust conditions. The data analyzed suggest a minimum correlation between the AOD, lightning, and wind shear. Therefore, it is necessary to have more cases to

(a)

(d)

(b)

(e)

(c)

(f)

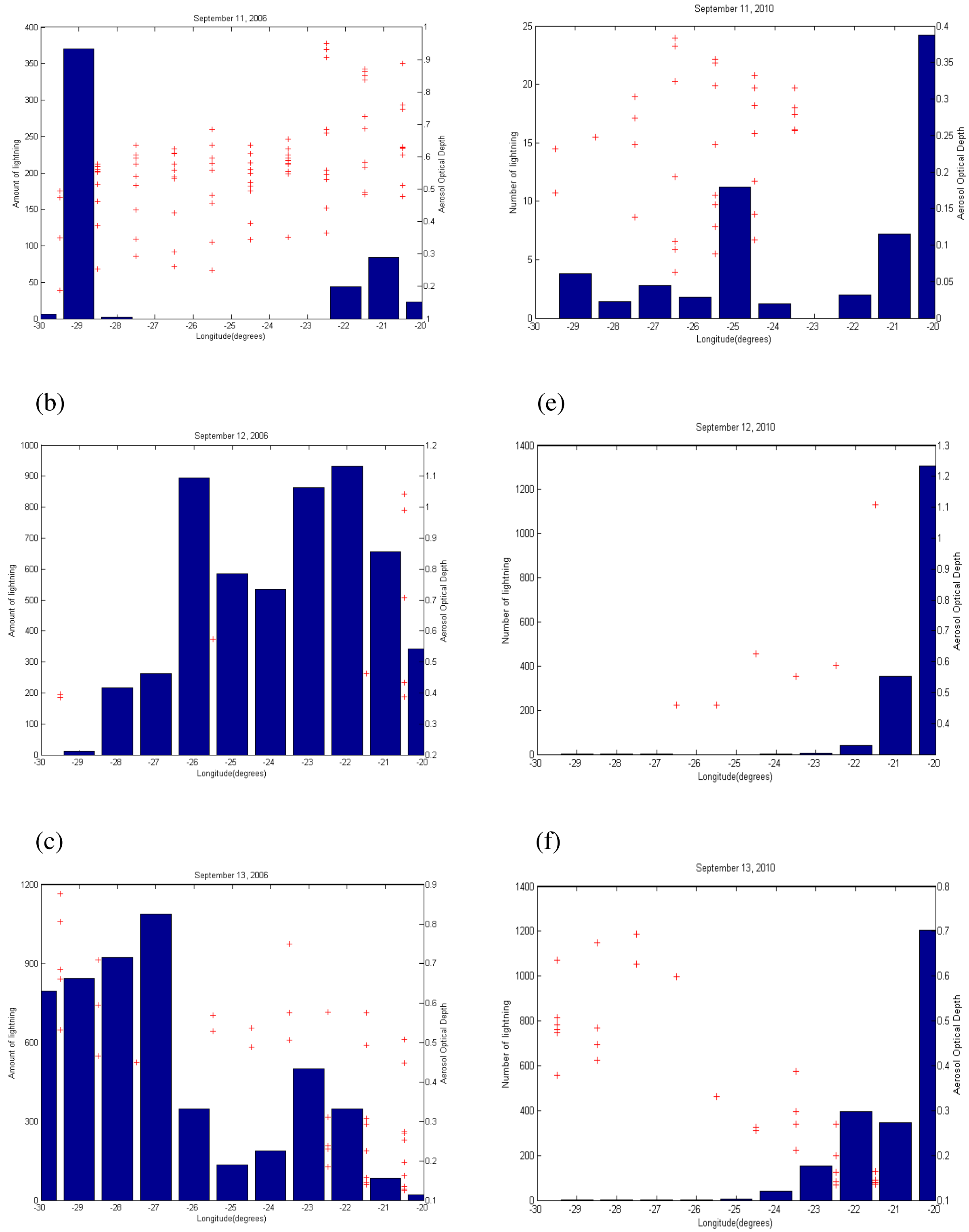

Figure 8. Comparison of ATD lightning data from Met Office and AOD from MODIS.

analyze under different environmental conditions (stronger/weaker dust outbreaks) and cases that experienced suppression of formation (non-develop cases). Overall, the results in this study suggest that dust is a contributor but may not be a factor to affect the formation of tropical cyclones. Our future work will involve the repetition of this analysis for non-develop cases to attempt to isolate key characteristics that define the formation stage of tropical cyclones. A second stage of this work will be conducted involving aerosols schemes from the WRF-CHEM model, Goddard Chemistry Aerosol Radiation Transport (GOCART) and Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) that will be use to recreate the environmental conditions and the influence of the dust on tropical cyclogenesis and observe the impact of the variation of the parameters in the systems. The primary interest in using the GOCART aerosol scheme is that we can simulate dust concentration and meteorological fields over West Africa (Drame et al. 2011), which is our principal area of interest and on of the primary regions for the formation of most tropical cyclones.

Table 1. Wind shear and RH analyses using sounding data from NAMMA 2006.

Date	Wind Shear (m/s)	Relative Humidity 850 hPa (%)	Relative Humidity 700 hPa (%)
2006/09/01	4.1	73.7	61.0
2006/09/02	7.4	78.0	61.2
2006/09/03	-3.6	97.6	100.0
2006/09/04	2.2	87.3	40.4
2006/09/05	9.7	51.9	41.0
2006/09/06	8.5	43.4	39.3
2006/09/07	6.1	42.3	42.9
2006/09/08	-4.3	33.7	44.7
2006/09/09	2.0	85.7	76.2
2006/09/10	2.0	66.3	57.0
2006/09/11	-5.8	44.5	48.5
2006/09/12	11.7	74.1	47.1
2006/09/13	3.5	98.1	63.0
2006/09/14	2.1	86.0	51.5

Table 2. Wind shear and RH analyses using sounding data from GRIP 2010.

Date	Wind Shear (m/s)	Relative Humidity 850hPa (%)	Relative Humidity 700hPa (%)
2010/09/01	0.9	19.5	29.4
2010/09/02	-8.8	18.2	26.7
2010/09/03	-1.8	22.3	20.3
2010/09/04	-1.0	11.2	63.6
2010/09/05	2.2	57.6	79.8
2010/09/06	0.3	45.7	58.6
2010/09/07	5.7	78.4	65.4
2010/09/08	-2.7	67.8	68.6
2010/09/09	-1.4	85.9	60.9
2010/09/10	-0.3	77.8	54.7
2010/09/11	-0.4	55.3	60.4
2010/09/12	-1.7	35.4	53.5
2010/09/13	2.5	87.4	72.8
2010/09/14	6.6	80.5	62.7

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