HURRICANE INTENSIFICATION IMPLICATIONS FROM AFRICAN DUST

by

Allison S Fairley
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Committee:

| | |
|---|---|
| ______________________ | Dr. Ruixin Yang, Thesis Director |
| ______________________ | Dr. Xianjun Hao, Committee Member |
| ______________________ | Dr. Donglian Sun, Committee Member |
| ______________________ | Dr. Peggy Agouris, Department Chair |
| ______________________ | Dr. Timothy L. Born, Associate Dean for Student and Academic Affairs, College of Science |
| ______________________ | Dr. Vikas Chandhoke, Dean, College of Science |
| Date: 30 April 2012 | Spring Semester 2012<br>George Mason University<br>Fairfax, VA |

# Hurricane Intensification and Implications from African Dust

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at George Mason University

by

Allison S Fairley
Bachelor of Arts
American University, 2009

Director: Ruixin Yang, Associate Professor
Department of Geography and Geoinformation Science

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George Mason University
Fairfax, VA

**DEDICATION**

Rain is the condensed moisture of the atmosphere visibly falling in separate drops from the clouds high above, through the atmosphere, and splashing upon the surface of the Earth.

This thesis is dedicated to all the hours spent watching the rain fall with you.

## ACKNOWLEDGEMENTS

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| Aerosol Optical Depth | AOD |
| Sea Surface Temperature | SST |
| National Hurricane Center | NHC |
| Saharan Air Layer | SAL |
| Knots | Kt |
| Geostationary Operational Environmental Satellite | GOES |
| Moderate-Resolution Imaging Spectroradiometer | MODIS |
| Tropical Rainfall Measuring Mission | TRMM |
| Level 1 and Atmosphere Archive and Distribution System | LAADS |
| Statistical Hurricane Intensity Prediction Scheme | SHIPS |
| Cloud Condensation Nuclei | CCN |
| 12-Hour Intensity Change | FD12 |
| Vertical Shear | SHRD |
| Relative Humidity | RHLO |

# ABSTRACT

HURRICANE INTENSIFICATION AND IMPLICATIONS FROM AFRICAN DUST

Allison S Fairley, M.S.

George Mason University, 2012

Thesis Director: Dr. Ruixin Yang

Understanding what factors cause significant intensification or weakening of tropical systems will enable meteorologists to better understand the complexities of a hurricane. Currently, scientists have a good understanding of the fundamental causes of a hurricane track prediction. However, grasping what causes a hurricane to intensify or diminish is still being intensely studied. Understanding hurricane behavior will allow better warnings and preventative measures for protecting lives and property. This thesis studies the Atlantic hurricanes from 2005 and 2006 and the role aerosol optical depth (AOD) plays in hurricane intensity and intensification changes. This thesis uses linear regression modeling to look at the effects of independent variables: sea surface temperature (SST), AOD, vertical shear, and relative humidity, have on the 12-hour intensity change. This regression is tested with each variable, and then in groupings: by year and then hurricane classification. The results are compared and, if possible, relationships within the selected data are determined.

The outcomes of the study show that there is significant linearity between the SST, AOD, relative humidity, and vertical shear, and the 12-hour hurricane intensity change. However, many other factors play a part in the strengthening and weakening of a tropical system such that AOD, vertical shear, SST, and relative humidity cannot solely define or predict the size and strength of a system (Khain 2010). Generally, the more cases and variables that can be linked to hurricane intensity, the better the prediction model for tropical systems can be developed to display the relationship with hurricane intensity change.

# CHAPTER 1: INTRODUCTION

## 1.1 Background

Natural disasters can cause an enormous amount of destruction. The amount and severity depend on a number of factors; geological composition of the land they hit, population of the area, type of natural disaster, and their intensity. By their very nature these phenomena occur with little, if any, warning and are difficult to accurately predict their path and how strong they will be when they arrive.

Hurricanes are one of the most destructive natural disasters and predicting intensification change is still largely inaccurate because the understanding of what causes hurricanes to intensify or weaken is incomplete. However, a hurricane's path can be tracked quite well a few days prior to landfall. Scientists are able to use winds, currents, and SST to predict a path for the hurricane by knowing the key physics of hurricanes; they require warm waters, a confluence of thunderstorms to act as catalyst, and an increased amount of wind. One example of this is Hurricane Andrew in 1992. The National Weather Center sent out predicated tracks for the hurricane as it intensified and warned the coastal areas close to the predicted path. The most significant changes in Andrew's track and intensity were generally well anticipated and the forecast tracks generally lie close to the actual track. However, the rate of Andrew's westward acceleration over the southwestern Atlantic was greater than initially forecast causing it to move slightly off track, reach warmer water, and intensify faster than anticipated. The

National Hurricane Center (NHC) forecast a rate of strengthening that was much less than what occurred during Andrew's period of rapid deepening which caused minimal estimates of the storm's potential (National Weather Center, 2012). This caused the area of Florida where Andrew hit land to be under prepared for the intensity of storm that hit their area.

`

## 1.2 Hurricane Formation

Hurricanes begin as a low pressure system in warm waters. Once the right atmospheric conditions are met the system begins to spin and feed off of the warm waters, taking on more warm water and creating uplift, a positive feedback loop, and continuing to pull energy from the clouds, atmosphere, and warm waters associated with the storm (National Weather Center 2012).

Then, a series of thunderstorms collect around the low pressure system (Wallace, 2006) and tropical depression status is reached. The system may eventually graduate to a tropical storm and then a hurricane. If the storm is classified as a tropical depression it has winds near the center of the clouds ranging between 23 to 39 mph. There is minimal organization within the storm, though imaging of the area shows a small amount of circulation between the multiple thunderstorms grouped together. Once the winds reach between 39 to 73 mph, the storm begins to have a more defined center, or eye. At this time the classification of the storm is upgraded to a tropical storm and it is given a name from the list of tropical storm names for the current year. The storm will continue to feed off warm waters (as long as they are available) and define its rotation and eye wall. At 73 mph the storm graduates to the hurricane classification (NWS, Hurricane Classifications).

Table 1, below, details the hurricane classification, categories 1 through 5, and their general destruction categories.

**Table 1: Hurricane Classification Table; http://www.nhc.noaa.gov/aboutsshws.php**

| Category | Winds | Summary |
|---|---|---|
| 1 | 74-95 mph<br>64-82 kt<br>119-153 km/h | Very dangerous winds will produce some damage |
| 2 | 96-110 mph<br>83-95 kt<br>154-177 km/h | Extremely dangerous winds will cause extensive damage |
| 3 | 111-129 mph<br>96-112 kt<br>178-208 km/h | Devastating damage will occur |
| 4 | 130-156 mph<br>113-136 kt<br>209-251 km/h | Catastrophic damage will occur |
| 5 | 157 mph or higher<br>137 kt or higher<br>252 km/h or higher | Catastrophic damage will occur |

### 1.3 The SAL & African Dust

As a system is developing, it will encounter multiple different atmospheric disturbances. For systems that develop in the eastern Atlantic, they are generally impacted by dust particles swept off of the deserts in Africa. African dust generally extends from spring to the early fall and can reach across the Atlantic Ocean to the southeastern United States from the western areas of Africa, specifically the Sahara and

Sahel deserts. The dust is swept off the deserts by strong winds and carried from the Sahara or other desert regions through atmospheric transport, out into the Atlantic and above the moist marine air layers directly over the Atlantic Ocean. In the skies over Africa and out into the Atlantic, the Saharan Air Layer (SAL) is filled with dust particles from Africa and those millions of tons of dust particles create a drier environment over the marine waters. The dust particles reduce the amount of sunlight that reaches the ocean by partially absorbing it and reflecting the rest back out of the atmosphere. This reflection causes the base water to be cooler, and with cooler water there is less of a chance for the Atlantic Ocean to provide enough energy for a tropical disturbance to occur or be strengthened (Rosenfeld 2011).

As reported by recent research, a decrease in African dust may be a reason for the increase in tropical systems in 2005 (28 storms) and the increase in African dust may have caused the 2006 hurricane season that only had 10 storms (USA Today 2006). This study hopes to review these years and draw statistical conclusions regarding the influence of aerosols on hurricane intensification.

### 1.4 Literature Review

Recently, African dust and the SAL have been intensely studied (Braun 2010; Karyampudi 2002; Rosenfeld 2011). Many studies seek to explain the relationship of the increase of aerosols and the decrease in hurricane activity (Khain 2007; Khain 2008; Jury 2012). Other studies show scientists using accessible data to retrace and create a history of African dust in the Atlantic (Lamb 2005). This data is extremely useful as it can be used to create dust records that can be used to show trends over a longer period of time and assist in the development of algorithms to better reflect reality. African dust has been studied with the intent of answering the question of why and how aerosol particles are able to affect the intensification and creation of hurricanes and what parameters of the hurricane are depressed or increased due to an increase or decrease in African dust and AOD.

According to Sun et al. (2009), African dust aerosols are negatively associated with hurricane activity in the Atlantic basin. Multiple numerical experiments have shown that tropical disturbances are generally found on the southern edge of the SAL and when the SAL extends into the core of the developing system, the system is essentially choked and will eventually weaken (Sun et al. 2009). Sun et al. (2009) concluded that the SAL increases parcel stability, inhibits the exchange of moisture between the atmosphere and the ocean, and reduces flux of moisture into the core of the developing storm. It also demonstrates that the SAL's warm temperature is one of many indirect causes for suppression of a developing storm, while dry stale air can be directly linked to the suppression of a developing storm.

Relating two years of hurricane activity, one vast and one minimal, may show which parameters directly affect the creation or intensification of hurricanes. Sun et al. (2008), by comparing hurricane attributes from the 2005 and 2007 hurricane seasons, concludes that in 2007 there was increasingly more dust over the Atlantic Ocean than there was in 2005, which eludes that the very active season in 2005 was influenced by the decrease in the amount of dust in the air. In 2007, the increase in dust diminished much of the potential for storms to develop. They also show that the 2007 hurricane season had increased wind in the main development region, increased moisture in the air near the eastern Atlantic while significant drying occurred toward the west, and there were significantly lower SSTs. According to Sun (2008), these parameter values are generally good indicators for a calmer hurricane season.

Dunion and Velden (2004) discuss how the Geostationary Operational Environmental Satellite (GOES) can effectively image and track the SAL and its interactions with potential tropical disturbances. In this particular study, the GOES satellite is a split window satellite looking at the North Atlantic, Caribbean, and Gulf of Mexico. Dunion and Velden (2004) state that the outcome of imaging the interactions with the SAL and aerosols with tropical disturbances show that the SAL is essentially suppressing tropical activity in the North Atlantic. However, the tropical disturbances that manage to move out from under the SAL rapidly develop into strong hurricanes, like Hurricane Erin in 2001. The authors also state that the size of the SAL over the Atlantic can exceed a region larger than the size of the contiguous United States which shows that the SAL can impact more area over the Atlantic depending on fluctuations in the SAL's size. Dunion and Velden's study (2004) also goes on to show that the Atlantic tropical activity recorded is 40 percent less than that of the Eastern North Pacific and 60 percent less than that of the Western North Pacific. Some of the difference can be attributed to climate; however the effect of the SAL on cyclogenesis and suppression of storm intensification in the Atlantic is thought to contribute.

## 1.5 Statement of Intent

This thesis will analyze the effect that African dust outbreaks and AOD have on hurricane intensification with the 2005 and 2006 Atlantic hurricanes. Selecting the 2005 and 2006 seasons allows this study to analyze data from a year with low AOD and a year with high AOD.

This thesis will address the possible linearity between hurricane intensification change and attributes, including AOD, SST, relative humidity, and vertical wind shear; that signify hurricane intensification or reduction in order to better predict hurricane strength in the future.

# CHAPTER 2: HURRICANE DATA SOURCES AND METHODOLOGY

## 2.1 Data description

This study uses level 3 data from the Moderate-Resolution Imaging Spectroradiometer (MODIS) and best track data from the NHC to compare the AOD in the Atlantic Ocean for all hurricanes from 2005 and 2006. The study uses this data to determine if there is a relationship between the amount of African dust, shown by the AOD, over the Atlantic Ocean at the specified daily location of the hurricane from when it reaches initial tropical depression classification to when it drops below the hurricane classification threshold through a regression analysis. The results were compared based on storm strength, AOD, and the storm's lifetime.

This study will use multiple databases, combining multiple variables to examine the effect of changing AOD. The databases are listed below:

1. MODIS Level 3 Daily Data: The Level 1 and Atmosphere Archive and Distribution System (LAADS) website maintained by NASA, which uses MODIS Aqua and Terra data is used to extract MODIS level 3 daily AOD values to show the AOD for a particular day. This study uses the data from the Terra/MODIS satellite from the terra atmosphere level 3 products; specifically it used the MOD08_D3- Level 3 Daily joint aerosol/water vapor/ cloud product.

2. Best Track Data: This study also uses the NHC's website to locate the storm's coordinates at daily stages of the hurricane. The storms coordinates during its time spent as a hurricane will be used in coordination with the MODIS data for that same time period to show the depth of aerosol particles from the western coast of Africa. The best track data will also be used to display the max wind speed to see if there is a pronounced relationship between the AOD in the area when tropical depression begins, the end maximum magnitude, and the duration of the storm.
3. SHIPS: The statistical hurricane intensity prediction scheme (SHIPS) database is used to access the 6-hour data for the vertical shear, relative humidity, and SST. The SHIPS database was also used to access the 12-hour future intensity change for the storm system.

## 2.2 Data and Data Handling

The methodology for this thesis involves data sets from multiple databases as described above. The information was collected as follows:

1. Timeframe: The 2005 and 2006 seasons were chosen due to their close temporal timeframe and substantial differences in the number of hurricanes and tropical systems. 2005 was the most active hurricane season in recorded history (Beven, 2008). There were 28 storms, 15 of which became hurricanes, 7 major hurricanes

(Beven 2008). 2006 was slightly below the current average of 10 storms per season, with only nine storms (Halverson 2007) and only 2 major hurricanes.

2. Date for hurricane classification: The NHC website, maintained through NOAA, is used to determine the date when each storm system was initially classified as a tropical depression, as well as when it reached its maximum strength, and when it dissipated below hurricane classification.
3. Best Track: The NHC best track data is used to retrieve the best track and storm report data to properly access the exact location of each storm daily. Daily latitude/ longitude pairs, wind speed, and minimum sea level pressure are recorded to give 6 hourly updates on the storms location and attributes.
    a. Wind speed: After collecting the wind speed information from the best track data, the scale denoted in Table 1 is used to convert wind speed to storm category/classification.
        i. After compiling the Saffir-Simpson hurricane classification for each storm, it was determined that for the 2005-2006 hurricane season there were 10 category 1 storms, one category 2 storm, four category 3 storms, one category 4 storm, and four category 5 storms.
4. AOD: For the days that the hurricane was active, the AOD is collected from the LAADS website along with the best track data previously accessed from NHC. This study looks at hurricanes, not all tropical systems, to review the effect AOD has on a system that history shows developed into a hurricane. This will examine

how much impact AOD has on storm systems that developed through tropical depression status, tropical storm status, and eventually reached hurricane classification.

a. AOD Analysis: After capturing the data, a scale area around the center of the hurricane is created and Matlab is used to analyze the data. Understanding that the fundamental part of a hurricane is cloud cover, and part of the images will be invalid as they are deterred by the large amount of clouds, it was necessary to create an average around the storms center (previously identified by the NHC). This is a 10 x 10 degree area. The system took all the pixels that are in the 10 x 10 degree area from the center and averaged them to give an AOD estimate reading which is calculated and recorded (pixels that are considered 'not available' due to increased cloud cover are excluded from the calculations). This is done for everyday each system is at hurricane status.

    i. For example, Figure 1 through Figure 7, below, show the AOD images accessed for Hurricane Katrina in 2005. These images show AOD readings accessed from the LAADS website for Hurricane Katrina. Images were created using Matlab. The red box indicates 10 x 10 area used to create the AOD averages and '+' shows center of the storm.

ii. In the images, the color bar shows the AOD values. The white pixels indicate invalid (cloud covered or undetectable) pixels while dark blue indicates minimal values.

The higher the AOD value present the lighter the colors represented in the images. Generally yellow to red indicates an AOD greater than 1.

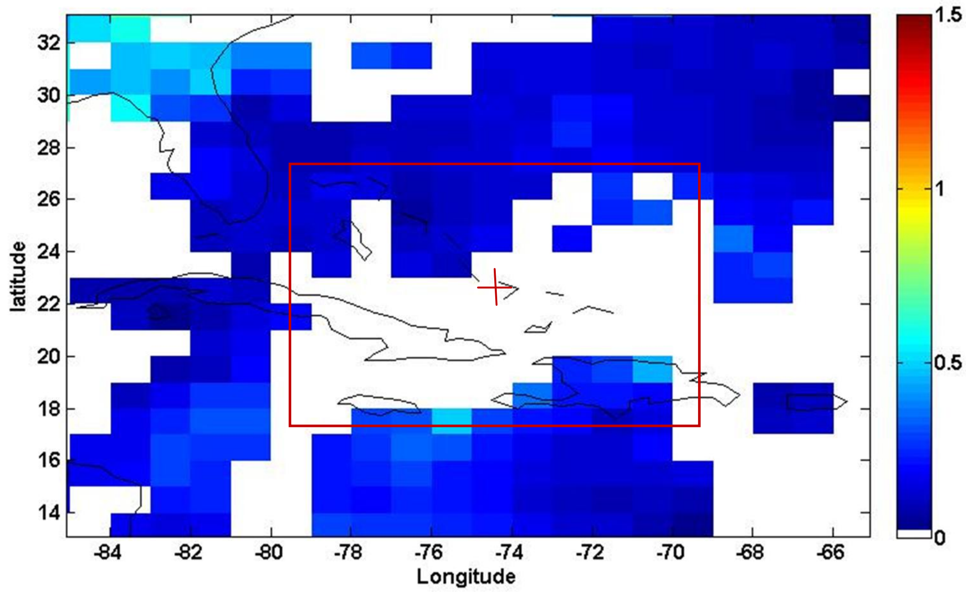


**Figure 1: Hurricane Katrina on 23 August 2005**

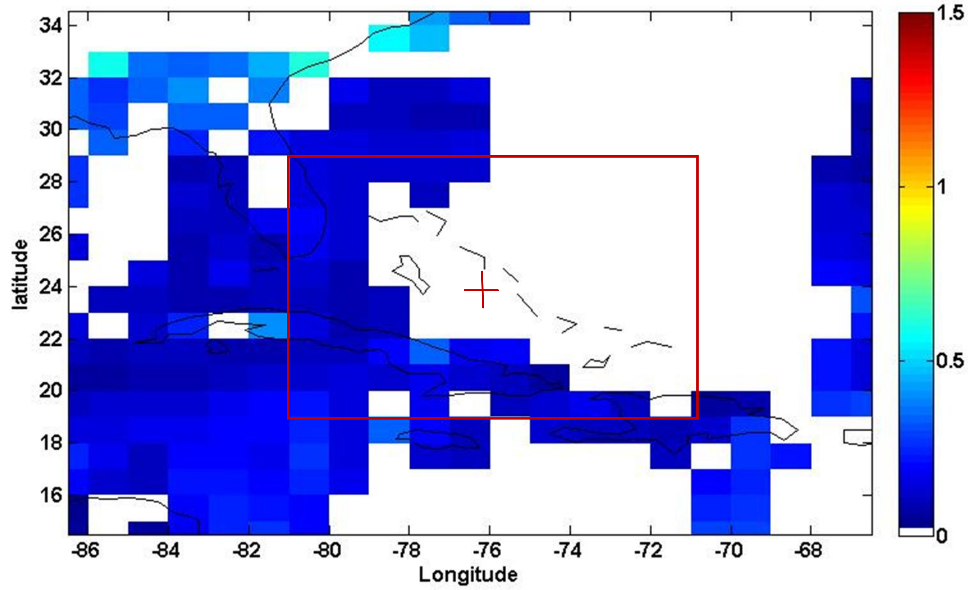


**Figure 2: Hurricane Katrina on 24 August 2005**

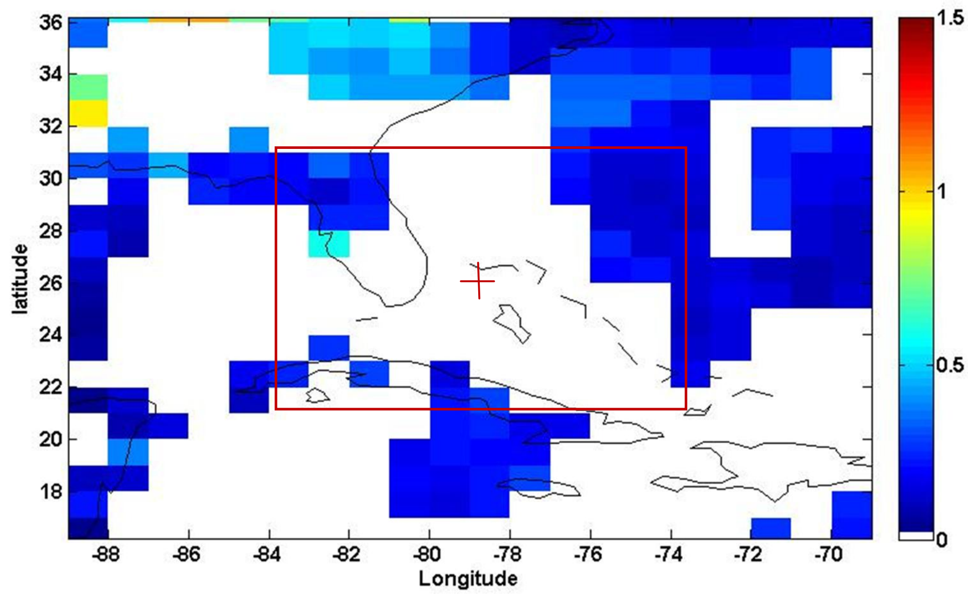


**Figure 3: Hurricane Katrina on 25 August 2005**

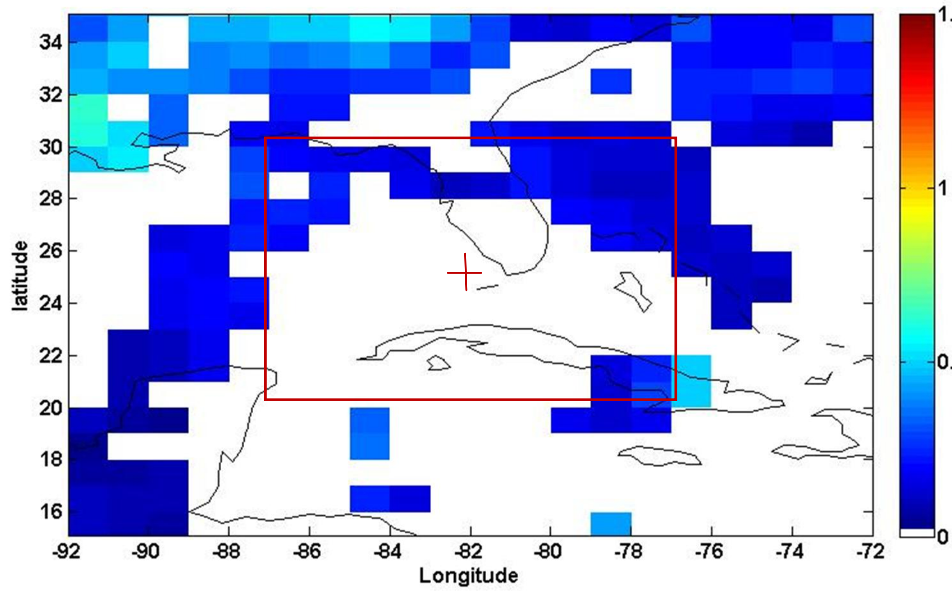


**Figure 4: Hurricane Katrina on 26 August 2005**

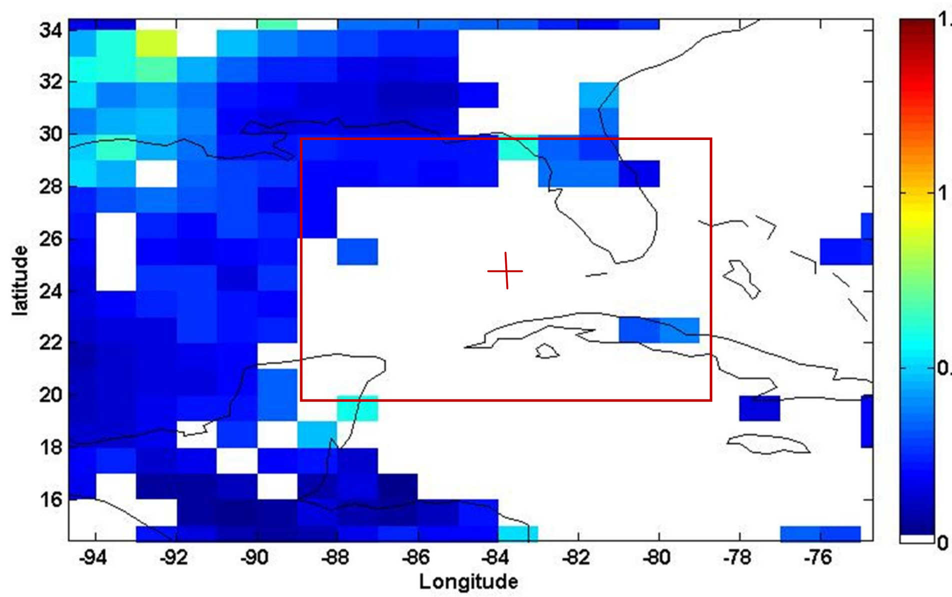


**Figure 5: Hurricane Katrina on 27 August 2005**

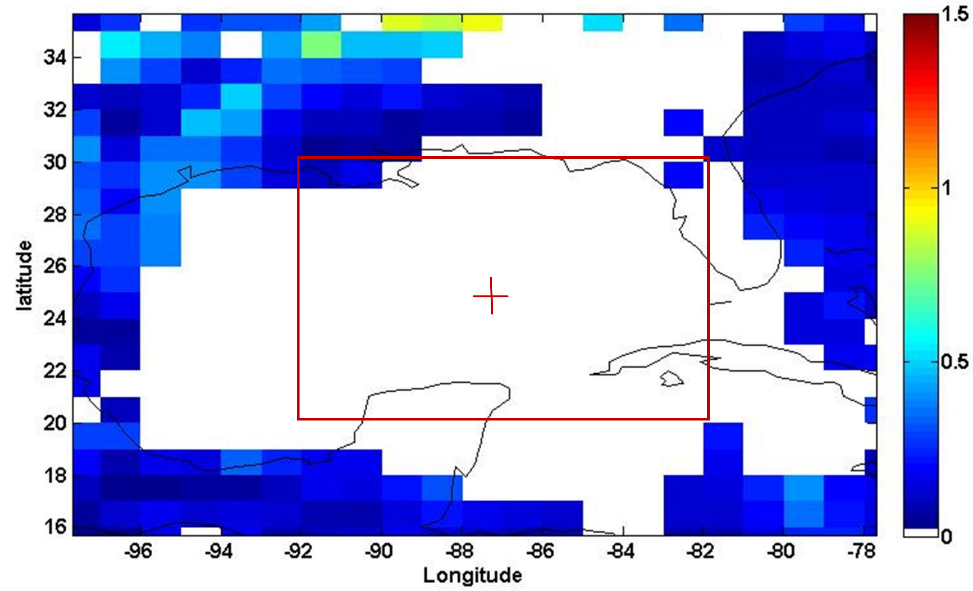


**Figure 6: Hurricane Katrina on 28 August 2005**

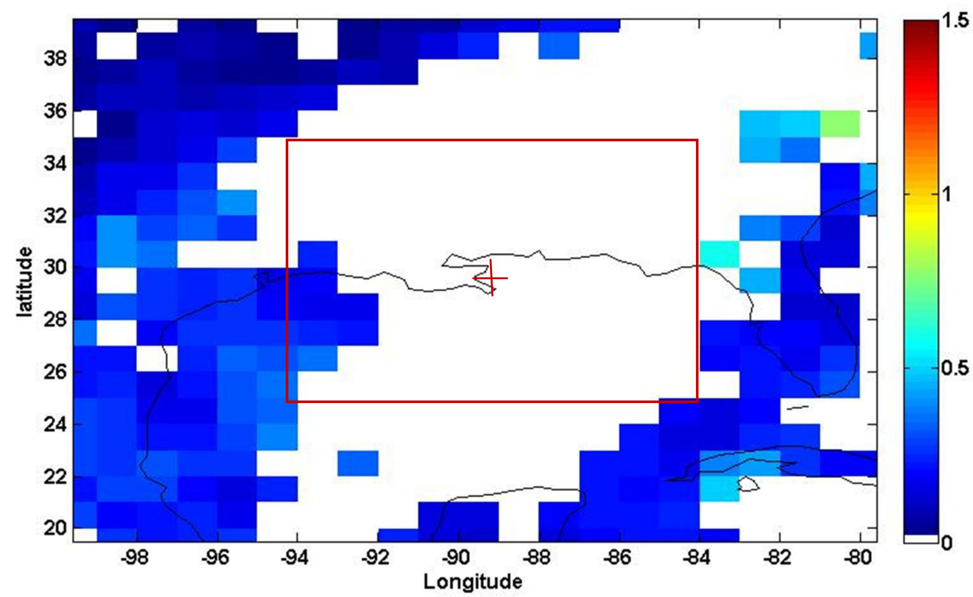


**Figure 7: Hurricane Katrina on 29 August 2005**

5. SHIPS: Next, the SHIPS database is used to access the vertical shear, SST, and relative humidity at each time point. These variables are used against the 12-hour intensity change, denoted FD12, also derived from SHIPS. Table 2 shows an example of the parameter values of Hurricane Katrina in August 2005.

**Table 2: Data collected for Hurricane Katrina, 2005**

| Date | Time | FD12 | RSST | RHMD | SHRD | AOD |
|---|---|---|---|---|---|---|
| 23-Aug | 18 | 0 | 299 | 69 | 105 | 0.0584 |
| 24-Aug | 0 | 5 | 300 | 67 | 86 | 0.0809 |
| 24-Aug | 6 | 10 | 302 | 65 | 129 | 0.0809 |
| 24-Aug | 12 | 10 | 303 | 61 | 129 | 0.0809 |
| 24-Aug | 18 | 10 | 305 | 66 | 126 | 0.0809 |
| 25-Aug | 0 | 10 | 306 | 70 | 59 | 0.1313 |
| 25-Aug | 6 | 10 | 307 | 68 | 82 | 0.1313 |
| 25-Aug | 12 | 15 | 307 | 67 | 107 | 0.1313 |
| 25-Aug | 18 | 5 | 307 | 68 | 143 | 0.1313 |
| 26-Aug | 0 | 5 | 308 | 70 | 133 | 0.1368 |
| 26-Aug | 6 | 20 | 308 | 64 | 157 | 0.1368 |
| 26-Aug | 12 | 15 | 307 | 64 | 152 | 0.1368 |
| 26-Aug | 18 | 10 | 305 | 68 | 183 | 0.1368 |
| 27-Aug | 0 | 10 | 305 | 66 | 149 | 0.1362 |
| 27-Aug | 6 | 5 | 304 | 67 | 186 | 0.1362 |
| 27-Aug | 12 | 0 | 304 | 63 | 164 | 0.1362 |
| 27-Aug | 18 | 25 | 303 | 62 | 97 | 0.1362 |
| 28-Aug | 0 | 45 | 303 | 66 | 69 | 0.1429 |
| 28-Aug | 6 | 25 | 303 | 61 | 141 | 0.1429 |
| 28-Aug | 12 | -5 | 305 | 64 | 102 | 0.1429 |
| 28-Aug | 18 | -25 | 307 | 69 | 36 | 0.1429 |
| 29-Aug | 0 | -30 | 310 | 68 | 95 | 0.1548 |
| 29-Aug | 6 | -45 | 313 | 71 | 141 | 0.1548 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 29-Aug | 12 | -60 | 314 | 70 | 163 | 0.1548 |
| 29-Aug | 18 | -40 | 310 | 70 | 242 | 0.1548 |

## 2.3 Methodology

After compiling the data as described above, the data is then input into Matlab in order to create a statistical analysis of all data parameters. This study performs a linear regression analysis. A linear regression analysis is a statistical way to compute the linear relationship between a dependant variable, y, and at least one other variable. For this study the dependant variable, y, is defined as the 12-hour hurricane intensity change. The independent parameters, x, are SST, vertical shear, relative humidity, and AOD. The data is input into Matlab and a 95% confidence interval is used to present statistical measures of the data.

This thesis initially tests the dependant variable, y, against each of the independent variables, noted above, individually using Matlab coding. Then the data is compiled into multiple groupings; all 2005-2006 data, 2005 data, 2006 data, category 1, category 2, category 3, category 4, and category 5 data and analyzed in Matlab.

After computing the data, the output variables of interest include $R^2$, adjusted $R^2$, b-intercept and p-value. The $R^2$ value represents how well the linear model fits the data. The value is between 0 and 1. It is the percentage of variation explained by the linear model. The value that is closer to 1 represents a better fit model. The b-intercept value represents the minimum and maximum bounds for the 95% confidence interval for each parameter. The p-value shows the probability that the relationship observed for the data is by chance. The p-value should be small, at least smaller than the 0.05 confidence used in the coding earlier in Matlab to show the relationship is not by chance. This is because if the p-value is smaller than the predefined significance level (5% in this case) the higher the likelihood that the linear model is valid.

# CHAPTER 3: STUDY RESULTS AND DATA RELATIONSHIPS

## 3.1 Results

Although the negative impact of AOD is generally identified in previous studies (Sun et.al, 2009; Dunion and Veldon, 2004), positive impact is also reported (Braun 2010). The controversy is possibly due to the different environmental conditions and hurricane status. This means the role of dust in hurricane development must be partially related to other factors such as vertical shear, relative humidity, and SST. In this study, these influential factors will be incorporated into multiple regression models to investigate the roles of dust in various conditions.

For dust to affect the creation of a tropical disturbance it must wrap along the northern part of the storm so the storm's winds will pull the dust into the storm and create layer mixing. This will decrease the amount of heat that reaches the sea surface thus decreasing the possibility for higher SST to be reached (which is necessary for hurricane creation) (Wallace 2006). The dust also acts as multiple cloud condensation nuclei (CCN), and since dust provides many particles it will increase the number of CCN in the clouds thus creating more droplets. Each drop will weigh less, have a smaller radius, and have a smaller possibility of falling out of the cloud as rain. This leads to the initial conclusion that the amount of dust in the air will directly affect the strength of the storm, or the likelihood one will be created (Dunion 2004).

By using multiple variables in the regression models, the model is better able to predict actuality. Since the roles of dust in tropical cyclone development can be both positive and negative in different conditions, it was necessary to analyze the data singularly and grouped. Grouping data (cases) based on the conditions can verify the conclusion with certain statistical significance levels.

The SHIPS database is used for obtaining the values for the other parameters. The values of the parameters are calculated in SHIPS database for every 6 hours at 0Z, 6Z, 12Z, and 18Z. SST, described above, the vertical shear measurements, denoted as SHRD, and relative humidity (RHLO) are included in this study. The vertical shear occurs when environmental winds blow in different speeds vertically; it is commonly considered as the weakening factor of hurricane development. According to Zehr (2003), vertical wind shear generally decreases a tropical system's potential to reach its maximum intensity. The vertical wind shear is generally seen to increase in El Niño years and is a good predictor as to whether or not a hurricane season will be very active (Aiyyer, 2011). Also incorporated is the relative humidity. Relative humidity is the amount of saturated water vapor in a parcel of air and generally represents the likelihood of precipitation. Hurricane intensification, which is based on thunderstorm activity, increases with a higher percentage of relative humidity. The units and value ranges of the parameters used in this study are listed in Table 3.

**Table 3: SHIPS Database parameters used (units, abbreviations, and range values)**

| Value | Units | Symbol | Range for 2005-2006 Hurricanes |
|---|---|---|---|
| 12-Hour Hurricane Intensity Change | Knots | FD12 | -80 - 75 |
| Sea Surface Temp | °C | SST | 21.3 - 31.4 |
| Vertical Shear | Knots | SHRD | 0.9 - 41.1 |
| Relative Humidity | Percent | RHLO | 25 - 82 |
| Aerosol Optical Depth | None | AOD | 0.0470 - 0.8931 |

The linear regression model requires the use of one dependant variable, y, 12-hour intensity change, and independent variable(s), x, which can be one of SST, vertical shear, relative humidity, and AOD, or their combinations. When completing the linear regression, output variables of interest include the value of coefficient of determination, $R^2$, the adjusted coefficient of determination, $R^2$ adj, the regression slopes, b, and their confidence interval and p-value based on the F-test of the overall model. The $R^2$ value represents how well the linear model fits the data. It is the variation of data explained by the linear model with a value range between 0 and 1. The value that is closer to 1 represents a better fit model. The adjusted $R^2$ ($R^2$ adj) value is a modification of $R^2$ that additionally corrects for the number of independent variables in a model. Unlike $R^2$, the adjusted $R^2$ increases only if the additional variables improve the model more than would be expected by chance. The slope value, b, represents the 12-hour intensity changes due to a unit change of the corresponding independent variable (predictor), and the confidence interval gives the minimum and maximum bounds of the slope with a given confidence level, 95%, for each parameter.

**Table 4: Calculated Values for Individual Variable Groupings; $R^2$, 95% confidence interval of intercept and slope, and p-values using linear regression models**

| Data Set | $R^2$, P-value | Confidence Interval |
|---|---|---|
| FD12 vs. SST | $R^2$= 0.0075<br>p-value=0.0388 | (0.0031 0.1181) |
| FD12 vs. RHLO | $R^2$= 0.0133<br>p-value=0.006 | (0.0435 0.2581) |
| FD12 vs. SHRD | $R^2$= 0.059<br>p-value=0 | (-0.0578 -0.0291) |
| FD12 vs. AOD | $R^2$= 0.0025<br>p-value=0.2419 | (-17.2606 4.3632) |

The data collected in this study for all 20 hurricanes from 2005 and 2006 shows linearity between the amount of dust in the air and the change in intensity of the hurricane; when using all the parameters mentioned above, more dust generally equates to a less intense hurricane. But after further analysis using AOD, SST, vertical shear, and relative humidity, there appears to be a complicated relationship when using all the 2005 and 2006 cases, and a relatively strong relationship when using storms separated by categorical rank (i.e. Category 1, Category 2, etc.).

Table 4, above, shows the $R^2$, p-value and confidence interval for each variable; SST, relative humidity, vertical shear, and AOD; against the 12-hour intensity change individually. The 95% confidence interval is shown for the denoted variable.

As shown in Table 4, the linear regression relationship between SST and FD12 is minimal; with a $R^2$ of only 0.0075 only a small portion of the data can be explained. For the FD12 vs. RHLO, there is a greater relationship though the model still only explains a small amount of the data. A $R^2$ of only 0.0133 does not imply a strong relationship between relative humidity and the 12-hour intensity change. Minimal relationship is determined for vertical shear and AOD, $R^2$ of 0.059 and 0.0025, respectively. Vertical shear, which is known to be negatively related to hurricane intensification, has the highest $R^2$ value.

By looking at the intercepts in the FD12 vs. SST and FD12 vs. RHLO cases, it is apparent that SST and relative humidity both have a positive relationship with the 12-hour intensity change since both sets of numbers are positive (0.0031 0.1181) and (0.0435 0.2581) respectively. Vertical shear shows a strong negative relationship with 12-hour intensity change. The vertical shear shows 95% confidence interval of the slope of (-0.0578 -0.0291) which shows a negative correlation. However, the AOD does not show a positive or negative correlation with an interval of (-1702606 4.3632). The fact that AOD shows no relationship implies that other factors and assessment are needed to analyze the impact of AOD on hurricane intensification.

**Table 5: Calculated Values for Annual Hurricane Groupings; $R^2$, $R^2$ adj, N, and p-value using linear regression models**

| Data Set, N | Data Relationship | Confidence Intervals |
|---|---|---|
| 2005-2006<br>N=566 | $R^2$= 0.0618<br>$R^2$adj= 0.0551<br>p-value= 0.0000 | SST: (-0.1129 0.0362) |
| | | RHLO: (-0.0439 0.1970) |
| | | SHRD: (-0.0617 -0.0280) |
| | | AOD: (-10.9041 12.2598) |
| 2005<br>N=407 | $R^2$= 0.0659<br>$R^2$adj= 0.0543<br>p-value= 0.0000 | SST: (-0.1280 0.0458) |
| | | RHLO: (-0.0808 0.2175) |
| | | SHRD: (-0.0747 -0.0301) |
| | | AOD: (-7.9757 23.5940) |
| 2006<br>N=160 | $R^2$= 0.0875<br>$R^2$adj= 0.0640<br>p-value= 0.0064 | SST: (-0.0782 0.2248) |
| | | RHLO: (-0.1283 0.2445) |
| | | SHRD: (-0.0437 -0.0029) |
| | | AOD: (-64.8115 3.2159) |

P-values closest to zero imply significant relationship between the data. The p-value for SST is just slightly smaller than the 0.05 confidence value which shows that the observed data is at least minimally related to the predicted values; however, there is still a chance that part of the data is coincidental. P-values for relative humidity and vertical shear are both approximately 0.0000. This is much smaller than the 0.05 predetermined significance value. Showing relative humidity and vertical shear have a strong relationship between the values of the 12-hour intensity change, the relative humidity, and vertical shear separately. AOD shows a very high p-value of 0.2419 which implies that a large portion of the model is by chance. There is very little relationship between the observed values and the predicted values. This implies more analysis is needed and additional variables should be taken into consideration when calculating the relationship between 12-hour intensity change and AOD.

Table 5, above, shows the $R^2$, $R^2$ adjusted, number of parameters (N), confidence interval, and p-score for the 20 2005-2006 hurricanes collected data in groups.

The initial case using all data values from both 2005 and 2006 shows relative linearity between the change in intensity and the SST, AOD, relative humidity, and vertical shear. With an $R^2$ value of 0.0618 and adjusted $R^2$ value of just 0.0551, the significance test shows minimal relationship with all variables; there is a possibility that the relationship within the data is by chance. The differences between the AOD in 2005 and 2006 are significant. The high AOD values in 2006 compared to the low AOD values in 2005 can be seen by the minimal cyclogenesis that occurred in 2006; only four category 1 storms and two category 3 storms while 2005 hurricanes reached each category of the Saffir-Simpson scale. An $R^2$ value of just 0.0697 for 2005, and 0.0875 for 2006 shows that there is only a relatively linear relationship between the data and the change in intensity for each year. Though both numbers are low, 2005 has a lower $R^2$ value probably due to the increased number of storms. Since there were only a few cases for 2006 and an increase in the AOD, more of the data is described by the linear relationship between the variables and the change in intensity. Generally, AOD plays stronger role when AOD level is high and weak role when AOD level is low, and since 2006 had high levels it seems to have had a more significant role and impact.

The 95% confidence intervals for the 2005-2006 case only show a strong relationship with vertical shear, as shown in Table 5. This is seen by the negative numbers for vertical shear (-0.0617 -0.0280). This reaffirms that vertical shear plays a very strong role in hurricane intensification and has a negative relationship. The SST, RHLO, and AOD values that span negative and positive intercepts show no relationship with intensity change for all 2005-2006 cases. This could be due to many factors including the change in dust from 2005 to 2006, or the number of storms being too small. The 95% confidence interval shows a strong relationship with the vertical shear data in both the 2005 case (-0.0747 -0.0301) and the 2006 case (-0.0437 -0.0029). Vertical sheer is the only variable that shows a consistent relationship with all cases. Vertical shear continues to have a negative relationship with all data. The negative relationship confirms that an increased vertical shear holds a negative relationship to hurricane intensification.

The p-value for the 2005-2006 case shows a value of 0, less than the defined alpha (significance) value of 0.05, which implies that there is a strong linear relationship. The 2005 grouping also shows a 0 p-value. This shows that there a strong relationship between the data for all 2005 cases. However, the 2006 grouping shows a p-value of 0.0064. Though this value is greater than zero and the values for 2005-2006 and 2005 groupings, it is still much below the designated alpha value which signifies there is a strong relationship.

**Table 6: Calculated Values for Hurricane Category Groupings; $R^2$, $R^2$ adj, N, and p-value using linear regression models**

| Data Grouping, N | Data Relationship | Confidence Intervals |
|---|---|---|
| Category 1<br>N=225 | $R^2$= 0.0693<br>$R^2$adj= 0.0524<br>p-value= 0.0036 | SST: (-0.0727 0.0431) |
| | | RHLO: (-0.0603 0.1322) |
| | | SHRD: (-0.0368 -0.0022) |
| | | AOD: (-16.3094 1.5276) |
| Category 2<br>N=52 | $R^2$= 0.0628<br>$R^2$adj= -0.0170<br>p-value= 0.0063 | SST: (-0.1727 0.0411) |
| | | RHLO: (-0.0767 0.1308) |
| | | SHRD: (-0.0349 -0.0023) |
| | | AOD: (-13.2503 2.1644) |
| Category 3<br>N=128 | $R^2$= 0.1534<br>$R^2$adj=0.1259<br>p-value= 0.0000 | SST: (-0.1585 0.0230) |
| | | RHLO: ( 0.0223 0.2952) |
| | | SHRD: (-0.0466 -0.0164) |
| | | AOD: (-13.8727 1.6887) |
| Category 4<br>N=31 | $R^2$= 0.0584<br>$R^2$adj= -0.0865<br>p-value= 0.0104 | SST: (-0.1947 0.0564) |
| | | RHLO: (-0.0338 0.3480) |
| | | SHRD: (-0.0624 -0.0074) |
| | | AOD: (-14.9883 9.5395) |
| Category 5<br>N=130 | $R^2$= 0.1188<br>$R^2$adj= 0.0833<br>p-value= 0.0039 | SST: (-0.8241 0.0937) |
| | | RHLO: (-0.7844 0.3119) |
| | | SHRD: (-0.1522 -0.0310) |
| | | AOD: (24.0998 199.4246) |

As shown in Table 6 the groupings by hurricane category appear to have a mild relationship within the data. Category 1, 2 and 4 all have $R^2$ values of less than 0.1. Category 1 storms from 2005 and 2006 have an $R^2$ value of 0.0693 which shows that there is not a very strong relationship within the data. The linear model does not fully explain the 12-hour intensity change for all category 1 hurricanes. Category 1 storms have the highest number of cases for all the grouping by storm category but still do not show a strong linear relationship. Category 2 storms have an $R^2$ value of 0.0628 and adjusted $R^2$ value of 0.1887 showing that there is also only a mild relationship within the data. However, only one category 2 storm occurred during 2005-2006 time period, making this data point questionable. The $R^2$ value is lowest for the category 4 storm, which also only shows one hurricane. The category 4 storm has an $R^2$ value of 0.0584. This shows a very weak linearity within the data and even less of the 12-hour intensity change data can be explained by the linear model.

Category 3 and 5 storms have a greater $R^2$ value, both greater than 0.1. Category 3 storms have an $R^2$ value of 0.1534 and adjusted $R^2$ value of 0.1259 and category 5 storms have an $R^2$ value of 0.1188 and adjusted $R^2$ of 0.08327. The $R^2$ and adjusted $R^2$ values for both category 3 and category 5 storms are relatively close together which shows that there is strong linearity within the data. This may show that the larger storms are impacted more by the AOD, and other variables, than the lower ranking storms. The reason the category four storms do not show the same trend may be due to small sample size of category 4 storms for 2005 and 2006.

Category 3 hurricanes show a p-values of 0, which in addition to its high adjusted $R^2$ value, the p-value shows strong relationship within the data. However, category 2 and 4 groupings show p-values of 0.0063 and 0.0104, respectively. This may be attributed to the fact that each category only shows one hurricane. The category 5 grouping has a p-value of 0.0039, significantly below the 0.05 confidence. This shows that category 5 hurricanes hold a good relationship with the observed and predicted values.

In summary, this thesis was expected to show that the SAL plays a strong role in tropical cyclone creation and intensification. Parameters, such as SST, relative humidity, and vertical shear, combined with an increase in African dust particles will show that once the dust reached the area of the Atlantic where cyclogenesis begins for a specific storm there will be a decrease in the intensity and number of storms. The data implies there is almost no relationship or very mixed relationship dependant on cases, between hurricane intensity changes and AOD. SST and relative humidity show only a mild relationship and varies with specific groupings. The groupings by hurricane category are generally much stronger relationship than those grouped by year. However, vertical shear shows a strong relationship throughout all data. This shows that vertical shear, does in fact, have a negative relationship with hurricane intensity.

### 3.2 Additional Research

This study presents itself very well to additional research. Looking at the time period when the tropical wave originated off the coast of Africa and the amount of African dust in the vicinity at that time may lend itself to drawing additional conclusions regarding the AOD necessary to create or diminish the possibility for hurricane cyclogeniesis.  Changing or adding additional parameters to the data analysis may lead to even better results. Another idea may be to expand the data to include all recorded hurricanes, or grouped by high and low dust years. The larger the data set, the better data anomalies will be minimized, and the better the understanding of the data and how it is impacted.

It may also be beneficial to analyze hurricanes based on major/ minor hurricane category. A major hurricane is defined by category 3 or above and minor hurricanes category 2 and below. Due to the massive size of most major hurricanes, there is generally much more rain than with minor hurricanes. The dust particles that generally make less rain fall due to the increased CCN subsequently would fall out of the atmosphere due to the increased rainfall associated with the major hurricane. This may decrease the impact of AOD on major hurricane systems. However, additional research is needed.

Analyzing the types of aerosols that are present when a storm develops using additional imaging techniques such as hyperspectral imaging may also lead to better understanding of what particular minerals inhibit hurricane intensification. Additionally, using better imaging systems that are not affected by cloud cover inherently caused by thunderstorms would enable better results and more accurate statistical measures. Understanding hurricane intensification is extremely important to disaster preparations and warning systems. Furthering research in this area will only better the response times and preparations for those living in the storm’s path.

## CHAPTER 4: CONCLUSION

African dust interacts every season with hurricanes and their developing stages. The particles are blown from the African deserts into the SAL which lies above the humid air over the tropical Atlantic. These particles are suspended in the air and generally act as a mirror for the sun's thermal energy. Depending on the thickness of the particles, more or less energy is allowed to reach the surface of the Atlantic. If the energy is reflected back into the atmosphere, the water below is not able to receive the thermal energy and generally will have a lower SST. The SAL also suppresses moist convection and minimizes the amount of precipitation (Braun, 2011), and since there is a cooler SST and less precipitation the tropical cyclones are much less likely to have all the right conditions to maximize into severe or higher ranked storms.

Even though AOD is generally thought to hold a negative relationship with hurricane intensity change there are still multiple studies and examples that show a positive relationship. Understanding what other factors have a role in the AOD interaction with hurricane intensity is still not fully understood. As shown in this study, AOD does not always equate to either positive or negative relationship. There appears to be other factors that influence the role AOD playa. It may be that larger ranked hurricanes have greater ability to intensify, maximize in size, and minimize the effect the AOD has on the intensity change. It also may be based on the amount of rainfall a larger storm can create as compared to a smaller hurricane. If the hurricane is larger, it creates more rain and thus will be able to pull the aerosols, which act as CCN, out of the sky as rain.

When all parameters, SST, relative humidity, vertical shear, and AOD, are taken into consideration the role of AOD in hurricane intensification size is not fully explained by this study. The groupings of the data do show different points-- vertical shear holds a negative relationship with the 12-hour intensity change, while SST and relative humidity generally have a positive relationship with the 12-hour intensity changes. AOD shows data values that neither confirm nor deny a positive or negative relationship with intensity change.

In conclusion this study shows the following: a sample size must be much larger than 20 hurricanes and more than 1 hurricane in each hurricane intensification category, and measuring AOD can still be more accurately measured. Using a different system that can image through the clouds of a hurricane and still retrieve accurate AOD values as well as imaging at least every 6 hours there would be more accurate results.

Understanding hurricane intensification is necessary for increasing early warning times for inhabitants of coastal areas, increasing our understanding will increase their warning and preventative measures. By continuing research in this area scientists are bettering the lives of those who live in hurricane's paths, and their property, family, and life time.

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## CURRICULUM VITAE

Allison S Fairley graduated from Brentsville District High School, Nokesville, Virginia, in 2005. She received her Bachelor of Arts from American University in 2009.