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SCHREYER HONORS COLLEGE

DEPARTMENT OF METEOROLOGY

THE EFFECTS OF VERTICAL WIND SHEAR AND SEA SURFACE TEMPERATURE ON THE CYCLOGENESIS AND INTENSITY OF HURRICANES

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ABSTRACT

Although great strides have been made in forecasting the track of hurricanes over the past 25 years, there has been almost no improvement in forecasting their intensities. A poor understanding of hurricane dynamics is to blame for this lack of progress. The goal of this experiment was to perform a reanalysis of Dr. Kerry Emanuel's Maximum Potential Hurricane Intensity (MPI) Theory and to relate my findings to other studies on hurricane dynamics. The effects of the magnitude of environmental vertical wind shear and sea-surface temperatures on the formation and maximum intensities of hurricanes were investigated during the reanalysis. This was done by running simulations using the Weather Research and Forecasting Model. Simulations with environmental vertical wind shear values of 0 m/s, 1 m/s, 5 m/s, and 7.5 m/s (2 km to 12 km), with all other environmental factors held constant, were used to analyze the effects of vertical wind shear. To determine the effects of sea surface temperature, simulations with sea surface temperatures of 27°C and 29°C were run with all other environmental factors held constant. Rapid intensification was found to start once the relative humidity values exceeded 70 percent above an approximate height of 6 km in all simulations. The greater the magnitude of the environmental vertical wind shear and the lower the sea surface temperature, the longer it took for this relative humidity criteria to be reached. It was determined that the magnitude of the environmental vertical wind shear affected the timing hurricane formation, but had little effect on the maximum intensity of the hurricane. On the other hand, the sea surface temperature had little effect on the development of the hurricane, but had a noticeable effect on the maximum intensity of the hurricane.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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I would like to thank Dr. Fuqing Zhang for helping with every aspect my research over the past two years. He approached me during the end of my sophomore year and asked if I would like to join his research group, which I thankfully did. He and his group were very inviting and helped me in many ways. They provided me with a wealth of data for my research, as well as guidance and help whenever it was needed. Dr. Zhang is also one of the main reasons why I decided to continue my education and pursue a graduate degree in Meteorology.

I would also like to thank Dr. Fuqing Zhang's graduate student, Dandan Tao. She helped me numerous times with acquiring, processing, and plotting the data used in my research. I knew I could always expect a timely response when I needed additional information.

Dr. Ken Davis has also helped me throughout my undergraduate career and in the editing and revising of this paper. I would also like to thank Dr. Davis and Dr. Zhang writing letters of recommendation for my applications to graduate schools.

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Chapter 1

Introduction

Hurricanes are among the costliest and deadliest natural disasters in the world. In 2005 Hurricane Katrina was responsible for $125 billion worth of damage to New Orleans and the Gulf coast and led to 1,833 deaths. More recently, Hurricane Sandy caused $71.4 billion worth of damage and 286 deaths when it impacted the northeastern coast of the United States.

A dramatic increase in coastal development over the past couple of decades has led to an increase in hurricane research. In 2008, the National Oceanic and Atmospheric Administration (NOAA) formed The Hurricane Forecast Improvement Project. The goal of this project is to improve the accuracy and reliability of hurricane forecasts. Specifically, NOAA hopes to reduce the average errors in hurricane track and intensity forecasts by 20% within 5 years and 50% within 10 years with a forecast period out to 7 days (Rogers et al. 2006).

Over the past couple of decades, there has been vast improvements in the modeling of a hurricane's physical processes, increased model resolution, as well as improved data assimilation. These advancements have aided in a significant improvement of forecasting hurricane tracks (Figure 1). Unfortunately, these advances in the modeling of hurricanes have had little effect on improving the forecasted intensity of hurricanes (Figure 2). This lack of improvement in the hurricane intensities forecasting is due to the extreme difficulty in creating a model that can accurately depict the large-scale flow of the atmosphere, while simultaneously representing the small-scale features of the inner core region that determine the strength of the hurricane.

Figure 1 - Change in National Hurricane Center (NHC) forecast track error from 1970 to 2005. The uncertainties were assessed by comparing all of NHC's 24, 48, 72, 96, and 120 hour forecasts of the center of the hurricane to the verified center of the hurricane at the end of the forecast time period.
(From http://www.hurricanescience.org/science/forecast/models/modelskill/)

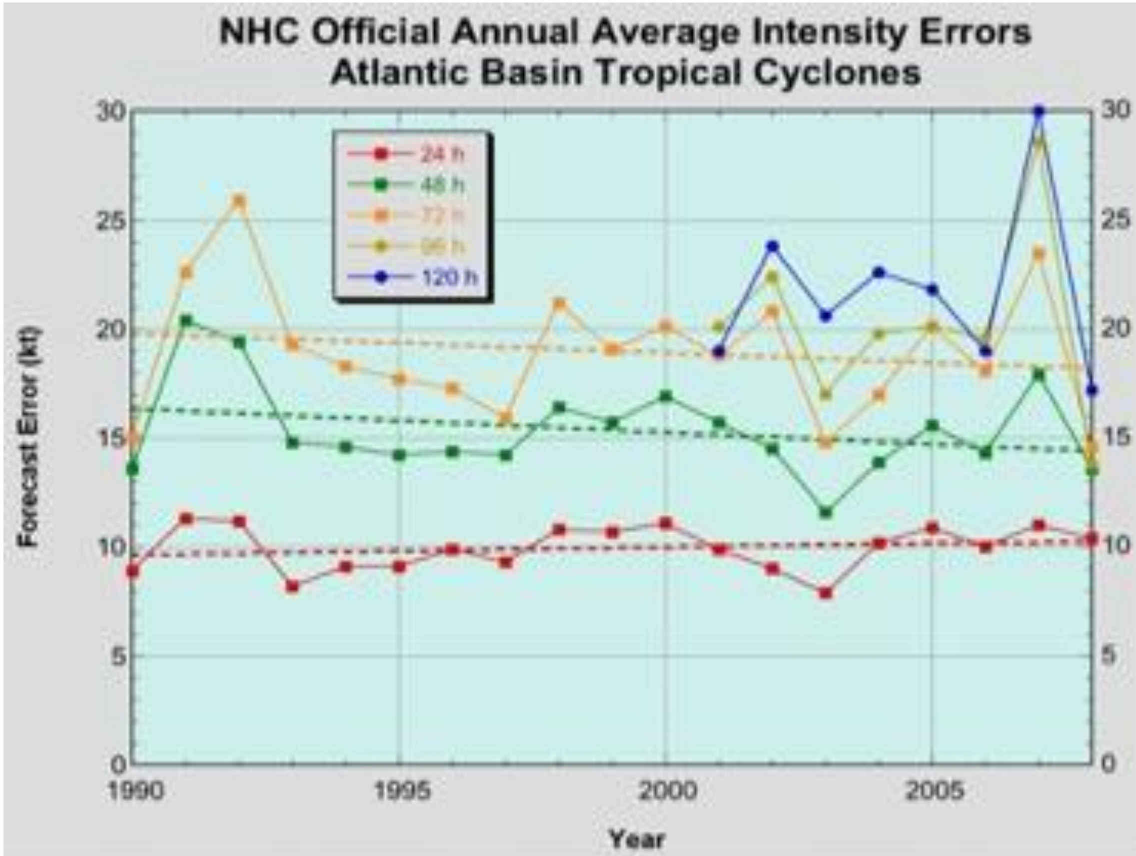

Figure 2 - Change in National Hurricane Intensity forecast intensity error from 1970 to 2005. The uncertainties were assessed by comparing all of NHC's 24, 48, 72, 96, and 120 hour forecasts of the hurricane's 1-min surface wind speed to the verified hurricane's maximum 1-min surface wind speed at the end of the forecast time period.
(From http://www.hurricanescience.org/science/forecast/models/modelskill/)

The focus of my thesis is on the effects of the magnitude of environmental vertical wind shear and sea-surface temperature on the formation and intensities of hurricanes. Vertical wind shear and sea-surface temperature are two of the most significant factors in the development and strength of hurricanes. The impact of these two factors on the dynamics of hurricanes is not yet fully understood.

Background on MPI Theory

Dr. Kerry Emanuel from the Massachusetts Institute of Technology has made major contributions to this area of research and has developed one of the most prominent theories on hurricane intensity called the Maximum Potential Hurricane Intensity (MPI) Theory (Emanuel 1986). Dr. Emanuel developed the MPI Theory around the idea that the intensification and maintenance of tropical cyclones depends exclusively on self-induced heat transfer from the ocean. His theory states that tropical systems develop and maintain their strength entirely by self-induced anomalous fluxes of moist enthalpy from the sea surface with no contribution from pre-existing convective available potential energy (CAPE). The air-sea interaction described by Dr. Emmanuel's MPI theory relies on a simple feedback between the radial temperature gradients that drive circulation and the radial gradient of sea-air heat transfers associated with the gradient of surface wind speed (Emanuel 1986).

Several assumptions must be made to apply Dr. Emmanuel's theory to a tropical system. These assumptions create an idealized axisymmetric, steady-state model for a mature tropical cyclone. Key assumptions include hydrostatic balance, gradient wind balance, and the assumption that the flow above a well-mixed surface boundary layer is inviscid and thermodynamically reversible. One other major assumption is that the vortex is neutral to slantwise moist convection. This means that above the boundary layer, the saturated potential temperature is uniform along surfaces of constant angular momentum (Emanuel 1986).

Using the MPI Theory, the maximum surface wind speed of a hurricane can be calculated with:

$$V_{Surface\,Max.}^{2} = a\,\frac{C_E}{C_D}(T_B - T_{out})(S_{surf} - S_{out}) \tag{1}$$

where ‘a’ is defined as the *efficiency* of the tropical system, C_E is the entropy coefficient, and C_D is the drag coefficient. T_B is the temperature of the heat source (ocean surface), while T_{out} is defined as the average temperature at which heat is exported from the system. S_{surf} is the entropy of the ocean surface and S_o is the entropy of the air (Emanuel 2013).

Effects of Vertical Wind Shear on Hurricane Intensity

In general, vertical wind shear is observed to be a negative factor in tropical storm intensification and is also the primary reason why most tropical systems never reach their maximum potential strength. Tang and Emanuel’s (2010) purely theoretical paper investigates the detrimental effects that vertical wind shear has on tropical cyclones by what is called the “ventilation hypothesis”. The basis of the “ventilation hypothesis” is that the weakening of a tropical cyclone by the infiltration of its mid and lower levels with low entropy air (Figure 3). Sea surface enthalpy fluxes allow hurricane heat engines to maintain their strength against frictional dissipation, so any process that acts as a source of low-entropy air would counter the air-sea fluxes that drive the mechanical energy generation.

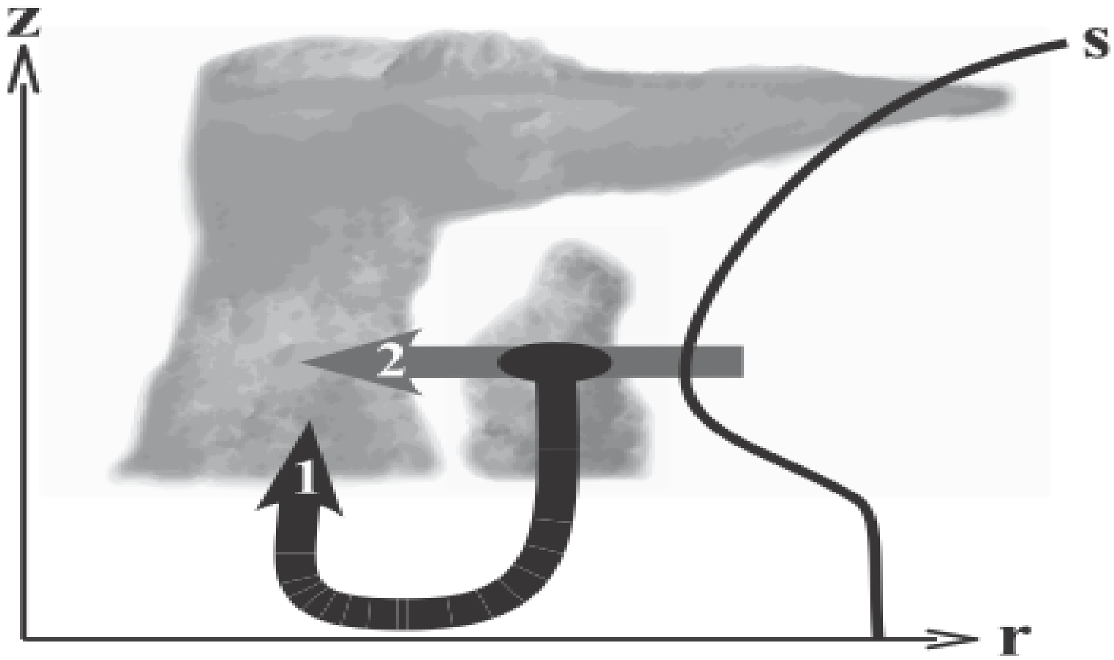

FIG. 1. Ventilation pathways by which low-entropy air can infiltrate the eyewall. (1) Low-level pathway: downdraft air from convection originating outside eyewall is advected inwards in the subcloud layer. (2) Midlevel pathway: eyewall directly ventilated by eddy fluxes. A sample entropy profile of the environmental tropical troposphere with a well-mixed subcloud layer is given on the right.

Figure 3 - Hurricane ventilation (Emanuel 2010)

The low-level ventilation pathway (Figure 3) is caused by low-entropy air that is transported via convective downdrafts to the sea surface and is then advected toward the eyewall by the radial inflow. The mid-level pathway (Figure 3) is the direct ventilation of the eyewall. In this instance the low entropy environmental air is forced into the eyewall by mid-level eddies. Although it may be obvious, it should be noted that in both scenarios the origin of the low-entropy air is at the mid-levels. Because of flow asymmetries and downdrafts, it is likely that ventilation occurs in many tropical cyclones. It is the magnitude and scope of these negative factors in the presence of vertical wind shear that are key to understanding the effects of vertical wind shear on a tropical cyclone's intensity (Emanuel and Tang 2010).

In order to conceptually understand the effects of vertical wind shear and therefore ventilation on a tropical cyclone, Tang and Emanuel (2010) describe the tropical cyclone as a Carnot heat engine both with and without ventilation. Emmanuel and Tang's paper provides an illustration of a tropical cyclone as a Carnot heat engine and how it is affected by ventilation (Figure 4). The Carnot heat engine is composed of four branches.

Branch A is isothermal, but is moving towards lower pressure. This causes dry adiabatic expansion and evaporation to occur, leading to cooler air. The air remains isothermal by adding heat from the sensible heat fluxes from the ocean surface and from frictional deceleration of the winds as they flow along the ocean surface. In branch B the air undergoes moist adiabatic ascent, so the saturation equivalent potential temperature is constant along the angular

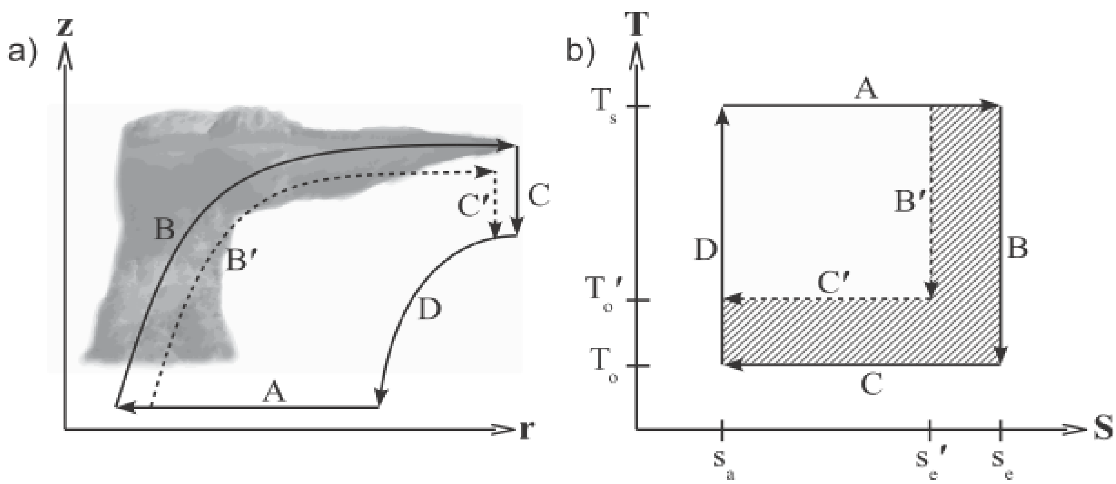

FIG. 2. (a) Secondary circulation of an idealized TC, along with (b) the legs of the secondary circulation represented on an entropy–temperature diagram. A TC without ventilation travels along A-B-C-D, whereas a ventilated TC travels along A-B′-C′-D. The hatched region in (b) denotes the work lost because of ventilation.

Figure 4 - Cyclone as a Carnot Heat Engine diagram (Emanuel and Tang 2010)

momentum surface. To calculate the temperature difference between the boundary layer and the outflow, all that is needed is the equivalent potential temperature at the boundary layer right underneath the eyewall and the height of the tropopause. At Branch C the air is much cooler due to moist adiabatic ascent. The air descends isothermally until it reaches the ambient equivalent potential temperature at r, or the surface directly below it. Branch D starts once the ambient equivalent potential temperature has been reached. The air then follows a constant angular momentum surface back down to the top of the boundary layer along branch D (Tang and Emmanuel 2010).

The dotted lines Figure 4 represent the effects of ventilation on the tropical cyclone as a Carnot heat engine. Ventilation into the eye wall through the midlevel pathway will result in a local decrease in entropy in the midlevels along branch B. This perturbation will then spread through the slantwise layer by convective motions. As a result the entropy of branch B will decrease from S_e to S_e' (Figure 4, part b). Also, the loss in buoyancy will lead to a decrease in the outflow level or an increase in the outflow temperature from T_o to T_o' along branch C. The low-level ventilation works very similarly to the mid-level ventilation. The low entropy air is transported to the tropical cyclone boundary layer via downdrafts. Assuming that the sea surface fluxes are unable to fully restore the entropy to its unperturbed value in the eyewall, the air will proceed to the lower value of entropy (S_e') in branch B. This will also cause the outflow temperature to increase (T_o'), similarly to mid-level ventilation (Emanuel and Tang 2010).

As shown in part b of Figure 4, these modifications to the tropical cyclone as a Carnot heat engine cause it to drastically weaken. As described in the first section of this literature review (Background on MPI Theory) in the provided equation, the product of the differences between the temperature of the boundary layer and the temperature of the outflow and the entropy of the ocean surface and the entropy of the air (along branch B) is a major factor in determining the strength of a tropical cyclone. Part b of Figure 4 illustrates how an increase in the outflow temperature (T_o') and an increase in the entropy of the air (S_e'), lead to a decrease in the differences of the temperature and entropy values. The size of the rectangle, which is the product of temperature and entropy differences, represents the strength of the tropical cyclone. The rectangle is clearly smaller after modifications have been made to the Carnot heat engine due to ventilation, leading to a weaker tropical cyclone (Emanuel and Tang 2010).

Effect of Sea Surface Temperatures on Hurricane Intensity

Rappin et al., (2010) examined, among other things, the effects of sea surface temperature (SST) on the development of tropical cyclones. In their simulations they created idealized environments in radiative-convective equilibrium with fixed SSTs, imposed mean surface winds, and an imposed profiles of vertical wind shear.

To create and run the simulations they used the Weather Research and Forecast (WRF) model. To initialize the simulation they used a sounding which was produced from 6-hour intervals of environmental conditions that were averaged from the last 30 days of a 90 day simulation of random convection. The random convection was conducted on a 150 km square for 90 days to achieve a state of radiative convective equilibrium. With all other factors held constant, they employed variations of the sea surface temperature and mean surface wind speed to determine how these factors affected the development of a tropical cyclone. For the purpose of my work, I am only interested in the effect of varied sea surface temperatures on tropical cyclogenesis.

In their paper they discovered that, contrary to what appears to be obvious, increasing the SST of a tropical cyclone increases the time that it takes for tropical cyclone genesis to occur. In this case, their simulations had a mean surface wind speed of 5 m/s. They found this to be true when the column-integrated saturation deficit (CISD), the amount by which the water vapor in the air must be increased to achieve saturation in the column without changing the temperature or pressure, and the associated dry convective downdrafts are accounted for. The surface fluxes and the time rate of change of the CISD are the two terms that compose the incubation parameter, a measure developed for this study. The incubation parameter was used to examine the thermodynamic nature of the simulations as tropical cyclone genesis occurred (Rappin et al., 2010).

The increase in the incubation period for increasing SSTs was due to dynamical effects. With the surface wind asymmetry fixed, the major change in variable SST simulations was the thermal structure of the troposphere. With tropospheric warming from increasing SSTs came an increasing altitude of the freezing level. This causes the diabatic heating profile to shift upward and, as a result, the developing mid-level mesoscale convective vortex (MCV) develops higher up in the shear profile. Essentially, the MCV develops in a stronger advecting flow. Because the MCV develops higher up in the shear profile, the mid-level circulation becomes decoupled from the surface circulation. With this decoupling, the surface of the core of the tropical cyclone becomes vulnerable to dry air from the quasi-balanced forced subsidence trailing the MCV. As a result, convection rooted to the surface entrains dry air. This dry air then causes strong downdrafts that disrupt the circulation (Rappin, Nolan, and Emanuel 2010).

Cione and Uhlhorn (2003) examined how changes in SST (inner core and ambient) affect a tropical cyclone’s strength. They looked at 23 tropical cyclones from 1975 to 2002 in the Atlantic, Gulf of Mexico, and Caribbean and analyzed how changes in the differences between the SST of the inner core of the hurricane and the ambient SST affect the intensities of the tropical systems (Cione and Uhlhorn 2003).

In their results they discovered that the differences between inner-core and ambient SST are significantly less than horizontal changes typically observed post storm (0-2°C vs. 4-5°C). They also concluded that under most conditions, upper-ocean heat content is an order of magnitude greater than the energy extracted by the storm. Their results also showed that very small changes in SST could have dramatic effects on the air-sea fluxes within the high-wind, inner-core storm environment. Their estimates show that a change of 1°C in SSTs can change the enthalpy fluxes by 40% or more. They were also able to statistically link the magnitude of the SST changes (inner-core minus ambient) to tropical cyclone intensity. In general, their results suggest that storms experiencing reduced levels of inner-core SST cooling experience an increase in surface enthalpy flux and thus are more likely to intensify (Cione and Uhlhorn 2003).

Effect of Moisture on Hurricane Intensity

Nolan (2007) looked into what causes tropical cyclones to develop from a pre-existing, weak, warm-core vortex. He used the Weather Research and Forecast model (WRF) to simulate the development of tropical cyclones under favorable conditions with no mean wind or wind shear, and the sea surface temperature held constant at 29°C. He discovered that during the time period (48 to 72 hours) before rapid intensification occurs, the pre-existing vortex matures as its inner core is humidified and moistened.

In his results he discovered that almost all of his simulations had an “incubation period” of about one to three days before tropical cyclone genesis occurs and rapid intensification began. He noticed that tropical cyclone genesis was marked by the very rapid appearance of a small scale, low-level vortex near the center of the surrounding mesocyclone vortex.

In the days and hours before tropical cyclone genesis occurs, Nolan identified critical changes in the dynamics and thermodynamics of the vortex core. He found that at the very start of all of his simulations, a burst of deep convection would form in and around the vortex. These bursts of deep convection would lead to a steady moistening of the atmosphere with 'near saturation' developing quickly at low altitudes and then spreading into the upper troposphere. Once the relative humidity exceeded 80 percent from the surface up to 10 km, a mid-level vortex began to form (if not already present) and slowly contract and intensify. In all of his simulations he discovered that when the mid-level vortex had contracted to a radius of maximum winds of about 60 km, with a maximum wind speed of about 12 m/s, an even smaller vortex would rapidly develop at the surface. Eventually this smaller-scale, low-level vortex would grow into a tropical cyclone.

Dr. Nolan evaluated the character of the convection that occurred in the 24 hours before tropical cyclone genesis by using contoured frequency by altitude diagrams. He determined that in the 24 hours before tropical cyclone genesis, the frequency of stronger, higher penetrating downdrafts increases, with corresponding increases in latent heat release. Despite an increase in middle and upper level humidity during this time period, the frequency and intensities of cool downdrafts showed little to no change.

Upon closer inspection of the vorticity and diabatic heating fields just before tropical cyclone genesis, Nolan discovered that the smaller-scale surface vortex was created by a single, long-lived updraft that erupts near the center of the larger, mid-level vortex. The trigger for tropical cyclone genesis is the formation of this long lasting updraft. This long-lasting updraft organizes the low-level vorticity into a single vortex through what might be considered a repeated diabatic merger process. In his simulations, these long-lived updrafts did not form until the thermodynamic and structural changes described above (near-saturation of the core and increased inertial stability) had taken place (Nolan 2007).

Objectives

As explained, Dr. Kerry Emanuel has produced several theories on the development and intensification of tropical cyclones, while Nolan, Rappin, Emanuel, and others have made great advances in determining the dynamic and thermodynamic changes that tropical cyclones undergo during tropical cyclogenesis. My goal is to perform an experimental analysis of Dr. Emanuel's work by running several simulations with varied values of environmental vertical wind shear and sea-surface temperatures, two factors he states have major impacts on hurricane development. I will then utilize the experimental findings with respect to the thermodynamic development of tropical cyclones by Nolan and others to better understand why cyclones form and strengthen the way they do.

Chapter 2

Experimental Design

In order to evaluate the effects of the magnitude of vertical wind shear and sea surface temperature on hurricane cyclogenesis and intensity, several simulations from the Advanced Research version of the Weather Research and Forecast (ARW-WRF) model were analyzed. These simulations were produced by Dandan Tao, a Meteorology Ph.D. student advised by Dr. Fuqing Zhang.

The WRF simulations were run using a two-way nested domain size of 720 km by 720 km with a horizontal grid spacing of 2 km. The simulations have 41 vertical levels from the ocean surface up to 20 km. The domain is movable and it follows the 850 hPa center of the hurricanes. The Yonsei University (YSU) boundary layer scheme (Hong et al. 2006) and WRF single-moment 6-class microphysics (Hong and Lim 2006) are utilized in the simulations. No cumulus parameterizations were used in the simulations. The simulations were initialized with an idealized Rankine vortex, a simple two-equation parametric description of a circular flow developed by William Rankine, with different distributions of random low-level moisture perturbations. These Rankine vortexes had a maximum azimuthal-mean surface wind speed of 15 m/s and a radius of 135 km. A constant Coriolis parameter of 20°N and a "moist tropical" mean hurricane season sounding is used for the environmental temperature and moisture profile (Dunion and Marron 2008).

The initial vortex, environmental conditions, and initial moisture perturbations in the simulations follow the recent study called NSM08 very closely (Sang et al. 2008). This study examined the predictability of tropical cyclones under quiescent (no mean flow) conditions with coarser resolution and less sophisticated model physics configurations using the fifth-generation Pennsylvania State University (PSU)– National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) (Zhang and Tao 2013). In some cases, the simulations are labeled with “SH0”, “SH1”, SH5” etc., which correspond to vertical environmental wind shear of 0 m/s, 1 m/s, and 5 m/s respectively. All of the simulations have a mean easterly wind of 2 m/s from 0 km to 2 km. The flow then changes linearly from 2 km to 12 km to create the desired vertical environmental shear (Figure 5).

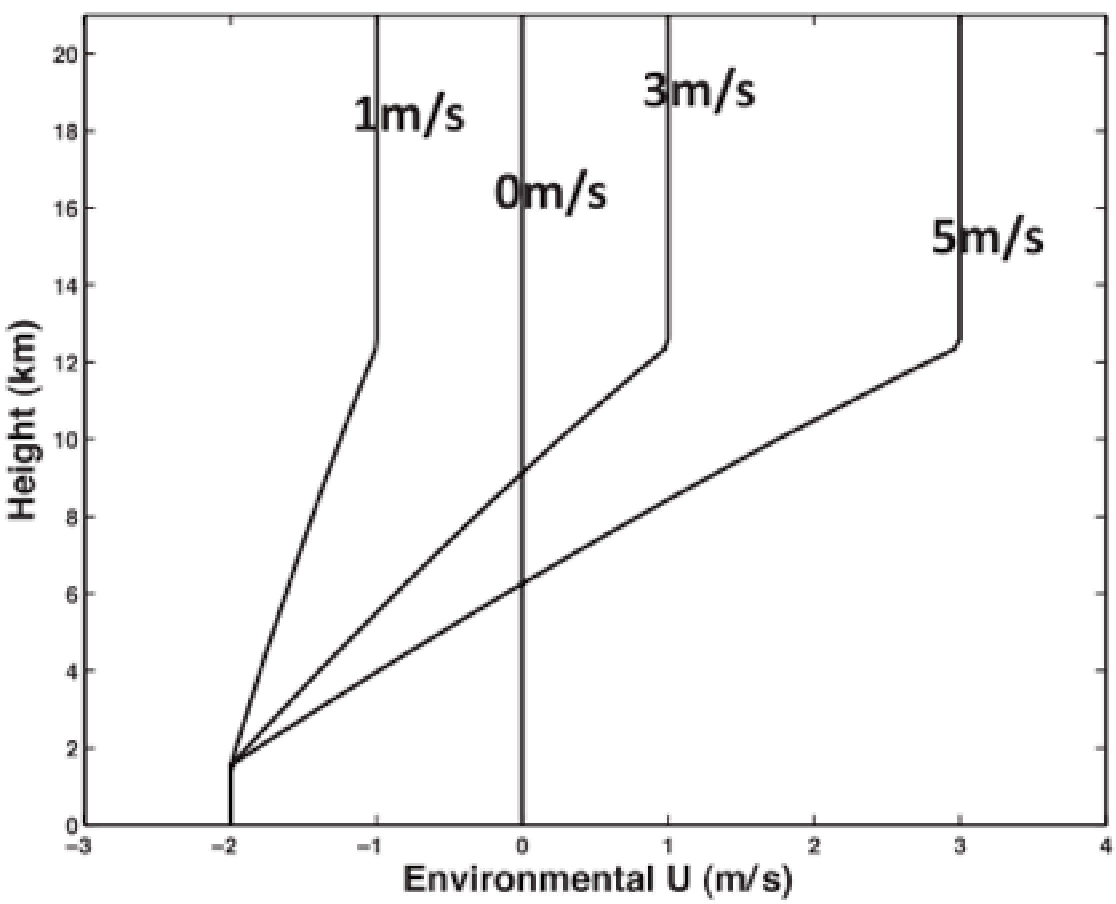

Figure 5 - Examples of vertical profiles of environmental wind shear used in the simulations (Zhang and Tao 2013)

To gain an understanding of the effects of the magnitude of vertical wind shear on the development and intensities of hurricanes, four simulations with varying values of environmental vertical wind shear were analyzed. All other variables were kept constant in these four simulations and the sea surface temperature was kept at a typical, constant 27°C throughout. Environmental wind shear values of less than 10 m/s are generally necessary for tropical cyclogenesis to occur (Frank and Ritchie 2001). Therefore, the four simulations that were analyzed had environmental vertical wind shear values of 0 m/s, 1 m/s, 5 m/s and 7.5 m/s from 2 to 12 km.

To investigate the effects of sea surface temperature (SST) on the development and maximum intensities on hurricanes, two simulations were run. All environmental factors were the same in each simulation, except for the sea surface temperature. One run had a constant SST of 27°C, while the other run had a constant SST of 29°C. Sea surface temperatures were held constant throughout the domain for the entire lengths of the simulations, with the cyclone having no impact on the sea surface temperature. Shapiro and Goldenberg (1998) determined that the sea surface temperature threshold for hurricane development in the Atlantic is 26.5°C, so 27°C is at the lower end of necessary sea surface temperatures for tropical cyclogenesis.

To determine the rate of strengthening and the maximum intensity, the minimum sea-level pressure of each simulation was analyzed. Vertical wind shear has the negative effect on tropical cyclone formation in that it replaces the moisture and heat from the mid and upper levels of hurricanes with dry air. Hurricanes are powered by the release of latent heat as water vapor condenses into liquid, so a lack of moisture should have a detrimental effect on the formation and strength of hurricanes. For this reason, horizontally averaged, vertical profiles were created for each simulation in order to gain an understanding of why the hurricane weakened or strengthened. These profiles provide a depiction of the thermodynamic structure of the hurricanes as they develop and strengthen.

Chapter 3

Results and Discussion

Results: Effects of Vertical Shear

Figure 6 displays the minimum sea level pressure (SLP) of each simulation with varied environmental vertical wind shear throughout its entirety. One obvious outlier is the simulation with an environmental wind shear of 7.5 m/s. In this simulation, the minimum SLP never changed significantly. In other words, the initial vortex was unable to strengthen into a hurricane. It is likely that the magnitude of the vertical wind shear was simply too great to form any kind of tropical cyclone. The other three simulations all formed strong hurricanes. In general, they began to strengthen around the 48-hour mark and leveled off at their peak intensities around the 168-hour mark. It’s important to note that during the period of rapid intensification, from about hour 96 to hour 144, there was the greatest spread among the minimum SLP of the 3 simulations at a certain hour. In other words, the three simulations had their specific periods of rapid intensification at slightly different times with the intensification occurring at slightly different rates.

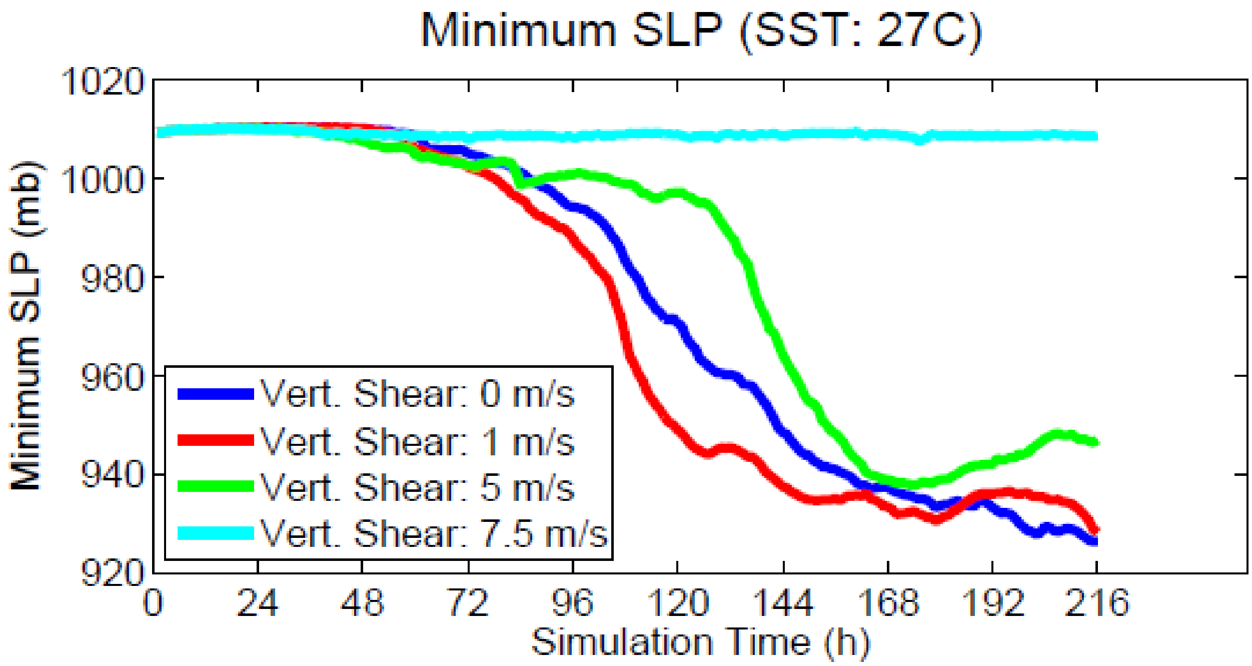

Figure 6 - The minimum sea-level pressure of each simulation during the life of the cyclones

Table 1 displays the absolute minimum SLP of the hurricane for its entire lifespan (216 hours). It is evident that the three simulations that formed hurricanes (SH0, SH1, and SH5) all reached fairly similar values of absolute minimum SLP. This shows that the effect of the magnitude of the environmental vertical wind shear on the maximum intensity of the hurricane has a strong nonlinearity. If the magnitude of the shear is below a certain value within the 5 m/s to 7.5 m/s range, then a hurricane will form and strengthen into a strong cyclone (920 mb to 940 mb). If the environmental wind shear is above this value, a hurricane will not form and the pre-exiting vortex will not strengthen.

Peak Intensity	
Simulation	Minimum SLP
SH0	926.3
SH1	928.1
SH5	937.6
SH7.5	1007.5

Table 1 - Values of minimum SLP for all simulations

To gain an understanding of why, and at what rate, each cyclone strengthened, plots displaying the percent relative humidity throughout the entire simulation were created (Figure 7). These vertical profiles are averaged horizontally out to 300 km from the minimum SLP at each vertical level for each hour of the simulations. They are useful in providing information about when the lower, middle, and upper levels of the atmosphere became saturated. Given that tropical cyclones strengthen from latent heat release, this data should help in better understanding when and why each cyclone strengthened. From Figure 7, vertical it should be noted that the moderate environmental vertical wind shear scenario (5 m/s) took much longer to moisten its mid and upper levels, while the 7.5 m/s simulation's mid and upper levels remained dry throughout the entirety of the simulation. As Nolan (2007) noticed, once the mid and upper levels (6 km and higher) of the atmosphere became sufficiently moist (greater than 70 percent relative humidity), the cyclones began to intensify. Figure 7 correlates nicely with Figure 6 in that the cyclones that were able to moisten their mid and upper levels the quickest (0 m/s and 1 m/s simulations) experienced their initial drop in minimum SLP first.

Discussion: Effects of Vertical Shear

The results show evidence that the magnitude of environmental vertical wind shear has a substantial effect on the development of a hurricane, but little to no impact on the maximum potential intensity of the hurricane, if a cyclone forms. The change in relative humidity with height throughout each simulation provides clues on the impact that the vertical wind shear has on the development of the hurricane.

As previously stated, hurricanes are powered by the release of latent heat. In the introduction it was discussed how vertical wind shear causes mid-level ventilation of low-entropy, dry air in to the cyclone. This mid-level ventilation interrupts the flux of warm, moist air from the sea surface into the middle and upper regions of the troposphere (Emanuel and Tang 2010). The simulation with an environmental vertical shear of 5 m/s (SH5) supports this hypothesis when compared to the SH0 and SH1 simulations. In Figure 7, it is evident that the middle and upper levels of the troposphere in SH0 and SH1 were moistened rather quickly, while it took about an extra 80 hours for the middle and upper levels of the SH5 simulation to fully moisten. Figure 6 shows that the moistening of the middle and upper levels correlates very well with the strengthening of the cyclone. SH0 and SH1 moistened quickly and therefore entered their period of rapid intensification first, while SH5, which took much longer to fully moisten, experienced a delayed entrance into its period of rapid intensification.

The results do not provide substantial evidence on whether or not the magnitude of environmental wind shear affects the absolute maximum intensity of a cyclone. Obviously if the vertical wind shear is high enough, like in SH7.5, and a cyclone never forms, then the magnitude of the vertical wind shear has an impact on the absolute maximum intensity of the cyclone. It appears that if the magnitude of the environmental shear is below a certain level and the initial vortex is able strengthen into a hurricane, the effects of vertical wind shear are diminished. Once the cyclone enters its period of rapid intensification, it seems like it has essentially won the battle against vertical wind shear. As the cyclone becomes stronger, vertical wind shear has less and less of an effect. The absolute minimum SLP reached in SH0, SH1, and SH5, which all developed strong hurricanes, are fairly similar (Table 1), which supports this theory.

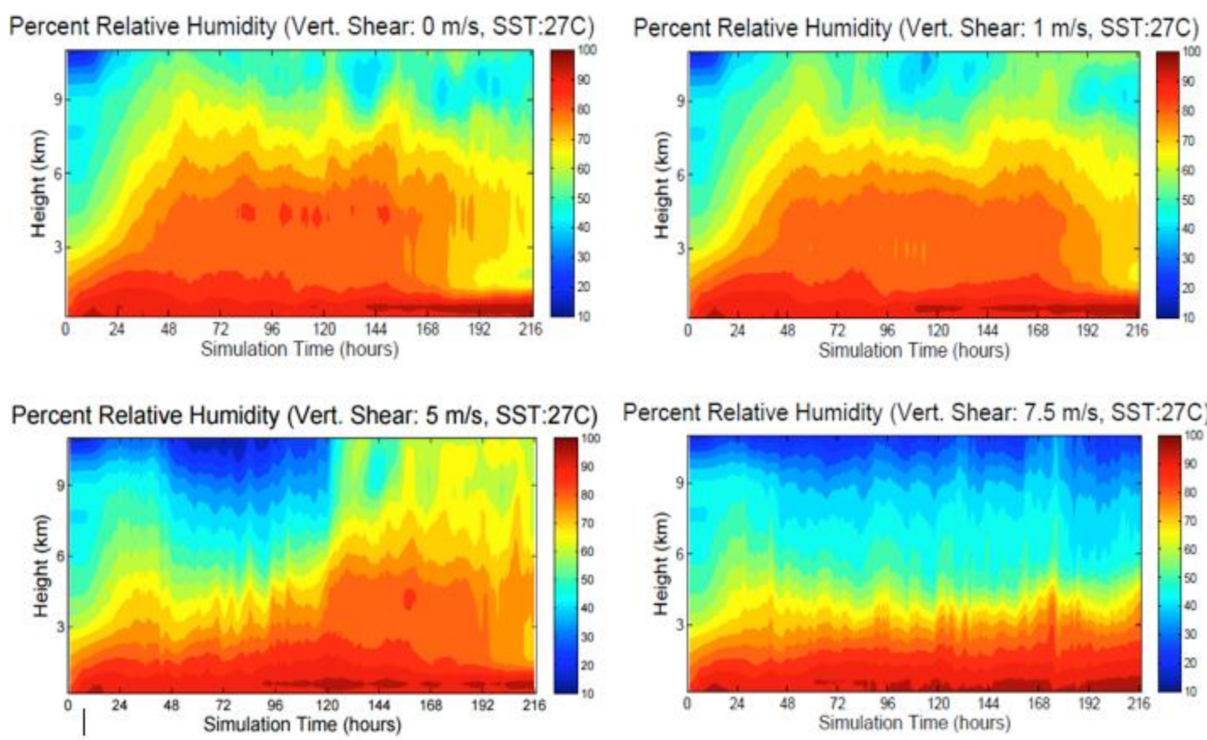

Figure 7 - Vertical profiles of relative humidity. They were created by taking the average humidity horizontally out to 300 km from the minimum SLP at each vertical level for each hour of the simulations.

Results: Effects of Sea Surface Temperature

As expected, the 29°C simulation reached a greater strength than the 27°C simulation as shown in Figure 8. In general, both simulations strengthened and weakened at the same time, with the 29°C simulation strengthening at a greater rate. Figure 9 shows that the middle and upper levels of 29°C SST simulation moistened more quickly and maintained a greater relative humidity throughout the development of the hurricane compared to the 27°C simulation.

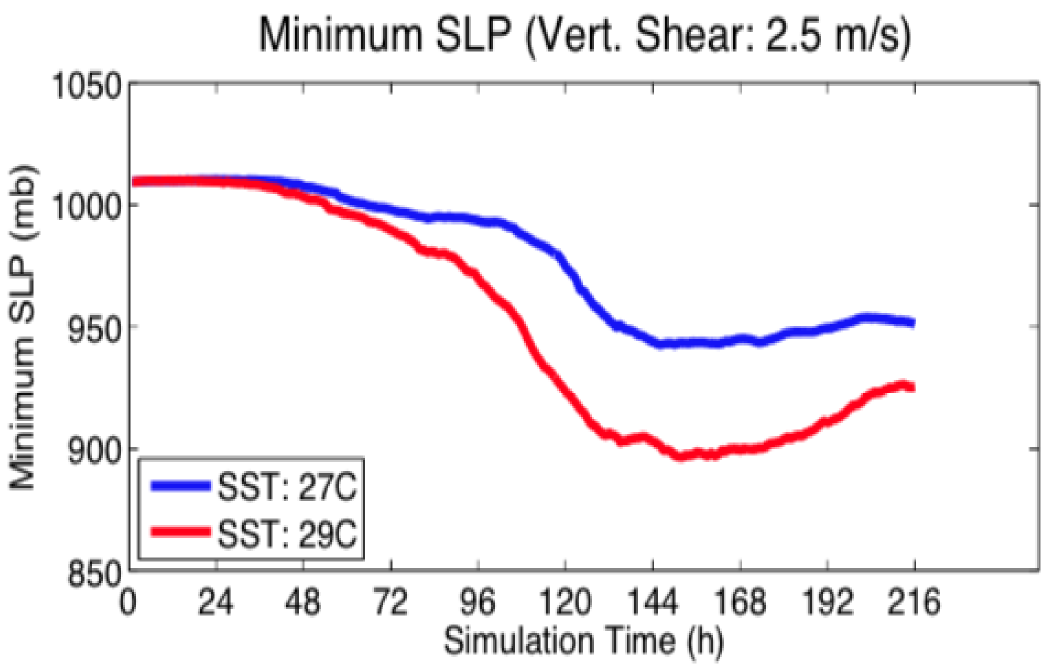

Figure 8 - Minimum sea-level pressure of the cyclone in each simulation

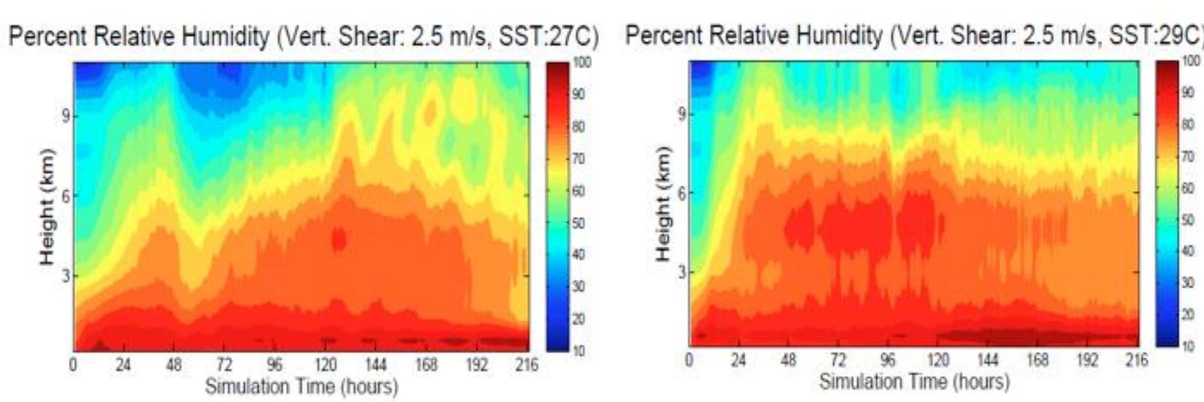

Figure 9 – Vertical profiles of relative humidity. They were created by taking the average relative humidity horizontally out to 300 km from the minimum SLP at each vertical level for each hour of the simulations

Discussion: Effects of Sea Surface Temperature

Different values of environmental wind shear appear to have an effect on when the period of rapid intensification starts, but little effect on the maximum intensity of the cyclone. Conversely, different values of SST appear to have little effect on when the period of rapid intensification starts, but a large impact on the maximum intensity that the cyclone reaches. As shown in Figure 8, both simulations entered their period of rapid intensification around the 96-hour mark and reached a steady level of intensity by the 144-hour mark. The difference here is that the 29°C simulation strengthened at a greater rate, causing its eventual maximum intensity to be greater. Looking at the relative humidity profiles in Figure 9, it can be clearly seen that, in both scenarios, the mid-levels of the troposphere were moistened rather quickly. The 29°C SST simulation reached and maintained higher relative humidity values throughout the simulation. This makes sense given that warmer sea surface temperatures result in a greater flux of warm, moist air into the atmosphere. These higher relative humidity values likely led to greater latent heat release and therefore, more energy for the cyclone to strengthen.

Chapter 4

Conclusion

Based on Dr. Kerry Emanuel's MPI Theory and his ventilation hypothesis, my results for the varied environmental vertical wind shear simulations are unexpected. Equation 1 states that the strength of a hurricane, which is directly related to its minimum SLP and maximum wind speed, is the product of the differences of temperature of the boundary layer and the temperature of the outflow and the entropy of the ocean surface and the entropy of the air. Figure 4 shows the impact that an increase in vertical wind shear should have on a hurricane, based on the MPI Theory. Dr. Emanuel's Ventilation hypothesis explains that vertical wind shear will result in a local decrease in entropy in the mid-levels along branch B from S_e to S_e' (Figure 4, part b). Also, the loss in buoyancy will lead to a decrease in the outflow level or an increase in the outflow temperature from T_o to T_o' along branch C. These changes will effectively decrease the size of the rectangle (Figure 4, part b), which represents the strength of the hurricane, as shown in Equation 1. My results show that the magnitude of environmental vertical wind shear had very little effect on the maximum strength of the hurricane (Table 1), as long as the shear was low enough that a hurricane could form.

The magnitude of environmental vertical wind shear did have an effect on the development of the hurricane. The greater the environmental wind shear, the longer it took for the cyclone to start to strengthen rapidly (Figure 6). Nolan (2007) found that once the relative humidity in a cyclone exceeded 80 percent from the surface of the ocean up to 10 km, the cyclone began to intensify. Although the high (greater than 70 percent) relative humidity values did not reach up to 10 km, Figure 7 and Figure 6 show that the timing of intensification of each hurricane is directly related to when its mid and upper levels became moist (greater than 70% relative humidity, above 6 km). Contrary to Dr. Emauel's MPI Theory, the magnitude of the environmental vertical wind shear had little effect the intensity of each hurricane, but it did affect the development of the hurricane. The greater the environmental vertical wind shear, the longer it took to moisten the mid and upper levels, which was shown to be necessary for the hurricane to strengthen and supports the work of Nolan (2007).

The results from my simulations with varied values of sea surface temperature were as expected based on Dr. Emanuel's MPI Theory. Figure 8 shows that the simulation with a higher SST (29°C) developed a stronger hurricane (lower minimum SLP) than the 27°C simulation. Equation 1 shows that this is expected with all other environmental factors held constant.

My results also support the findings of Nolan (2007). The hurricane in the 29°C simulation was able to quickly moisten its mid and upper levels (relative humidity values above 70% up to and above 6 km in height), which led to early strengthening (Figures 8 and 9). On the other hand, the hurricane in the 27°C simulation took longer to moisten its mid and upper levels and thus, took longer to begin to rapidly strengthen (Figures 8 and 9). Overall, my results in the varied SST simulations supported Dr. Emanual's MPI Theory and the findings of Nolan (2007).

Rappin et al., (2010) determined that increasing the SST of a tropical cyclone increases the time that it takes for tropical cyclone genesis to occur, due the MCV developing higher in the atmosphere. My results do not support their findings. Their simulations imposed a much greater surface wind speed of 5 m/s, which may be a reason why their results differ from mine.

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Academic Vita

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EDUCATION

2011 – Present **Pennsylvania State University, University Park, PA**

- *Schreyer Honors College*
- B.S. Meteorology, with a minor in Energy, Business, and Finance
- Undergraduate advisor: Fuqing Zhang
- Expected Graduation: May 2015

RESEARCH EXPERIENCE

Summer 2014 **Intern at the National Center for Atmospheric Research (NCAR), Boulder, CO**

- Member of SIParCS program within NCAR's Computational and Information Systems Laboratory (CISL)
- Completed *Profiling Application Performance* research project, mentored by Shawn Needham.
- Ran advanced profilers on NCAR's Yellowstone supercomputer to identify performance bottlenecks in CESM.
- Developed new techniques and guidelines for running profilers with CESM on Yellowstone.
- Acquired advanced skills necessary for setting up and executing MPI-based scientific applications on supercomputers.
- Presentation available online at: <https://www2.cisl.ucar.edu/siparcs/calendar/profiling-parallel-application-performance>

2013 – Present **Undergraduate Research**

- Member of Dr. Fuqing Zhang's Penn State Meteorology research group
- Researching the effects of vertical wind shear, sea surface temperature, and moisture on the cyclogenesis and intensity of tropical cyclones.
- Plan to publish results and complete Schreyer Honors College thesis during Spring 2015.

TEACHING EXPERIENCE

Fall 2014 **Undergraduate Teaching Assistant**

- *METEO 003 (Introductory Meteorology)*
- Run weekly lab section for approximately 60 students
- Prepare and present lectures and guide students through labs
- Hold office hours, lead exam reviews, and grade labs reports

2013-2014 **Forecasting Shift Leader**

- *Penn State Campus Weather Service*
- Taught students forecast techniques for regions across Pennsylvania

HONORS AND AWARDS

2011 – Present	**Enrolled in Penn State University Schreyer Honors College**
2011 – Present	**Schreyer Honors College Academic Excellence Scholarship**
2013 – Present	**National Meteorology Honors Society (Chi Epsilon Pi)**
2014	**Robert Case Memorial Scholarship for Meteorology**
2014	**Marie Radomsky and Vernon W. Ellzey Honors Scholarship**
2013	**Kruhoeffer Endowed Scholarship for Meteorology**
2012	**John and Elizabeth Holmes Teas Scholarship**
2011	**Dean's Freshman Scholarship**

TECHNICAL SKILLS

Programming	**Fortran, MPI, Matlab, Python, Bash, MySQL**
Computer	**Linux, Mac OSX, Windows, Microsoft Office Applications**

ACTIVITIES AND AFFILIATIONS

2013 – Present **Secretary, Penn State Weather Risk Management Club**

- Record, publish, and distribute meeting minutes
- Organize and help prepare bi-weekly meetings and events

2011 – Present **Active in Penn State University Branch of the American Meteorological Society (PSUBAMS)**

2011 – Present **Member of the American Meteorological Society (AMS)**

- Attended 2014 AMS Conference in Atlanta, GA as Penn State undergraduate invitee

2012 – Present **Active Member in the PSU Ski Club**