AN ENSEMBLE MODELING APPROACH TO EXAMINING THE IMPACT OF THE SAHARAN AIR LAYER ON THE EVOLUTION OF AN IDEALIZED TROPICAL CYCLONE

BY

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THESIS

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ABSTRACT

The Saharan air layer (SAL) is a warm, dry, dusty layer of air that resides over the tropical Atlantic Ocean. While some studies have found that the SAL may indirectly promote tropical cyclone (TC) development, others have identified potential inhibiting factors for TC development. One uncertainty is whether TC evolution depends on increases in cloud condensation nuclei, thought to occur in the SAL, in a predictable manner. In this study, the Regional Atmospheric Modeling System (RAMS) was used to test if a systematic dependence of the evolution of TC intensity on cloud condensation nuclei (CCN) concentration exists in the context of uncertainties induced by perturbations in other parameters describing the meteorological conditions and properties of the initial vortex.

First, RAMSv6.0 was used to show that minor differences in computational architecture across platforms resulted in maximum surface wind speed, $V_{\text{max}}$, variations of 8.1 ms$^{-1}$ as early as 12 hours into simulations with identical initial conditions. Results were identical when simulations with the same initial conditions were conducted on the same compute node. Second, RAMSv6.0 simulations on the same compute node examined how TC evolution responded to changes in the initial warm bubble temperature used to initialize convection and in the initial radius of maximum winds (RMW) in the vortex. Two and three grid
simulations assessed the importance of horizontal resolution on the magnitude of the sensitivity to changes in these parameters. The sensitivity was greater in the 2 grid simulations than in the 3 grid simulations with a spread in $V_{\text{max}}$ at 96 hours of 14.4 ms$^{-1}$ and 8.8 ms$^{-1}$ respectively for the RMW tests.

Finally, RAMSv4.3 was used to assess the impacts of dust acting as CCN on TC evolution in the context of changes in other initial conditions by conducting an ensemble of simulations. For CCN of 100, 101, 1000 and 2000 cm$^{-3}$, a series of simulations with varying environmental temperature, relative humidity, warm bubble temperature, vortex height, and RMW were conducted. A monotonic relationship was seen such that the mean MSLP increased and mean $V_{\text{max}}$ decreased with increasing CCN. Although the difference in mean $V_{\text{max}}$ of TCs simulated with CCN concentrations of 100 vs. 101 cm$^{-3}$ was larger than one standard deviation in the first 24 hours of simulated time, beyond 36 hours the mean values were within a standard deviation of each other. With a few exceptions, the mean $V_{\text{max}}$ and MSLP for simulations with CCN of 100, 1000 and 2000 cm$^{-3}$ differed by more than one standard deviation from each other. Thus, the analysis suggests that the effect of CCN on TC intensity is greater than uncertainties in intensity induced by non-linear amplification of noise in the initial conditions.
ACKNOWLEDGMENTS

While there are countless individuals to whom I owe my gratitude for helping to make this M.S. thesis possible, I must begin with a reflection. Even at the young age of 25, I have embarked on an extraordinary journey in life. It is unfathomable to me that I have gone from writing daily journal articles about the weather as early as 3rd grade to now having earned my M.S. degree in atmospheric sciences. The journey from a hobby in weather to a dream career in meteorology is far from over, and even getting to this point has not been without setbacks; however, I have always carried a positive attitude and strived to meet the challenges of the moment.

When I succeed at something I take great pride that hard work and commitment to seeing things through has paid off. On the other hand, when I do not quite make it through with the strides I could have hoped for, I take comfort in the fact that I have learned a great deal from having attempted a challenge rather than walking away. While figuring out the things one is talented at and what one wants to do in life are important, also finding out what isn’t quite the right fit can also be incredibly beneficial. A rigorous graduate program in atmospheric sciences at the University of Illinois at Urbana-Champaign combined with an incredible support team who believed
in me even when times were tough have enabled me to make my experiences here remarkably rewarding. I have not only been able to affirm that a career in meteorology is a perfect fit for me, but I have also learned a great deal about my strengths and weaknesses and I am certain this will be important to ensuring a long-term career upon graduation. As a result, there are countless to whom I am thankful.

I must first express my warmest heartfelt thank you to my advisor, Greg McFarquhar. As an undergraduate at Lyndon State College I made initial contact with him to express an interest in his research and the program here. I made it known that I was very passionate and motivated and that I wanted to acquire a deeper understanding of atmospheric science principles. While I had dreamed of becoming a weather forecaster someday, I realized that the landscape was competitive. I knew that a master’s degree would enhance my career opportunities and enable me to dabble into other areas within the field such as research. I also wanted a chance to better myself at a skill that has fought with me tooth and nail as an undergraduate, computer programming. And even though I was not an all-star student with a 4.0 GPA or ideal graduate record exam (GRE) scores, Greg took me in under his wing and gave me the opportunity I desired.

There have been a number of positive benefits as a result of my experiences here. I had the opportunity to travel around
the country to present at conferences (29th Conference on Hurricanes and Tropical Meteorology at Tucson, AZ & the 13th Conference on Cloud Physics in Portland, OR). Having been a part of an exciting project, I even considered continuing on for a Ph.D. for a time. While in Ft. Lauderdale however, I gathered forecasting experience between 03 and 18 September 2010 as part of NASA’s Genesis and Rapid Intensification Processes (GRIP) field campaign. That reaffirmed to me my passion for operational weather forecasting. Beyond this, while I was delighted to have the opportunity to work on computer programming skills, I continued to struggle, and I realized more and more that a career involving this skill set was not the right match for me. However, it was my advisor, Greg, who upon coming here to UIUC, has helped me to figure that out. That is because he quite literally gave me every opportunity in the world to succeed. For that I am endlessly grateful. Even when I had endured very serious personal matters in my life, Greg has always been understanding and continued to believe in me. It seems at times he will stop at nothing to see his students succeed, and that is why I tremendously valued my time here, even having endured a number of shortcomings. Greg, in more ways than he will ever realize, has been a true inspiration to me.
I would also like to thank my co-advisor Brian Jewett for all of his support during my stay here. Without his help and optimistic attitude, I would not be where I am today. He has taken upon himself numerous efforts to assist me in coding and trying to get me to overcome my struggles. He has always made himself available when I had questions and has been a miracle worker when it came to helping me understand modeling at a level I never thought could be possible before coming here.

Scott Braun at NASA Goddard’s Space Flight Center in Greenbelt, MD is also owed a tremendous thank you for providing me with an opportunity to work for him during the summer of 2011. That summer was one of my most memorable and it was a fantastic learning opportunity.

I would like to thank Eric Snodgrass for allowing me to be his teaching assistant during the spring of 2012. Here I was able to get exposure to a different aspect of the field, and I walked away with a new found appreciation to just how much effort goes into grading assignments and exams. I fully understand why sometimes it took professors a week or more to get an assignment back to me for my classes! Thank you so much for helping me to see the light!

I also need to extend a thank you to UIUC’s Department of Atmospheric Sciences and their computing resources staff, as well as the San Diego Supercomputer Center (SDSC) computational
resources. I must further acknowledge the NASA Hurricane Science Program grant (GrantNNX09AB82G) for financial support.

Lastly, I would like to thank countless friends, as well as my family, who have been there for me since day one. Whether it has been experiencing the blizzard on my 18\textsuperscript{th} birthday, graduating high school on the first day of the Atlantic hurricane season in 2005, starting college when Katrina entered the Gulf of Mexico as a dangerous hurricane, or moving hundreds of miles away to attend graduate school, my family has always given me love, support, and encouragement to reach my dreams. Without them, and without everyone mentioned herein, I would never have been able to take the steps necessary to turn what was once a childhood hobby into a remarkable career of my dreams. With the deposition of this thesis, I become one step closer to reaching my version of the American dream. Thank you all from the bottom of my heart.
# TABLE OF CONTENTS

1. INTRODUCTION.................................................................1
    1.1 Motivation of Study.....................................................1
    1.2 Overview of SAL Impacts on TC Evolution.........................3
    1.3 Objectives...............................................................6

2. METHODOLOGY........................................................................9
    2.1 Description of RAMS......................................................9
    2.2 Model Configuration for RAMSv6.0 Sensitivity Tests...........9
    2.3 Description of RAMSv6.0 Sensitivity Tests.......................11
    2.4 Model Configuration for RAMSv4.3 Ensemble Runs...............13
    2.5 Description of Ensemble Runs Using RAMSv4.3.................14
    2.6 Tables............................................................................15

3. RESULTS SECTION...............................................................19
    3.1 Discussion of RAMSv6.0 Sensitivity Tests.......................19
    3.2 Discussion of RAMSv4.3 Ensemble Runs.........................28
    3.3 Figures..........................................................................37

4. CONCLUSIONS & FUTURE WORK............................................62
    4.1 Concluding Remarks.....................................................62
    4.2 Future Plans...............................................................64

REFERENCES............................................................................67
CHAPTER 1
INTRODUCTION

1.1 Motivation of Study

Tropical cyclones (hereafter, TCs) have been widely studied. They are among nature’s most lethal phenomena and can leave behind a steep price tag. TCs are often associated with damaging winds, heavy rainfall, storm surge, beach erosion, inland flooding, and even tornadoes. TCs are often identified as primary causes for many societal and economic problems. These impacts have motivated decades of research into the factors that influence the development and evolution of TC track and intensity. The Galveston Hurricane of 1900 claimed the lives of more than 8000 people and is considered the deadliest TC to have affected the U.S. More recently in 2005, Hurricane Katrina was responsible for at least 1500 fatalities and is among the top three deadliest TCs to impact the U.S. in recorded history (Blake et al., 2007). Emanuel et al. (2006) described Katrina as the single most costly natural disaster for the United States, carrying a $125 billion price tag. The impacts of Hurricane Mitch of 1998, responsible for 11,000 deaths in Central America were also immense. Undoubtedly, improved TC forecasts could have important societal and economic benefits.

Aberson (2001) discussed how numerical guidance has led to improved hurricane track forecasts since 1976 by approximately
0.7% per year. However, intensity forecast improvements have not been as robust. Poor collection of inner-core data for numerical model assimilation, limitations in computational resources, and lack of understanding of TC physics and environmental interaction may all be responsible for the lag in TC intensity forecasting improvements (Rogers et al., 2006). Davis et al. (2010) discussed the challenges in hurricane intensity prediction that still exist even after four decades of research and suggested that there is a need to further investigate the environmental and internal processes that modulate TC intensity changes.

There are many factors that influence the development and evolution of TCs. Gray (1968) showed that large wind shear between 250-850 hPa inhibits TC activity in the southwestern Atlantic and central Pacific. He also discussed the importance of high sea surface temperatures (hereafter, SSTs) and high low-mid tropospheric moisture on TC development and intensity. Emanuel (2005) established that increasing SSTs linked to global warming may partly increase average TC intensity; however, other factors such as the decrease 250-850 hPa vertical wind shear by approximately 0.3 ms$^{-1}$ per decade from 1949-2003 may have also played a role in increasing the average intensity of TCs. Webster (2005) explained an upward 30 year trend of more frequent and stronger hurricanes in the context of global
warming; however, he concluded that a longer global data record is needed before 30 year trends can be attributed to global warming. Kossin (2007) did not find increases in TC intensity over the last 30 years in any basin other than the Atlantic. Vecchi and Soden (2007) showed that increases in June-November vertical wind shear across the tropical Atlantic projected by climate models may also have implications for TC activity. Other factors that influence TCs are related to interannual teleconnections such as the El Niño Southern Oscillation (Pielke and Landsea, 1999). Therefore, the effect of increasing global SSTs on TC intensity is uncertain due to the myriad of other factors that also affect intensity.

1.2 Overview of SAL Impacts on TC Evolution

While some studies have focused on factors that affect TC frequency, evolution, intensity, and structure (such as the impacts of warm SSTs, vertical wind shear, moisture and temperature vertical profiles, etc.), more recent investigations have begun to focus on how microphysical processes such as those induced by potential effects of enhanced dust from the Saharan Air Layer (hereafter, SAL), impact TC evolution. Twomey (1974, 1977) showed that increases in atmospheric cloud condensation nuclei (hereafter, CCN) concentrations lead to increases in cloud droplet number and a decrease in mean cloud droplet size under conditions of constant liquid water content through what
is referred to as the first indirect aerosol effect. In turn, this results in clouds reflecting more solar radiation. Albrecht (1989) discussed the second aerosol effect where smaller cloud droplets result in lower collision and coalescence efficiencies and therefore inhibit the formation of large raindrops, which leads to suppressed precipitation. These two effects could conceivably impact TC evolution. Therefore, continuing investigations into aerosol influences on TCs may eventually lead to improved understanding of TC evolution and predictability.

Carlson and Prospero (1972) performed the first systematic study on the SAL. The SAL, a deep isentropic air layer over the Saharan Desert, has high potential temperatures, low water vapor mixing ratios, high aerosol concentrations, and a midlevel jet along its southern periphery (Karyampudi et al., 1999). Studies of SAL impacts on TCs have thus far yielded mixed conclusions with some suggesting it may enhance the potential for TC development and others suggesting the SAL may cause a reduction in TC intensity. Dunion and Velden (2004) suggested that the SAL suppressed TCs by introducing dry, stable air into the storm, and by enhancing the local vertical wind shear and preexisting trade wind inversion. Several studies reached similar conclusions that the SAL can inhibit TC development. Evan et al. (2006) identified an inverse relationship between Atlantic dust
and TC activity. Wu (2007) suggested that the SAL activity is enhanced during drought when there is increased atmospheric dust loading which may lead to the suppression of TC activity. Twohy et al. (2009) suggested that since the Saharan dust is hydroscopic it could serve as CCN. Rosenfeld et al. (2007) showed that increases in CCN suppress the warm rain process and weaken TCs through low-level evaporative cooling of cloud drops and increased cooling due to precipitation melting. But, using data from the NASA African Monsoon Multidisciplinary Analysis (NAMMA, 2006), Jenkins et al. (2008) indicated that dust may affect cloud microphysics by increasing convective activity. Zhang et al. (2007, 2009) found that increases of CCN associated with the SAL could induce changes in the sizes and number concentrations of cloud droplets, changing the distribution of latent heating in the eyewall and spiral rain bands, thus influencing TC evolution through associated dynamical changes. However, a monotonic response of TC intensity to CCN concentration was not seen and TC intensities exhibited sensitivity to the environmental conditions and to the time at which the dust was injected.

As a result of the study by Zhang et al. (2007), Cotton and Saleeby (2008) hypothesized that the dust impact on TCs suggests a path toward modifying the intensity of hurricanes. Cotton and Krall (2012) showed that ingestion of enhanced CCN
concentrations leads to smaller cloud droplet sizes, especially in the outer TC rainbands, which, in turn leads to three effects. First, there is a suppression of cloud droplet collision and coalescence. Second, smaller particles have reduced fall speeds which increases liquid water contents at upper levels. Third, smaller droplets have reduced probability to be collected by ice particles and therefore freeze. Cotton and Krall (2012) showed that the increase in supercooled liquid water altered the vertical heating profile of the TC and resulted in an increase in downdrafts and therefore cold pool enhancement, and therefore reducing the TC intensity. While some studies suggested changes in dust and the SAL dramatically affect TCs, Braun (2010), on the other hand, suggested the role of SAL on TC evolution may have been overemphasized.

1.3 Objectives

The primary purpose of this study is to extend the studies of Zhang et al. (2007, 2009) which found a non-monotonic decrease in TC intensity with increasing CCN concentration. Due to this non-monotonic response, it is conceivable that the response to aerosols might be akin to response seen as a result of small perturbations in initial conditions. Sippel and Zhang (2008) performed MM5 ensemble simulations that revealed subtle differences in initial conditions induced large uncertainties in TC evolution. Therefore, aerosol effects need to be interpreted
in the context of other effects and processes that impact the
evolution of TCs. The ocean-atmosphere system operates
chaotically as small perturbations in initial conditions result
in increasingly large changes in the state of the atmosphere
with the passage of time (Lorenz, 1963). As such, instead of an
aerosol effect weakening or enhancing TC intensity, it is
possible that the sensitivity of TC evolution to CCN
concentration may be the result of amplification in non-linear
noise associated with perturbations in initial conditions
induced by small changes in aerosol concentrations.
Understanding the sensitivity of TCs to microphysical factors is
complicated by this nonlinear chaotic amplification of noise.

This study extends the work by Zhang et al., (2007, 2009)
by conducting an ensemble of model simulations to address
questions surrounding the effects of Saharan dust acting as CCN
on TCs in the context of how other initial model fields affect
TCs. Other factors that are known to affect the evolution of TCs
include the environmental temperature, relative humidity, the
depth and radius of maximum winds (hereafter, RMW) of the vortex
used to represent the initial disturbance, and the
characteristics of the warm bubble used to initiate convection.
This study aims to determine the extent to which the aerosol
effect is masked by the amplification of perturbations in
initial fields as previously described. In addition, the degree
to which model results are reproducible is examined. In the next section, a detailed description of the model chosen for these simulations is presented, as well as a complete overview of the experiments designed to meet these objectives. This is then followed by a summary of results, conclusions, and future work.
CHAPTER 2

METHODOLOGY

2.1 Description of RAMS

In this chapter, the methodology used for investigating the sensitivity of TCs due to changes in initial model conditions is presented. Additional model simulations conducted to assess the reproducibility of the model are also described. Lastly, an ensemble of simulations conducted to investigate the response of TCs due to changes in CCN concentration in the context of changes in other initial conditions is detailed.

The Regional Atmospheric Modeling System (hereafter, RAMS) was selected for the purposes of these investigations. A detailed overview of RAMS can be found in Cotton et al. (2003). Since RAMS has the ability to explicitly simulate CCN activation and includes double moment parameterization schemes for liquid and ice microphysical parameters, its use for studying aerosol impacts on clouds is appropriate. Additionally, the use of RAMS allows for a comparison against the results of previous studies that used this model to examine the impacts of Saharan dust acting as CCN on TCs (Zhang et al., 2007, 2009).

2.2 Model Configuration for RAMSv6.0 Sensitivity Tests

It was previously discussed that Zhang et al. (2007) identified a non-monotonic response of changes in TC intensity to initial CCN concentration. It is reasonable to question
whether chaotic behavior (Lorenz, 1963), namely amplification of non-linear noise associated with small perturbations in initial conditions, may have played a role in those results. Using RAMSv6.0, released in January of 2006, a series of model sensitivity tests was designed in order to investigate this possibility. The model configuration and setup for these simulations is summarized in Table 1. The model setup mimicked the earlier Zhang (2007, 2009) studies as closely as possible so that the results of the different studies can be compared. The setup consisted of a parent domain and two inner nests with horizontal grid spacing of 24 km, 6 km, and 2 km, respectively. The domain center was placed at 15° N latitude and 40 ° W longitude. There were 40 vertical levels which extended from the surface to 30 km. The vertical resolution varied from 300 m near the surface increasing to 1 km near the domain top.

The vortex used to initialize the RAMSv6.0 simulations used an axisymmetric mesoscale convective vortex (MCV) similar to that of Montgomery et al. (2006). The initial vortex characteristics included a maximum tangential velocity of 6.63- ms⁻¹, 8 km depth, and a 75 km radius. In order to initiate convection, a 3.0 K temperature perturbation (warm bubble) was placed 50 km east of the domain center.

The microphysical parameterization scheme was based upon that of Meyers et al. (1997), which includes a large liquid droplet
mode and explicit CCN activation, as detailed in Saleeby and Cotton (2004). Prognostic hydrometeors included small cloud droplets, pristine ice, rain, snow, aggregates, graupel, hail, and large cloud droplets.

The idealized environment in which the vortex was placed consisted of no vertical wind shear, a constant ocean surface SST of 29 °C, and vertical profiles of temperature and humidity consistent with the Jordan (1958) sounding, which is based on the 1946-1955 mean for stations in the West Indies area. These conditions were applied in a horizontally uniform fashion in all domains.

The model setup only differed from the Zhang et al. (2007, 2009) studies in that the Chen and Cotton (1988) radiation scheme was used instead of that of Harrington (1997). Originally, the use of the Harrington radiation scheme was planned; however, trial runs with this scheme exhibited sources of numerical instability that could not be identified. While accounting for condensate in the atmosphere, the Chen and Cotton (1988) radiation scheme has a limitation in that it does not consider whether it is cloud water, rain, or ice.

2.3 Description of RAMSv6.0 Sensitivity Tests

Using this configuration, tests were designed to examine the sensitivity of TC evolution to perturbations in initial conditions. These simulations were conducted on manabe, the
local Linux cluster maintained by the University Of Illinois Department Of Atmospheric Sciences computing support staff. The simulations were run in parallel, meaning that multiple processor cores were used to perform the simulations. Since there may be minor differences in the compilation and execution of codes on different processors, initial tests were performed to determine the extent to which simulations were reproducible. Additional tests where the temperature of the warm bubble and the radius of maximum winds (hereafter, RMW) were perturbed were also performed. The three sets of simulations were categorized as, and will be referred to in the results section as node tests, bubble temperature tests, and RMW tests. These sets of simulations are summarized in Table 2, and explained in more detail below.

Simulations with identical initial conditions were executed to examine the effect of the computing environment on TC evolution. These simulations were run on ten different nodes of manabe. For the bubble temperature tests, all initial conditions except the temperature of the warm bubble used to initialize convection were held constant. The warm bubble, with an 8 km height, was placed 50 km east of the domain center with bubble temperatures of 2.0 K, 2.9 K, 3.0 K, 3.1 K and 4.0 K. The variations of ±0.1 K and ±1.0 K about the base value of 3 K were used to investigate the response to smaller and larger changes
of the initial bubble temperature, respectively. The third suite of sensitivity tests varied the RMW with initial values of 70 km, 74.9 km, 75 km, 75.1 km, and 80 km used, representing variations of ±0.1 km and ±1.0 km about the base value. All of the above sensitivity tests were run using three grids with the finest horizontal resolution being 2 km. An additional set of bubble temperature and RMW tests were repeated using only two domains with the finest resolution of 6 km to determine whether the sensitivity to these parameters depended on resolution.

2.4 Model Configuration for RAMSv4.3 Ensemble Runs

RAMSv4.3 was used to conduct the ensemble of simulations, where the response of the TC to changes in CCN concentration in the context of the variation of other parameters was investigated. The RAMSv4.3 version was used for this ensemble instead of the newer RAMSv6.0 because a more sophisticated CCN code was available in RAMSv4.3 at the time the model simulations were performed (Cotton, 2010, personal communication).

The same model configuration that was used for the initial sensitivity tests with RAMSv6.0 was also used for the RAMSv4.3 ensemble. Initial tests with this code suggested that the Harrington radiation scheme was stable in RAMSv4.3 and therefore simulations with this scheme were performed. These simulations were conducted using single processors on the supercomputer,
Trestles, available at the San Diego Supercomputer Center (SDSC). The configuration is summarized in Table 3.

2.5 Description of Ensemble Runs Using RAMSv4.3

Table 4 summarizes the initial conditions chosen for the ensemble of simulations conducted with RAMSv4.3. The CCN concentrations were varied over the range observed during NAMMA (Slusher et al. 2007). Specifically, concentrations of 100, 101, 1000, and 2000 cm\(^{-3}\) were applied initially, horizontally uniformly in all domains. The simulation with a concentration of 101 cm\(^{-3}\) was included to test the impact of small perturbations in CCN on simulated storm properties. For each CCN concentration, simulations with vortex depths of 6 km and 8 km, and RMWs of 70 km, 75 km, and 80 km were performed. The vortex properties were the same that were used for the RAMSv6.0 tests. The range of values selected for perturbations in the vortex properties chosen here are consistent with airborne Doppler observations (Reasor et al., 2005) of the pre-Dolly MCV over the tropical Atlantic in 1996 and observations during the Tropical Experiment in Mexico (TEXMEX; Raymond et al., 1998).

The vertical profile of the temperature and humidity associated with the Jordan (1958) sounding was also varied for each CCN concentration. At all vertical levels, the environmental temperature was randomly perturbed by ± 0.1°C and the humidity (mixing ratio) was also randomly perturbed by ± 1%
at each vertical level. Bubble temperatures of 2 K, 3 K, and 4 K were also used for each CCN concentration. This represented 72 simulations for each CCN value for a total of 288 simulations. The results of these simulations are discussed in the next chapter.

2.6 TABLES

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<thead>
<tr>
<th>Vortex Radius of Maximum Winds (RMW)</th>
<th>75 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vortex Depth</td>
<td>8.0 km</td>
</tr>
<tr>
<td>Maximum Tangential Velocity (Initial)</td>
<td>6.63-m s^{-1}</td>
</tr>
<tr>
<td>Bubble Temperature</td>
<td>3.0 K, 50 km E of vortex center</td>
</tr>
<tr>
<td>Two-Moment Microphysics Scheme</td>
<td>Cotton (2003)</td>
</tr>
<tr>
<td>Radiation</td>
<td>Chen and Cotton (2008)</td>
</tr>
</tbody>
</table>

Table 1. Conditions used for control simulations conducted with RAMSv6.0.
<table>
<thead>
<tr>
<th>1. Reproducibility Tests</th>
<th>Identical Simulations, 10 different nodes on manabe</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Vortex Radius of Maximum Winds (RMW)</td>
<td>70, 74.9, 75, 75.1 km</td>
</tr>
<tr>
<td>3. Bubble Temperature</td>
<td>2.0, 2.9, 3.0, 3.1, 4.0 K</td>
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Table 2. Summary of simulations conducted with RAMSv6.0.
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<tbody>
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<td><strong>Vortex Radius of Maximum Winds</strong> (RMW)</td>
<td>75 km</td>
</tr>
<tr>
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<td>8.0 km</td>
</tr>
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<td><strong>Maximum Tangential Velocity</strong> (Initial)</td>
<td>6.63-m⁰s⁻¹</td>
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</tr>
<tr>
<td><strong>Two-Moment Microphysics Scheme</strong></td>
<td>Cotton (2003)</td>
</tr>
<tr>
<td><strong>Radiation</strong></td>
<td>Harrington</td>
</tr>
</tbody>
</table>

*Table 3. Conditions used for control simulations conducted with RAMSv4.3.*
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCN Values</td>
<td>100, 101, 1000, 2000 cm$^{-3}$</td>
</tr>
<tr>
<td>Environmental Temperature</td>
<td>Jordan, ± 0.1 °C Perturbation (For each CCN)</td>
</tr>
<tr>
<td>Environmental Humidity (q)</td>
<td>Jordan ± 1% Perturbation (For each CCN)</td>
</tr>
<tr>
<td>Vortex Depth Values</td>
<td>6.0, 8.0 km (For each CCN)</td>
</tr>
<tr>
<td>RMW</td>
<td>70, 75, 80 km (For Each CCN)</td>
</tr>
<tr>
<td>Bubble Temperature</td>
<td>2.0, 3.0, 4.0 K (For Each CCN)</td>
</tr>
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</table>

*Table 4. Summary of simulations conducted with RAMSv4.3.*
CHAPTER 3
RESULTS SECTION

3.1 Discussion of RAMSv6.0 Sensitivity Tests

In this chapter, the results of the RAMSv6.0 sensitivity tests, including the effects of small perturbations in initial conditions on TCs, are first discussed. Second, the results of reproducibility tests conducted on different nodes on manabe are given. Finally, the outcome of the ensemble of simulations, conducted with RAMSv4.3 in order to investigate the impact of changes in CCN concentration in the context of changes in other initial conditions, is provided.

The local Linux cluster maintained by the University of Illinois, manabe, was utilized for RAMSv6.0 simulations to determine the magnitude of the response to perturbations in non-linear conditions. Since processors on these nodes have minor differences that may affect the way that codes are compiled and executed, it was first necessary to carry out initial tests to determine the extent to which the simulations were reproducible. Ten simulations were conducted under different processor cores in order to carry out this objective. The nodes on which these tests were conducted are as follows: manabe25, manabe33, manabe14, manabe34, manabe23, manabe44, manabe41, manabe45, manabe42, and manabe46.
The results were identical for simulations run on manabe25 and manabe14 when comparing the binary output files of minimum sea level pressure (MSLP) and maximum surface wind speed ($V_{\text{max}}$). Likewise, simulations run on manabe33, manabe45, manabe42, and manabe46 exhibited identical results to each other. Each additional simulation produced unique results. This describes a total of six different solutions from ten simulations with identical initial conditions. The 96 hour time evolution of MSLP and $V_{\text{max}}$ is shown in figure 1. Note that there are only six lines present because some of the simulations were identical, as previously discussed. During the first 12 hours of simulated time, the TC intensities ranged from 30.1 ms$^{-1}$ to 38.2 ms$^{-1}$, or differed by 8.1 ms$^{-1}$; however, beyond 12 hours the spread in solutions begins to increase. The spread in the solutions at 24 hours increased to 10.5 ms$^{-1}$. The sensitivity of solutions remained constant from about 24 hours through 84 hours, at which time the solutions further diverged. Differences in storm intensities between 84 and 96 hours were greater than 15 ms$^{-1}$. Within this timeframe, the strongest TC intensities exhibited $V_{\text{max}}$ values greater than 80 ms$^{-1}$, while the weakest TC intensities exhibited $V_{\text{max}}$ values around 65 ms$^{-1}$. As an example, at 92 hours of simulation time, intensities varied from 65.9 to 82.5 ms$^{-1}$, or ranged by 16.6 ms$^{-1}$. 
Another way to quantify TC intensity is through the minimum sea level pressure (MSLP). Figure 2 shows the evolution of MSLP over the same 96 h period. Again, there were six unique solutions for MSLP for the ten simulations discussed above. There was little in the way of solution variation up until about 12 hours at which time the MSLP varied by 2.5 hPa, ranging from 999.9 hPa to 1002.4 hPa. Thereafter, the solutions diverged more. By 24 hours, the sensitivity more than doubled and reached 6.4 hPa, ranging from 982.3 hPa to 988.7 hPa. The sensitivity remained similar through about 72 hours at which time the spread in solutions diverged further. Between 84 and 96 hours, the simulations exhibited the largest sensitivity. At the 96 hour of the simulations the MSLP values ranged by 8.6 hPa or from 930.0 hPa to as high as 938.6 hPa.

The simulations run on the same compute node were found to be repeatable. Therefore, the impact of varying computer architecture was eliminated by running all tests on the same compute node. This strategy of conducting simulations on the same compute node was implemented for the RWM and warm bubble three grid and two grid sensitivity tests. Figure 3 shows the evolution of the surface maximum wind speed with varying initial bubble temperatures of 2.0, 2.9, 3.0, 3.1, and 4.0 K.

Through about the first 12 hours of the simulations, there was very little in the way of sensitivity. However, by 12 hours
the solutions varied between 28.6 and 37.1 ms$^{-1}$, or by only 8.5 ms$^{-1}$. While the TCs continued to show a general intensification trend throughout 96 hours, the rate of intensification slowed beyond 48 hours. At 48 hours the TCs exhibited a range in intensity of 8.3 ms$^{-1}$, comparable to that of 12 hours; however, the intensities were stronger, varying from 63.0 ms$^{-1}$ to 71.3 ms$^{-1}$. At 96 hours, the intensities ranged from 67.1 to 75.0 ms$^{-1}$. This represents a total variation of 7.9 ms$^{-1}$.

There is no monotonic relationship between storm intensity and the magnitude of the bubble temperature used to initialize convection. The response of the TC due to changes in the warm bubble temperature most likely just shows how non-linear noise amplifies some small uncertainties in initial conditions.

The time evolution of MSLP for the three-grid simulations with varying temperatures of the bubble used to initialize convection is shown in figure 4. There is little variation in the solutions due to changes in initial conditions through about the first 12 hours. In fact, by 12 hours, intensity only varied between 1000.8 and 1003.2 hPa, or by 2.4 hPa. The MSLP ranged from about 984.0 to 989.3 hPa by 24 hours. Thus, the sensitivity more than doubled as it increased to 5.3 hPa. However, the spread in solutions appeared to converge again around 36 hours (3.7 hPa variation) and again between 72 and 84 hours before spreading out again at 96 hours. At 76 hours, the solutions
varied by only 1.2 hPa. At 96 hours, however, the MSLP solutions once again exhibited larger variation the smallest value at 934.0 hPa and the weakest TC exhibiting an MSLP of 937.9 hPa.

Additional three grid simulations varying the RMW were conducted to examine the response to other variations in initial conditions. Figure 5 shows the evolution of the surface maximum wind speed for simulations with initial RMW values of 70, 74.9, 75.0, 75.1, and 80.0 km. The solutions begin to exhibit notable spread even by 12 hours of simulation time. At 12 hours TC intensities varied between 26.1 and 37.2 ms$^{-1}$, or by 11.1 ms$^{-1}$. As the TCs intensified throughout the 4 day evolution, the sensitivity actually exhibited decreased from that seen at 12 hours. In fact, by 48 hours of simulation time there was 8.3 ms$^{-1}$ spread in TC intensities, ranging from 63.0 to 71.3 ms$^{-1}$. This sensitivity thereafter changed very little through the rest of the simulated time. At 96 hours, the intensities ranged from 67.0 to 75.9 ms$^{-1}$, representing an 8.8 ms$^{-1}$ difference. Note that these results that are observed were similar when compared with the warm bubble temperature sensitivity tests. The sensitivity increased through 12 hours, and thereafter leveled off through the remainder of the simulated time. This suggests that amplification of noise in the initial conditions caused the differences in these simulations seen as early as 12 hours.
The evolution of the MSLP is also examined to interpret the results of the RMW tests. These results are shown in figure 6. There was little variation as the simulations began; however, beyond 12 hours the spread in solutions increased. At 12 hours there was only a 1.9 hPa difference in TC intensities, ranging from 1001.3 to 1003.2 hPa. By 24 hours, however, the spread more than doubled to 4.2 hPa, ranging from 983.8 to 988.0 hPa. Beyond this time period, the increase in sensitivity leveled off; although the spread in solutions tended to decrease between 60 and 72 hours. At 68 hours of simulation time, there was only a 1.0 hPa difference in intensities, ranging from 954 to 955 hPa. Beyond 72 hours the spread in solutions increased once again and at 96 hours when the simulations ended the intensities ranged from 932.2 hPa to 937.5 hPa, representing a 5.3 hPa spread.

These warm bubble temperature and RMW tests were repeated on 2 grids in order to determine if there was a dependence of sensitivity on the horizontal resolution of the model. Figure 7 shows the evolution of surface maximum wind speeds through 96 hours for idealized TCs initialized with bubble temperatures of 2.0, 2.9, 3.0, 3.1, and 3.0 K. As in the three grid simulations, the solution spread diverges beyond 12 hours. At this time the TC intensities varied between 22.2 and 26.2 ms\(^{-1}\) or by 4 ms\(^{-1}\). This spread amplified with time and by 24 hours the solution spread was 4.7 ms\(^{-1}\) at which time TC intensities varied between
21.5 and 26.2 ms\(^{-1}\). By the end of the 96 hours of simulation time, the TC intensities varied from 48.4 to 62.4 ms\(^{-1}\) or 14.0 ms\(^{-1}\). While the TC intensification trends are generally similar for the two and three grid simulations, this spread is actually larger than the 2 grid simulations, indicating that the horizontal resolution of the simulations in fact may play a role in the observed sensitivity in solutions.

The evolution of MSLP is summarized for the warm bubble temperature tests simulated on two grids in Figure 8. Perhaps one of the more notable differences in this figure is that as compared with other tests in which the TCs appeared to intensify at a steady rate throughout the first 36 hours before a gradual reduction in intensification rate for the remainder of the four days. Here, as well as for the other 2 grid sensitivity tests, the TCs intensified initially during 12 hours, but then the intensification leveled off until 36 hours. Beyond this the TCs intensified again at a steady rate through 96 hours. As with the other simulations the spread in solutions increased beyond 12 hours. The sensitivity, in general, varied little and remains at around 4.0 hPa. At 24 hours the solutions varied between 1005.8 and 1009.7 hPa, representing a 3.9 hPa difference. In fact, even by 84 hours the solutions varied by 4.1 hPa, or between 954.4 and 958.5 hPa. At 96 hours, however, the solutions varied between 939.4 and 947.5 hPa, or by 8.1 hPa, almost double that
of only 12 hours prior. Here again, the sensitivities observed were larger than with the three grid higher resolution simulations.

The final sensitivity test that was conducted with RAMSv6.0 was a series of two grid simulations in which the RMW was varied. These simulations followed a similar intensification trend and sensitivity characteristics to that of the warm bubble temperature sensitivity tests conducted on two grids, and are summarized in figure 9. At 12 hours, the TC intensities varied between 20.7 and 28.4 ms$^{-1}$, or by 7.7 ms$^{-1}$. By 48 hours this sensitivity increased to 9.1 ms$^{-1}$ at which time TC intensities varied between 31.2 and 40.3 ms$^{-1}$. This spread continued to increase, in general, throughout four days and by 96 hours was at 14.4 ms$^{-1}$ with the weakest TC having an intensity of 48.8 ms$^{-1}$ and the most intense at 63.2 ms$^{-1}$. Again, this sensitivity was larger than the three grid simulations where at 96 hours the sensitivity for the RMW tests was observed to be 8.8 ms$^{-1}$.

Lastly, the results of two grid RMW sensitivity tests summarized in terms of the four day evolution of MSLP is shown in figure 10. The MSLP at 12 hours exhibited a 2.7 hPa difference, ranging from 1004.3 to 1007.0 hPa. The sensitivity increased with time and by 48 hours was observed to be 4.9 hPa, ranging between 991.4 and 996.3 hPa. At 96 hours the spread grew to 13.5 hPa, ranging from 939.6 to 949.1 hPa. This spread is
again larger than that observed with the three grid RMW simulations where a 5.3 hPa spread was observed at 96 hours. This lends further support to the idea that of the degree to which small perturbations in initial conditions amplifies is dependent upon the horizontal resolution of the model.

In summary, the sensitivity tests conducted with RAMSV6.0 reveal the importance of considering the architecture of the computational platforms on which model sensitivity tests are run since TC intensities simulated on different processors can vary by 8.1 ms$^{-1}$ or 2.5 hPa even as early as 12 hours of simulation time. Furthermore, given the uncertainties due to variations in initial conditions observed in the warm bubble temperature and RWM two and three grid simulations, it is reasonable to question whether the response of TC intensity due to variations in CCN is at least partly caused by amplification of initially small differences in model simulations. Perhaps the furthest reaching result from these tests is that it is important to use the same node when conducting series of sensitivity simulations.

The next section of this chapter examines the response of TCs to varying aerosol concentrations in the context of responses to small changes in initial conditions by conducting an ensemble of simulations. In doing so, this extends the studies of Zhang et al. (2007, 2009) because it offers insight as to whether they were seeing a physical response due to
variations in aerosol concentrations or merely a response of the system to variations in initial conditions.

3.2 Discussion of RAMSv4.3 Ensemble Runs

Of the 288 simulations that were executed, only 142 successfully reached the end of the 4-day simulation period. The other 146 simulations terminated early; however, the cause of the model failures could not be isolated. While there was no common line of code in which all of the run failures occurred, a majority of the failures were associated with radiation call errors, posing questions about the numerical stability of the Harrington radiation scheme. Further investigation is needed to verify the precise causes of these run failures as there was no consistent trend as to whether the model crashed for a particular initial condition or model setting. In the remainder of this subsection, the ensemble of simulations is analyzed. First, the times and conditions under which some of the simulations failed are examined. Thereafter, the impact of variations of the aerosol concentrations on TC intensity is discussed in the context of varying initial conditions first for only the simulations that successfully completed and then for all simulations, but only including the times for each simulation up until it failed.

The fraction of runs that were successfully completed varied according to the CCN concentration. Of the total 72
simulations for each CCN concentration, there were a total of 55 fully completed runs with a CCN concentration of 100 cm$^{-3}$, 50 for runs with a concentration of 101 cm$^{-3}$, 19 for runs with a concentration of 1000 cm$^{-3}$, and 18 for runs with a concentration of 2000 cm$^{-3}$. At this time it is unknown why the runs with higher CCN concentration were more prone to failure.

Figure 11 shows a histogram of the time at which each of the 288 simulations stopped. The stop time can correspond to a natural finish (i.e., when the four day period of simulation was completed) or when the simulations failed. There are two clusters of times at which the model runs stopped. The highest frequency appears at 96 hours because 142 of the 288 model runs successfully ran for a total of four days. Although only 3 total simulations stopped within the first 24 hours, there was a larger cluster of model failures between 24 and 48 hours with a total of 104 simulations having stopped by the end of 48 hours. After 48 hours, however, there were very few model runs that failed until beyond 78 hours.

This analysis can be separated according to the initial CCN concentration. In figure 12, it is seen that there were only 2 runs containing a CCN concentration of 100 cm$^{-3}$ that failed prior to 48 hours. However, there were a total of 12 run failures by 48 hours. There were no additional simulations that stopped until after 84 hours. Between 84 and 96 hours there were 2
additional simulations that stopped prematurely and 55 simulations finished successfully at 96 hours. Figure 13 shows this same analysis for simulations with CCN concentrations of 101 cm$^{-3}$. By 48 hours there were a total of 12 run failures; however, 11 of them occurred after 42 hours. Beyond that run failures occurred more slowly, and in fact by 84 hours of simulation time there were only 3 additional simulations that stopped prematurely. At 96 hours, 50 of the 72 runs completed successfully, without complications. Simulations with CCN concentrations of 1000 cm$^{-3}$ failed in greater numbers, with only 19 finishing successfully at 96 hours as shown in Figure 14. While only one failure occurred between 0 and 24 hours, the largest number of model simulations that stopped occurred from 24 to 48 hours when an additional 39 simulations had failed. Finally, simulations with a concentration of 2000 cm$^{-3}$ exhibited 2 large clusters with greater frequency of end runtime as shown in figure 15. It should be pointed out that with these simulations there were no run failures during the first 24 hours. Between 24 and 48 hours there were 40 failures. While only 3 additional simulations stopped by 84 hours, an additional 11 simulations stopped between 84 and 96 hours. Only 18 simulations were completed successfully with CCN concentrations of 2000 cm$^{-3}$. 
This information can also be presented by displaying the cumulative percentage of model runs that stopped as a function of time after the model was initialized. Figure 16 shows that up until 24 hours, only 1% of the simulations had stopped. By 48 hours, however, 36% of the simulations had stopped. Thereafter, the rate of failure was slower with only 39% of the simulations having stopped by 84 hours. Up to (but not including) the 96th hour of simulation time, 45% of the total number of simulations had stopped.

In figure 17, the cumulative frequency of the percentage of runs stopping as a function of time for simulations conducted with an initial CCN concentration of 100 cm$^{-3}$ is shown. Through the first 42 hours, only 1% of the model simulations had failed. However, at 48 hours there was a sharp increase in the number of model simulation failures since by that time 17% of the model simulations had stopped. From 48 hours to just prior to 96 hours, the percent of model runs that stopped increased slowly and reached 19% within the final hour of simulation time. Figure 18 shows the cumulative percent of runs that have stopped for simulations with a CCN concentration of 101 cm$^{-3}$. Just 3% of runs failed before 48 hours, but this rises sharply to 17% after 48 hours. This value rises to 19% just prior to the 96 hour of simulation time. The remaining 81% of simulations finished at the end of the simulated time. Figure 19 shows that the
cumulative percent distribution of simulations with CCN concentrations of 1000 cm$^{-3}$ stopping as a function of simulation time looks different in that from 24 to 48 hours, the percent of runs that failed gradually increases from 0% to 56% by 48 hours. Thereafter few runs failed until the remaining model runs finished at 96 hours. Lastly, figure 20 shows the cumulative percent distribution of stopped runs for all model simulations with a CCN concentration of 2000 cm$^{-3}$. While none of these simulations fail before 24 hours, there is a steady rise in the number of runs that failed beyond that, and by 48 hours approximately 56% of the simulations had stopped. This value does not increase again until 84 hours. By about 90 hours nearly 80% of the simulations had failed. The remaining 18 simulations were successfully completed at 96 hours.

Figure 21 shows the mean surface wind speed, $V_{\text{max}}$, computed for simulations of each CCN concentration along with the standard deviation (shaded) and excluding all of the model simulations that failed prematurely. Throughout almost the entire four day period, there was a monotonic response in $V_{\text{max}}$ to changes in aerosol concentrations. This result differs from the Zhang et al. (2007, 2009) studies in that they found a non-monotonic response of $V_{\text{max}}$ to CCN concentration. This suggests that the response of the idealized TC to variations in CCN is stronger than the variations that occur due to non-linear
amplification of noise in the initial conditions. It is important to realize that Zhang’s initial studies solely looked at changing CCN concentrations and not many of the other factors considered in this study.

Simulations with initial CCN concentrations of 100 and 101 cm\(^{-3}\) were performed to test the magnitude of response to a small change in CCN. Through the first 24 hours, the difference in average \(V_{\text{max}}\) of TCs simulated with initial CCN concentrations of 100 vs. 101 cm\(^{-3}\) was larger than one standard deviation. Beyond 36 hours, the \(V_{\text{max}}\) for simulations initialized with CCN concentrations of 100 and 101 were within one standard deviation of each other. However, it is important to note that while the standard deviations overlapped occasionally, as discussed, the mean value of \(V_{\text{max}}\) decreased with increasing CCN at all times. Between 24 and 60 hours the differences between the 1000 and 2000 cm\(^{-3}\) simulations were mostly within a standard deviation of each other and then the solutions diverge through 96 hours with the weaker TCs associated with higher CCN concentrations.

The four day evolution of MSLP is plotted in Figure 22, where the mean MSLP and standard deviation for all simulations that successfully terminated at 96 hours for each CCN concentration is plotted. There were essentially two different clusters of solutions after 24 hours up until 96 hours. The simulations with 1000 and 2000 cm\(^{-3}\) CCN initially consistently
remained within one standard deviation of each other, with the mean MSLP crossing repeatedly. The 100 and 101 cm$^{-3}$ solutions remained outside of one standard deviation of each other through the first 36 hours; however, from 36 to 96 hours the average MSLP for the two families were within one standard deviation of each other. But, the mean MSLPs crossed less than those of the 1000 and 2000 cm$^{-3}$ simulations. While it is unclear why there was more overlap in the solutions of mean MSLP as compared with $V_{\text{max}}$, it is clearly seen that the simulations with higher concentrations of CCN were persistently weaker when compared with those of lower CCN concentrations.

To assess the potential importance of the failed runs on the findings, the analyses presented in figures 21 and 22 were repeated to include results from all model simulations up until the time they stopped. Figure 23 shows the four day evolution of mean $V_{\text{max}}$ and its standard deviation sorted according to the initial CCN concentration. A monotonic response in $V_{\text{max}}$ to changes in CCN concentration was again seen. The reliability of the results will be less questionable if the same trends hold, and in fact generally that is the case. Not only did these results hold up, but the 100 and 101 cm$^{-3}$ concentration simulations stayed within a standard deviation again beyond 36 hours. Additionally, while the 1000 and 2000 cm$^{-3}$ concentration simulations remained within a standard deviation occasionally
through the first 48 hours, it was observed as before that the means never crossed. Again the weaker TCs were associated with the highest CCN concentrations. The most notable difference from the analysis considering only the runs that successfully finished is that the 1000 cm$^{-3}$ simulations were considerably weaker beyond 48 hours when failed runs were excluded; however, the solutions were still more than one standard deviation away from those conducted with 2000 cm$^{-3}$ CCN concentrations initially, and the overall conclusions made previously remain intact. This is shown more clearly when the results are placed side by side in figure 24.

Lastly, the four day evolution of mean MSLP and standard deviation separated by CCN concentration for all runs up until the time at which they stopped is shown in Figure 25. The same conclusions that were obtained when the failed runs were not included still hold. The solutions essentially diverged into two clusters beyond 24 hours and remained as such through 96 hours. However, unlike the $V_{\text{max}}$ analyses, the means of the MSLP plots did occasionally cross as seen in Figure 23; however, the lower CCN concentration simulations remained persistently stronger than that of higher CCN concentrations. The most notable difference is that when the failed runs were included, the 1000 cm$^{-3}$ concentration simulations were somewhat more intense as compared to when they were not included. This is consistent with
what was seen in Figure 23 and is particularly noted between 48 and 72 hours where the solutions between 1000 cm$^{-3}$ and 2000 cm$^{-3}$ concentration simulations diverged. That phenomenon does not occur when the failed runs were excluded.

The next chapter summarizes the main conclusions derived from these results in context of the findings from previous studies. It also provides implications on what these results may mean surrounding the impacts of the SAL on TCs. There remain many unanswered questions as a result of this study and furthermore, there may be a need to rerun simulations to obtain a more robust dataset where the entire ensemble of simulations is run successfully for four days. Suggestions for further investigation are also presented in the next chapter.
3.3 Figures

Fig. 1. Four day time series of $V_{\text{max}}$ for 3 grid simulations conducted on ten different nodes with identical initial conditions. Simulations were repeatable when run on the same node.
Fig. 2. Four day time series of MSLP for 3 grid simulations conducted on ten different nodes with identical initial conditions. Simulations were repeatable when run on the same node.
Fig. 3. Four day time series of $V_{\text{max}}$ for 3 grid simulations conducted on the same node with varying warm bubble temperature perturbations used to initialize convection.
Fig. 4. Four day time series of MSLP for 3 grid simulations conducted on the same node with varying warm bubble temperature perturbations used to initialize convection.
Fig. 5. Four day time series of $V_{\text{max}}$ for 3 grid simulations conducted on the same node with varying RMW perturbations in the vortex used to initialize the TC.
Fig. 6. Four day time series of MSLP for 3 grid simulations conducted on the same node with varying RMW perturbations in the vortex used to initialize the TC.
Fig. 7. Four day time series of $V_{\max}$ for 2 grid simulations conducted on the same node with varying warm bubble temperature perturbations used to initialize convection.
Fig. 8. Four day time series of MSLP for 2 grid simulations conducted on the same node with varying warm bubble perturbations used to initialize convection.
Fig. 9. Four day time series of $V_{\text{max}}$ for 2 grid simulations conducted on the same node with varying RMW perturbations in the vortex used to initialize the TC.
Fig. 10. Four day time series of MSLP for 2 grid simulations conducted on the same node with varying RMW perturbations in the vortex used to initialize the TC.
Fig. 11. Histogram of frequency of occurrence of end runtime sorted into 6 hour bin widths for all 288 simulations.
Fig. 12. As in Fig. 11, except for only simulations initialized with CCN concentrations of 100 CCN cm$^{-3}$. 
Fig. 13. As in Fig. 11, except for only simulations initialized with CCN concentrations of 101 CCN cm$^{-3}$. 
Fig. 14. As in Fig. 11, except for only simulations initialized with CCN concentrations of 1000 CCN cm$^{-3}$. 
Fig. 15. As in Fig. 11, except for only simulations initialized with CCN concentrations of 2000 CCN cm$^{-3}$. 
Fig. 16. Cumulative percentage of all 288 simulations stopping before the time indicated on horizontal axis.
Fig. 17. As in Fig. 16, except only for 72 simulations initialized with CCN concentrations of 100 CCN cm$^{-3}$. 
Fig. 18. As in Fig. 16, except only for 72 simulations initialized with CCN concentrations of 101 CCN cm$^{-3}$. 
Fig. 19. As in Fig. 16, except only for 72 simulations initialized with CCN concentrations of 1000 CCN cm\(^{-3}\).
Fig. 20. As in Fig. 16, except only for 72 simulations initialized with CCN concentrations of 2000 CCN cm$^{-3}$. 
Fig. 21. Mean $V_{\text{max}}$ (solid line) for simulations initialized with indicated CCN concentration as a function of simulation time for all 142 successfully completed simulations. Shading denotes one standard deviation about the mean with following color scale based on initial CCN concentration: 100 cm$^{-3}$ (blue), 101 cm$^{-3}$ (green), 1000 cm$^{-3}$ (yellow), and 2000 cm$^{-3}$ (red).
Fig. 22. As in Fig. 21, except for MSLP.
Fig. 23. As in Fig. 21, except for \( V_{\text{max}} \) computed considering all simulations, including those that failed, using times up until the run stopped.
Fig. 24. A comparison of 48-96 hour time series of mean $V_{\text{max}}$ for all simulations including the failed runs up until the model runs stopped (left) and for the 142 successfully completed runs (right) separated by CCN concentration. Shading denotes one standard deviation about the mean value for the following initial CCN concentrations: 100 cm$^{-3}$ (blue), 101 cm$^{-3}$ (green), 1000 cm$^{-3}$ (yellow), and 2000 cm$^{-3}$ (red).
Fig. 25. As in Fig. 23, except for MSLP.
4.1 Concluding Remarks

Previous studies have hypothesized that one of the mechanisms by which the Saharan Aerosol Layer (SAL) can impact tropical cyclones (TCs) is through the action of dust as cloud condensation nuclei (CCN). In this investigation, a series of idealized simulations were performed with the Regional Atmospheric Modeling System (RAMS) version 6.0 to examine the reproducibility of simulations running on different computational nodes and to sensitivity of TC evolution to small perturbations in the warm bubble temperature and the radius of maximum winds (RMW) used to initialize convection. Thereafter, RAMSv4.3 was used to conduct a series of ensemble simulations with inner domain resolutions of 2 km allow an initial vortex to evolve for 4 days where different ensemble members varied initial CCN concentrations of 100, 101, 1000, and 2000 cm\(^{-3}\) in the context of changes in initial conditions input into the model. Overall conclusions from all of these simulations are discussed in this chapter.

First, the series of simulations conducted using RAMSv6.0 with identical initial conditions on different processor cores showed that model solutions were different depending on the choice of node. This occurred due to minor differences in the
computational architecture across platforms. By simply running on different nodes, simulations produced TCs with intensity spreads by as much as 8.1 ms$^{-1}$ or 2.5 hPa as early as 12 hours into simulation time. When experiments were repeated on the same node, however, the results were identical. This has important implications for the conduct of sensitivity studies in that series of simulations should be conducted on isolated nodes so that the response to changes in initial conditions or parameterization schemes is isolated from responses due to changes in architecture.

The second series of sensitivity tests involved 2 and 3 grid simulations on RAMSv6.0 to examine how large and small perturbations in the initial RMW and the temperature of the warm bubble used to initialize convection affected TC evolution. By about 12 hours of simulation time, lasting throughout the remainder of the 96 hour runs, the response to perturbations was observed to be largely amplification of non-linear noise. While the storms intensified overall throughout 96 hours, there were notable differences in the spread of the sensitivity, namely that in general, two grid simulations tended to have a greater range in intensities. For example, the spread at 96 hours for two grid RMW tests was calculated to be 14.4 ms$^{-1}$ which compared to the three grid RMW tests where the spread was observed to be 8.8 ms$^{-1}$.
The third series of sensitivity tests conducted using RAMSv4.3 involved an ensemble of simulations designed to study the impacts of dust acting as CCN on TCs in the context of uncertainties induced by variations in other initial conditions. This extends the studies by Zhang et al. (2007, 2009) which looked at only at the effect of changing CCN centration on TCs. Because those studies found a non-monotonic response of TC intensity to increases in CCN concentration, it was hypothesized that the non-linear amplification of perturbations in initial conditions observed in the RAMSv6.0 experiments might mask an aerosol effect on TCs. It was observed throughout the 96 hour evolution that as CCN concentration increased, the intensity of the TCs decreased. It is also important to note that of the 288 simulations planned, only 142 were completed in full while 146 had stopped prematurely due to unidentified causes. While this did not appear to affect the mean results, the simulations with 1000 cm$^{-3}$ were weaker beyond 48 hours when including the failed runs in the analysis for times up until the model runs stopped. However, any differences induced by including the failed runs were not large enough to affect the monotonic relationship found between changing CCN concentrations and a decrease in TC intensity. These findings lend support to the idea that the dust in the SAL may play an important role in the evolution of TCs.

4.2 Future Plans
While this study suggests that there is a physically-based impact of changing aerosol concentrations on TC intensity, it is important to note that there was a spread in solutions for a constant CCN both in the ensemble of simulations conducted with RAMSv4.3 with varying initial conditions and in the sensitivity simulations conducted with RAMSv6.0. Because only 142 of the planned 288 ensemble simulations with RAMSv4.3 completed successfully, it will be necessary to reproduce these simulations without failures. It needs to be determined whether the numerical instability was due to the Harrington radiation scheme or other causes to identify exactly why 146 of the 288 simulations failed.

The ensemble of simulations was conducted using a horizontally homogenous 3-D vertical profile of CCN concentrations at the time the TC first formed. Further investigations should examine the effects of introducing CCN at the TC lateral boundaries at varying stages of its evolution to represent the situation where dust is drawn into the circulation of a TC. Most importantly, it is necessary for the results presented here be analyzed to investigate the physical mechanisms by which increasing dust concentrations led to reductions in TC intensity.

Specifically, future work will need to compare the results to that of Cotton and Krall (2012) which showed that an
ingestion of enhanced CCN concentrations leads to smaller cloud droplet sizes causing a suppression of cloud droplet collision and coalescence, an increase in liquid water contents at upper levels, and an increase in supercooled water which altered the heating profile of the TC and resulted in increases in downdraft and cold pool enhancement and therefore reducing the TC intensity. These types of analyses and future work will begin to enhance the physical understanding of the results obtained in this study, the first to identify a monotonic response of increasing CCN concentrations to a reduction in TC intensity.
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