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The Influence Of Tropical Cyclone Size On Its Intensification

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This is to certify that the Master's Thesis of

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Biographical Sketch

Cristina Alexandra Carrasco was born on January 4, 1986, in Miami, Florida. She attended Miami Coral Park Senior High School in Miami, Florida. She received her Bachelor of Science degree in Meteorology in May of 2008 from the University of Miami. She matriculated to North Carolina A & T State University where she began her research on hurricane rapid intensification under the tutelage of Dr. Yuh-Lang Lin in partial fulfillment for her Master of Science degree in Physics.

Dedication

I dedicate my Master's Thesis to four very influential people in my life. Firstly, to my loving father, George Carrasco, who left us all too soon. Yet, his love continues on and has helped me every day since. The eagerness he had to constantly learn more than he already knew has always been an inspiration for me. To my amazing mother, Maria Isabel Carrasco, who took on the role of both parents when I was only four; because of her perseverance, hard work, encouragement, and love I have been able to get where I am today. To my dear friend Cecilia Batista, who helped me countless times with applications, reference letters, and supported me through everything. I am also here today because of your help and dedication to my family. And finally to my best friend, colleague, and love, Adrian Santiago. You have always been by my side, continuously encouraging and challenging me intellectually, supporting everything I do, and making sure I always have a smile on my face.

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I would like to take this opportunity as well to express my sincere gratitude towards my family, whose prayers and encouragement continue to help me as I keep pursuing my educational dreams. I would also like to thank Father Alberto Múnera for faithfully continuing to honor the promise he made to my dad twenty-two years ago. I thank him for being my teacher, mentor, uncle and friend throughout these last twenty-two years. And finally I would like to thank Adrian Santiago, whose constant enthusiasm towards anything which has to do with meteorology inspires me and makes me love the field even more.

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List of Abbreviations

EBT	Extended best track
TAFB	Tropical Analysis Forecast Branch
HURDAT	North Atlantic hurricane database
ITCZ	Intertropical Convergence Zone
NCAR	National Center for Atmospheric Research
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
Non-RI	None rapid intensification
MM5	Mesoscale Model version 5
REYE	Radius of the eye
RI	Rapid intensification
ROCI	Radius of outermost closed isobar
RMW	Radius of maximum winds
SHIPS	Statistical Hurricane Intensity Prediction Scheme

Abstract

This study investigates the tropical cyclones of the past two decades (1990-2010) and the correlation, if any, between their size and their ability to undergo rapid intensification (RI). A rapid intensification period is considered to be anything greater than or equal to 30 kt over 24 hours. Three different parameters are chosen to define the size of a tropical cyclone: radius of maximum wind (RMW), radius of outermost closed isobar (ROCI), and the average 34 kt radius and are compared in order to observe any different intensification tendencies. The data for this study, mainly coming from the extended-best track (EBT) dataset, is organized into 24-h intervals of intensification (RI periods) and/or constant intensity periods (Non RI periods). Each interval shows the maximum wind speed, RMW, ROCI, and average 34 kt radii at the beginning of the constant or intensification period and the change of intensity in knots during the 24-h period. Biases including all extra-tropical, sub-tropical storms, depression stages, and storms that made landfall within 24 hours of genesis are taken out as well as intervals with no data in at least one of the size parameters.

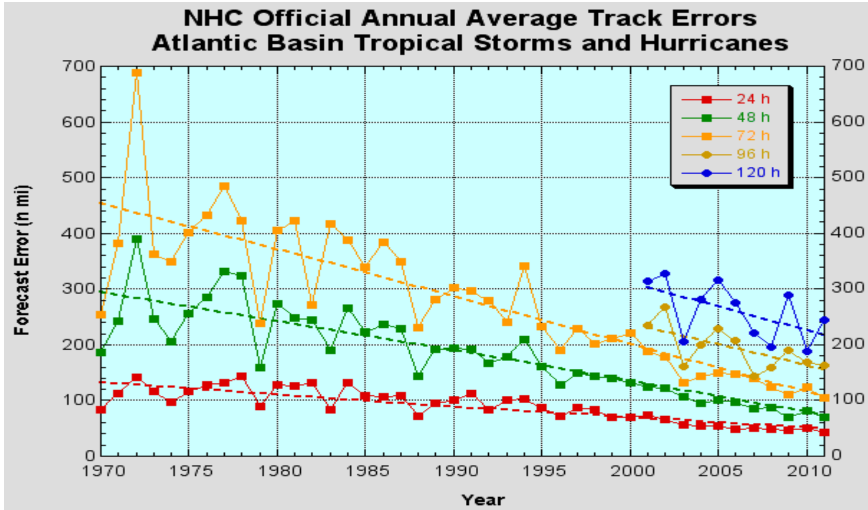
Results show that rapidly intensifying storms do show sensitivity to initial size. Comparisons between RI and non-RI storms confirm that tropical cyclones that undergo RI are more likely to be smaller than those that do not. Findings show that the RMW and the average 34kt radius have the strongest negative correlation with the change of intensity. Alternatively, there is no correlation between ROCI and the subsequent change of intensity. Scatter plots made for the RI storms imply there is a threshold for RI. Both thresholds lie at the boundary separating the medium and large storms, suggesting that once a tropical cyclone is too large, it is very difficult to it to undergo RI. During the past two decades, a tropical cyclone was three to four times more likely to undergo rapid intensification if it was small.

CHAPTER 1

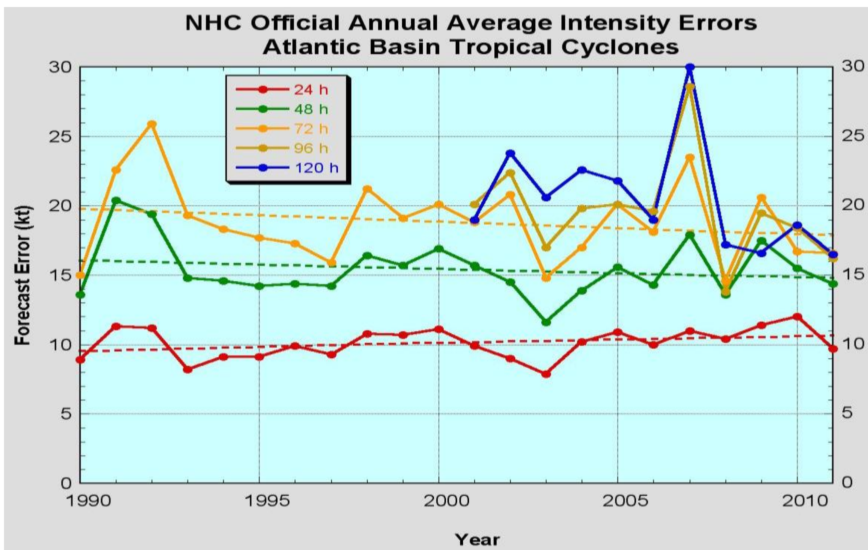
Introduction

The prediction and forecasting of tropical cyclones in the United States have evolved significantly since their beginning stages in the late 1800's. Routine hurricane track forecasts for the Atlantic Basin began in 1954, but the forecasts could only be given one day in advance. By 1964, forecasting improved to three days advance notice and finally in 2003, the National Hurricane Center (NHC) began issuing forecasts five days in advance. A major reason why the forecasting of tropical cyclones has improved throughout the decades has been because of the vast amount of data now available due to the increased amount of observing systems or instruments like aircraft reconnaissance, polar orbiting and geostationary satellites.

All these tools have helped increase the knowledge on the genesis, movement and dissipation of tropical cyclones. According to the NHC, their track predictions have improved significantly in the last few decades due to the fact that there are more accurate numerical models, more observations over the open ocean, and a better understanding of the physics of tropical cyclone movement (Figure 1.1a). In recent years, the operational tropical cyclone intensity forecasting has only improved slightly. Yet, according to the National Hurricane Center Official Annual Average Intensity Errors of Atlantic Basin Tropical Cyclones (Figure 1.1b), there has been no progress in predicting changes in tropical cyclone intensity (as defined by the 1-min maximum sustained wind) in the past two decades. Moreover, the "operational prediction of rapid intensification has proven to be especially difficult and, given the significant impacts of such episodes, has prompted the National Hurricane Center to declare it as its top forecast priority" (Kaplan, DeMaria, Knaff, 2010, p. 220).



(a)



(b)

Figure 1.1. (a) Annual average official track errors for Atlantic basin tropical storms and hurricanes for the period 1970-2011, with least-squared trend lines superimposed, (b) Annual average official intensity errors for Atlantic basin tropical cyclones for the period 1990-2011, with least-squares trend lines superimposed (Source: NHC/NOAA).

Rapid intensification has been proven difficult to forecast because of a general lack of understanding of the physical mechanisms that are responsible for these rare events (Kaplan et al., 2010) as well as the complex interactions between these physical processes. It has been studied that the main processes associated with rapid intensification are: the interaction with warm ocean and deep mixing layer, inner-core processes (concentric eyewall cycles), vortex Rossby waves, external forcing from upper-level troughs, and association with low vertical wind shear. However, no research has been done on how the size of a tropical cyclone plays a role in its intensity change. Detecting if there is any correlation between the size of a tropical cyclone and its ability to go through rapid intensification can help forecasters better predict if there is a higher chance for a certain tropical cyclone to undergo rapid intensification. Therefore, this study analyzes and compares the various sizes of tropical cyclones that underwent rapid intensification versus those that are steady state or slowly intensifying during the past two decades (1990-2010) in the Atlantic basin. The goal is to investigate if there is a parallel between small or large tropical cyclones and their intensification. Literature about size parameters and rapid intensification is also discussed.

1.1 Literature Review

The two main topics of tropical cyclone research that is being investigated in this literature review are the size and the rapid intensification process. Because there are many tropical cyclone size parameters to be considered, research is done to find which size parameters are best to use for this study. In addition, and in order to have an accurate analysis, what is considered to be a small or a large tropical cyclone is also explored. In some studies, rapid intensification is measured by the deepening of tropical cyclones' pressure and in others by the maximum sustained winds over a period of time. For this reason, various papers on rapid intensification are examined in order to find its accurate and most recent definition.

1.1.1 Tropical cyclone size parameters. Merrill (1984) examines the climatology and structure of, and some possible reasons for, the different sizes of tropical cyclones. The data used is a set of tropical cyclone positions and sizes for the Atlantic basin from 1957-1977. Two ways that forecasters use to measure the size of a tropical cyclone are described: the extent of winds above a certain speed, usually gale force (17 ms^{-1}), or as the average radius of the outer closed isobar (ROCI). Throughout the paper, the ROCI is used as a measure of size. The radius of outer closed isobar is defined as the average of the distances to the north, east, south and west from the cyclone center to the closed isobar having the highest value (Merrill, 1984). An example of this measurement is shown in Figure 1.2. When the outer closed isobar is elongated or distorted,

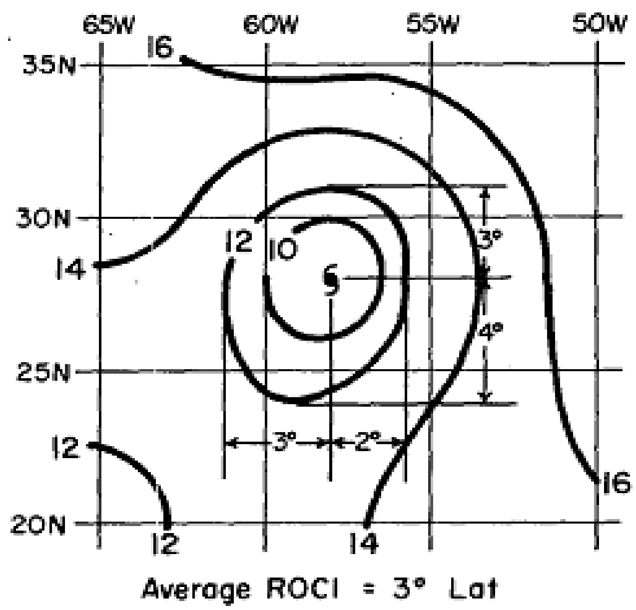


Figure 1.2. Example of the method Merrill used to determine the average radius of the outer closed isobar (ROCI) of a tropical cyclone.

usually when the tropical cyclone is forming or dissipating, the next-lower-valued isobar is taken as the outer closed isobar. Merrill defines a large cyclone to be one with a ROCI ≥ 4° latitude. It is suggested that the average cyclone forms with a ROCI of 2.5° and remains at about this size for 3.5 days, and then grows slightly to 4° as its maximum winds reach 60 ms^{-1}. Merrill discovered that the frequency of large tropical cyclones in the North Atlantic reaches a minimum in midsummer and a maximum in October, and is the highest in the subtropics in autumn. It is also observed that large tropical cyclones have more angular momentum that small ones and that tropical cyclone size is only weakly correlated with tropical cyclone intensity.

In 2004, Kimball and Mulekar establish, for the first time, a climatology of tropical cyclone size parameters for the North Atlantic basin. This study consists of the tropical cyclones from 1988 to 2002. Such climatology provides operational forecasters and emergency management authorities with important statistical information on the seasonal and spatial distribution of tropical cyclone size parameters in the North Atlantic basin (Kimball and Mulekar, 2004). This paper provides the following six tropical cyclone size parameters estimated by the operational forecasters in the National Hurricane Center:

- The radius of the eye (REYE)
- Radius of maximum winds (RMW)
- Mean radius of 32.9 ms^{-1} (64 kt) winds (R33)
- Mean radius of 25.7 ms^{-1} (50 kt) winds (R26)
- Mean radius of 17.5 ms^{-1} (34 kt) winds (R17)
- Mean radius of the outer closed isobar (ROCI)

The behavior of size parameters in weakening, steady-state, and intensifying tropical cyclones is compared, and the differences between size parameters of storms of different Saffir-Simpson categories and during different months are presented (Kimball and Mulekar, 2004). One of the findings is that Gulf of Mexico storms tend to have larger ROCIs, but smaller eyes, R33s, R26s, and R17s than North Atlantic storms between 50° and 80°W. The R17, R26, and R33 tend to increase as the storms move poleward and westward. Also, June and July storms tend to be small and September storms are the largest with strong inner and outer cores. October storms are still large with strong inner cores, but November storms are large and have weak inner cores.

Most importantly, Kimball and Mulekar (2004) show that the extended best-track dataset is consistent with general tropical cyclone theories and in agreement with past studies and for this reason the dataset can be used for further study. The original best-track dataset maintained by the National Hurricane Center contains track and intensity information every 6 hours for tropical cyclones since 1851. However, it does not include any information about the sizes of the systems. Starting in 1988, the six size parameters were combined with the best-track data and the extended best-track dataset (EBT) was created.

Both papers utilize the R17 and ROCI to quantify the size of the entire tropical cyclone. For this reason, two of the three size parameters being used in this study to determine the size of a tropical cyclone are the ROCI and the average 34 kt wind radii. The average 34 kt wind radius is the same as the R17 (mean radius of 17.5 ms^{-1} or 34 kts). The extended best-track dataset is also being used to compare the size of the tropical cyclone with its intensification rate.

1.1.2 Rapid intensification. Kaplan and DeMaria (2003) examine the large-scale characteristics of rapidly intensifying Atlantic basin tropical cyclones in their paper. Every tropical cyclone from 1989 to 2000 is analyzed and the mean initial conditions of cases that undergo rapid intensification are compared to the non-rapid intensification cases. A fundamental conclusion reached in this paper is the establishment of a definition for rapid intensification for Atlantic tropical cyclones. It is defined as a maximum sustained surface wind speed increase of 15.4 ms^{-1} (30 kt) or more over a 24-h period.

Other findings are that rapid intensification cases tend to occur farther south and west than the non-rapid intensification cases. They are also found to be farther from their maximum potential intensity and developed in regions of warmer water and higher lower-tropospheric relative humidity than the cases without rapid intensification. Kaplan and DeMaria also determine that rapid intensification most likely occurs in systems that are in an environment where forcing from upper-level troughs or cold lows is weaker than average. In addition, a simple technique for estimating the probability of rapid intensification was developed and it was employed in real time during the 2001 Atlantic hurricane season for the first time (Kaplan and DeMaria, 2003).

Kaplan et al. (2010) also perform an analysis of the climatology of rapid intensification cases in the Atlantic and eastern North Pacific basins. The analysis shows that the Atlantic rapid intensification cases tend to occur over a fairly widespread region as opposed to the eastern North Pacific cases that tend to be more tightly clustered and were mainly found between 10°-20°N and 95°-140°W (Kaplan et al., 2010). Both basins have the most amount of rapid intensification cases develop in the month of September. However, the Atlantic has about twice as many occurrences in October and November compared to June and July. In contrast, the earlier months in the eastern North Pacific have about twice as many rapid intensity occurrences as the latter months.

According to previous studies, vertical wind shear is one of the mechanisms that play a major role in the intensification process of a tropical cyclone**.** Frank and Ritchie (2001) used the Pennsylvania State University-National Center for Atmospheric Research (Penn State-NCAR) Mesoscale Model version 5 (MM5) to study how vertical shear would impact tropical cyclone intensity. Their results showed that wind shears in the 5-15 ms^{-1} range can cause major changes in hurricane intensity and structure: low shear results in rapid intensification of the tropical cyclone and high shear can tear a storm apart (Frank and Ritchie, 2001). Mark DeMaria (1996) performs large-scale analyses of the 1989-1994 Atlantic hurricane seasons and concludes that the size, latitude, and intensity of the cyclone can affect the impact of vertical shear on the intensification. DeMaria mentions that high-latitude, large, and intense tropical cyclones tend to be less sensitive to the effect of vertical shear than low-latitude, small, and weak storms. Even though this demonstrates how the size could alter the way vertical shear can affect the intensification of the cyclone, it does not give a direct comparison between size of a cyclone and rapid intensification.

DeMaria and Kaplan (1994) develop and describe a model for predicting intensity changes of Atlantic tropical cyclones at 12, 24, 36, 48, and 72 hours. This model is identified as the Statistical Hurricane Intensity Prediction Scheme (SHIPS). SHIPS is designed using a standard multiple regression technique with climatological, persistence, and synoptic predictors (DeMaria and Kaplan, 1994). The sample data used to test the model included all of the named Atlantic tropical cyclones from 1989 to 1992, with a few additional cases from 1982 to 1988 and they included only the times when the storms were over the ocean. During the development of SHIPS, "DeMaria and Kaplan (1994) performed a statistical analysis of the 1989 to 1992 cases that exhibited the largest 48 hour intensification rates" (Kaplan and DeMaria, 2003, p. 1095). Their results show that for the rapidly intensifying cases, the vertical shear and the size variables are smaller than average. It was concluded that vertical shear is negatively correlated with intensification, but size is positively correlated with intensification. However, the average value of size for the rapidly intensifying cases was less than the average for the total sample. They found that nearly all of the rapidly intensifying cases are early in the life cycle of the storms.

This result suggests that the rapid intensification of storms occurs before the outer wind circulation (measured by the SIZE parameter) increases (DeMaria and Kaplan, 1994).

CHAPTER 2

Methodology

2.1 Updated Saffir-Simpson Hurricane Wind Scale

The Saffir-Simpson scale is used in this study in the classification of tropical cyclones. The first version of this scale, known as the Saffir-Simpson Hurricane Scale, categorized tropical cyclones from a scale of 1 (weakest) to 5 (strongest) using the tropical cyclones' maximum sustained surface wind speed, central pressure, and storm surge approximations. Pressure/wind relationships were used as a first guess of hurricane intensity until an actual observation was found (Sheets, 1990). However, in order to avoid confusion and misconception, the central pressures and storm surge approximations were removed from the scale in 2009. Hurricane Ike in 2008 and Hurricane Charley in 2004 are good examples of how the previous scale could have had some misconceptions. Hurricane Ike was a very large Category 2 hurricane: it had hurricane force winds that extended as much as 125 miles from the center and caused a storm surge of about 20 ft. On the other hand, Hurricane Charley was a major Category 4 hurricane but only had hurricane force winds that extended at most 25 miles from the center and created a storm surge of only about 7 ft (Schott et al., 2012). Even though Hurricane Ike was just a Category 2, it could have easily been considered a Category 4 or 5 just by looking at the storm surge values.

The Saffir-Simpson Hurricane Wind Scale was updated once again in February 2012 in order to resolve issues regarding the conversions of units used for wind speeds. Because there is always an uncertainty in estimating tropical cyclone intensities, the National Hurricane Center assigns intensities in 5-knot (kt) increments. The knots are also converted into miles per hour (mph) and kilometers per hour (km/h) and rounded to the nearest 5 mph and 5 km/h increments as well.

However, the conversion from knots to miles per hour or kilometers per hour would bring up an issue when calculating for a Category 4 hurricane. A Category 4 hurricane ranged from 114-135 kt (131-155 mph or 210-249 km/h). But when a wind speed of 115 kt (Category 4) was converted to mph it would yield 132.3 mph which would then be rounded to 130 mph and subsequently fall into the Category 3 range. A similar conversion issue would also happen when converting 135 kt to km/h. In order to fix this conversion issue, the Category 4 wind speed range was changed by adding one mph at each end thus making the range now from 130-156 mph (113-136 kt, 209-251 km/h). Because of this change, the Category 3 and 5 ranges were also modified by adding one mph at the end of the range of both categories. The latest updated version of the Saffir-Simpson Hurricane Wind Scale is used in this study.

2.2 Data Source: HURDAT vs. Extended Best Track (EBT)

Since the 1960's, the National Hurricane Center (NHC) has kept and continues to maintain a database of all Atlantic tropical cyclones since 1886, known as the North Atlantic hurricane database (or HURDAT) (Jarvinen et al., 1984). This database contains estimates of the latitude, longitude, 1-minute maximum sustained surface winds, minimum sea-level pressure, and information whether the storm was tropical, subtropical or extra-tropical at 6-hour intervals for each storm. From the time that HURDAT was created our understanding of tropical cyclones has grown and analysis techniques at NHC have changed over the years which led to biases in the historical database that had not been addressed (Landsea, 1993). HURDAT also contained many systematic and random errors and had a lot of missing data that was uncovered by Jose Fernandez-Partagas as he discovered previously undocumented historical tropical cyclones from the mid-1800s to early 1900s (Partagas and Diaz, 1996a). As a result, the Atlantic Hurricane Database Re-analysis Project was created around 2001 in order to improve both the accuracy and consistency of HURDAT for the years of 1886 to 1910 as well as extending the data back to 1851 (Landsea et al., 2004).

Even though the Re-analysis Project has helped in revising and adding data into the database, HURDAT still does not contain any information about the size of each tropical system. Therefore, the “extended best-track” (EBT) was created by supplementing HURDAT with additional parameters like a maximum radial extent of 34, 50 and 64 kt wind in four quadrants, radius of maximum wind, eye diameter if available, and pressure and radius of the outer closed isobar (Demuth, DeMaria, and Knaff, 2006). Table 2.1 shows a list of the parameters contained

Table 2.1

List of Parameters Contained in EBT Dataset

Parameter	**Units**
Storm identification number	----
Storm name	----
Month	----
Day	----
Time	UTC
Year	----
Latitude	°N
Longitude	°W
Maximum wind speed	kt
Minimum central pressure	hPa
Radius of maximum wind	nmi
Eye diameter	nmi
Pressure of the outer closed isobar	hPa
Radius of the outer closed isobar	nmi
Radii of 34 kt wind to the NE, SE, SW and NW of the storm center	nmi
Radii of 50 kt wind to the NE, SE, SW and NW of the storm center	nmi
Radii of 64 kt wind to the NE, SE, SW and NW of the storm center	nmi

Note. List of parameters contained in every line of data for each date and time period (00, 06, 12 and 18 UTC) of every storm. Listed in the order in which it is written in.

in the dataset. Similar to HURDAT, the data in the EBT is arranged in 6-hour intervals (00, 06, 12, and 18 UTC) for each date of every storm. The EBT data file is continuously being updated every year after NHC completes the best track data for each storm at the end of the season. The radius of maximum wind, eye diameter, pressure and radius of the outer closed isobar are not best tracked or post storm quality controlled. All these parameters are operational estimates. However, starting in 2004, NHC began to post-storm best track the 34, 50 and 64 kt wind radii. Hence, the radii used in the data are operational estimates before 2004 and best tracked after 2004. Given that this study focuses on the size of tropical cyclones and their comparison between rapidly and non-rapidly intensifying storms, the extended best-track dataset is used and is the main contributor of data in this study.

2.3 Rapid Intensification (RI)

The rapid intensification of tropical cyclones is measured by the deepening of the tropical cyclones' pressure or by the increase of the maximum sustained winds over certain period of time, usually over a 24 hour period. The National Hurricane Center defines rapid intensification as an increase in the maximum sustained winds of a tropical cyclone of at least 30 kt in a 24 hour period ("Glossary of NHC Terms," n.p.). In Kaplan and DeMaria (2003), rapid intensification was defined as the 95th percentile of 24 hour intensity change of all the tropical cyclone cases used in their study. Even though the 95th percentile of 24 hour intensity change distribution in their study is 16 ms^{-1} (31 kt), they utilize a rapid intensification threshold of 15.4 ms^{-1} (30 kt) because it is in better agreement with the 16 ms^{-1} threshold than the next-closest change of 18 ms^{-1} (35 kt) due to the 5 kt resolution of the HURDAT file.

Including just the rapid intensification phases, there were a total of 296 RI cases when using the $\geq$ 30 kt/24 hr threshold. In addition to being the threshold being used at the National

Hurricane Center for rapid intensification, an increase of 30 kt over 24 hours is an increase of about two Saffir-Simpson categories over 24 hours. This definition of rapid intensification is the one being used in this research.

2.4 Size Parameters

DeMaria, Pennington, and Williams (2011) mention that "as a part of the operational forecasting procedure, NHC routinely estimates the radii of 34, 50, and 64 kt winds, the radius and pressure of the outermost closed isobar, radius of maximum wind, and the diameter of the storm eye, if one exists". For this study, three measures of tropical cyclone size are used for comparison: the radius of maximum winds (RMW), the radius of outermost closed isobar (ROCI) and the average radius of 34 kt (gale) winds. The radii of 50 and 64 kt are not used because this study includes tropical storms, in which the maximum sustained winds range from 34-63 kt. If the radius of 50 kt winds were to be used, some weaker tropical storms would be missing from the data. The radius of 64 kt is not used because this parameter would only include storms of Category 1 (winds of 64-82 kt) or stronger and will exclude all tropical storms (winds 34-63 kt). The radius of the eye is also not being used because that describes the size of the inner core of a storm and is not available in all cases. This study focuses only on the overall size of an entire storm, not just the inner core.

The RMW is defined as the distance from the center of a tropical cyclone to the location of the cyclone's maximum winds ("Glossary of NHC Terms," n.p.) and is expressed in nautical miles (nmi) in the EBT dataset. RMW is typically measured directly by reconnaissance aircraft when available in the Atlantic basin. Several methods have been formulated to estimate maximum surface winds from flight-level reconnaissance wind measurements (Powell, Uhlhorn, and Kepert, 2009). When reconnaissance aircraft is not able to reach the tropical cyclone, the hurricane specialists estimate the RMW by observing satellite data. Rappaport et al. (2009) mention that 70% of the time the monitoring is only done by satellite. However, this is only an estimate and the RMW is not best tracked like the 34 kt radii.

The ROCI values in the EBT dataset are also expressed in nautical miles. Occasionally, some ROCI data is missing from certain storms or time periods. In order to fill in most of the missing data, the ROCI is calculated using the Tropical Surface Analysis and NWS Unified Surface Analysis maps from the Tropical Analysis Forecast Branch (TAFB). These synoptic maps are created every six hours and depict the sea level pressure with lines of equal pressure, usually in increments of four millibars. The analysis also depicts important surface features including areas of high and low pressure, frontal systems, troughs, tropical cyclones, tropical waves, the Intertropical Convergence Zone (ITCZ), drylines, and squall lines. Figure 2.1

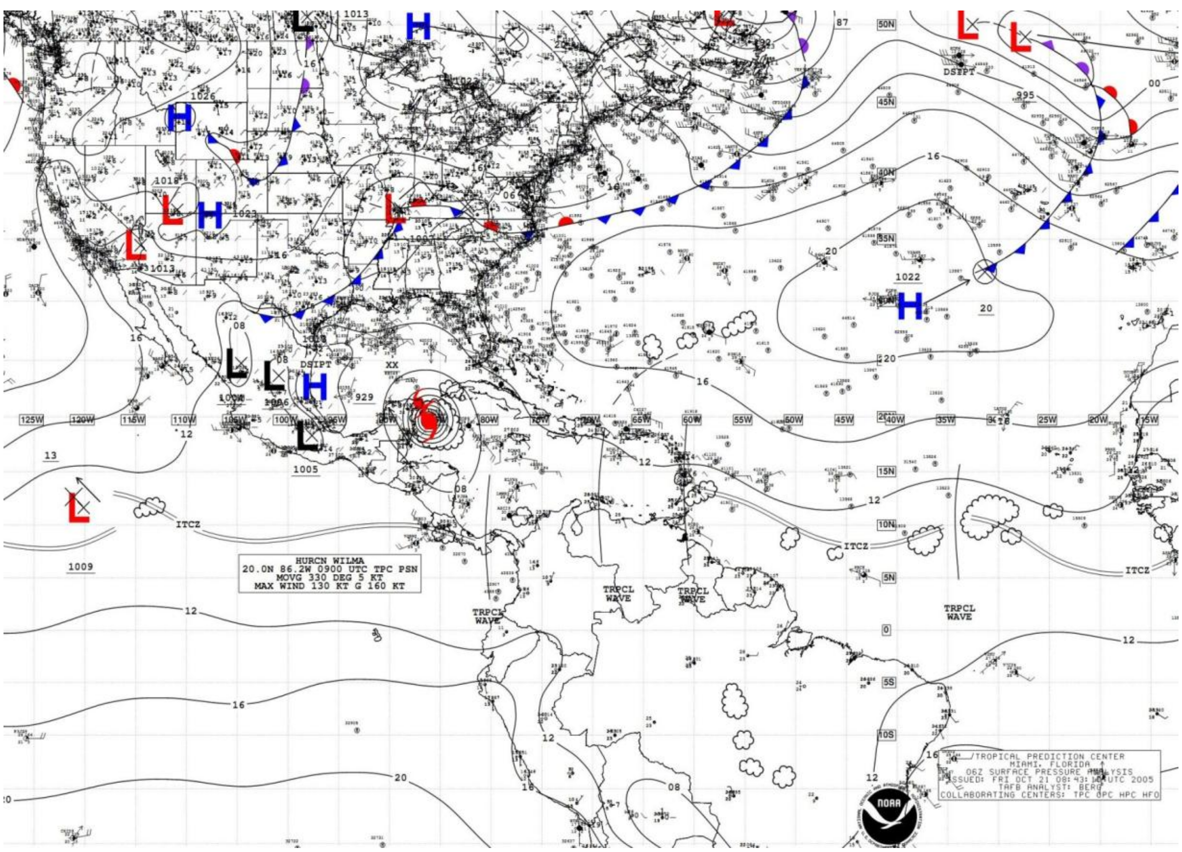


Figure 2.1. Example of surface analysis map (map of 10/21/05 06Z).

shows an example of the surface analysis map. The ROCI is defined as the average of the distances to the north, east, south and west from the cyclone center to the closed isobar having the highest value (Merrill, 1984). Therefore, the ROCI is computed by measuring the distance in degrees latitude from north-south of the outermost closed isobar as well as from east-west and finding the average of the two. Once that is found, it is then divided by 2 again in order to get the average radius. In order to convert the degrees latitude into nautical miles, the averaged radius found is multiplied by 60 since 1 degree latitude is approximately 60 nmi. Figure 2.2 shows

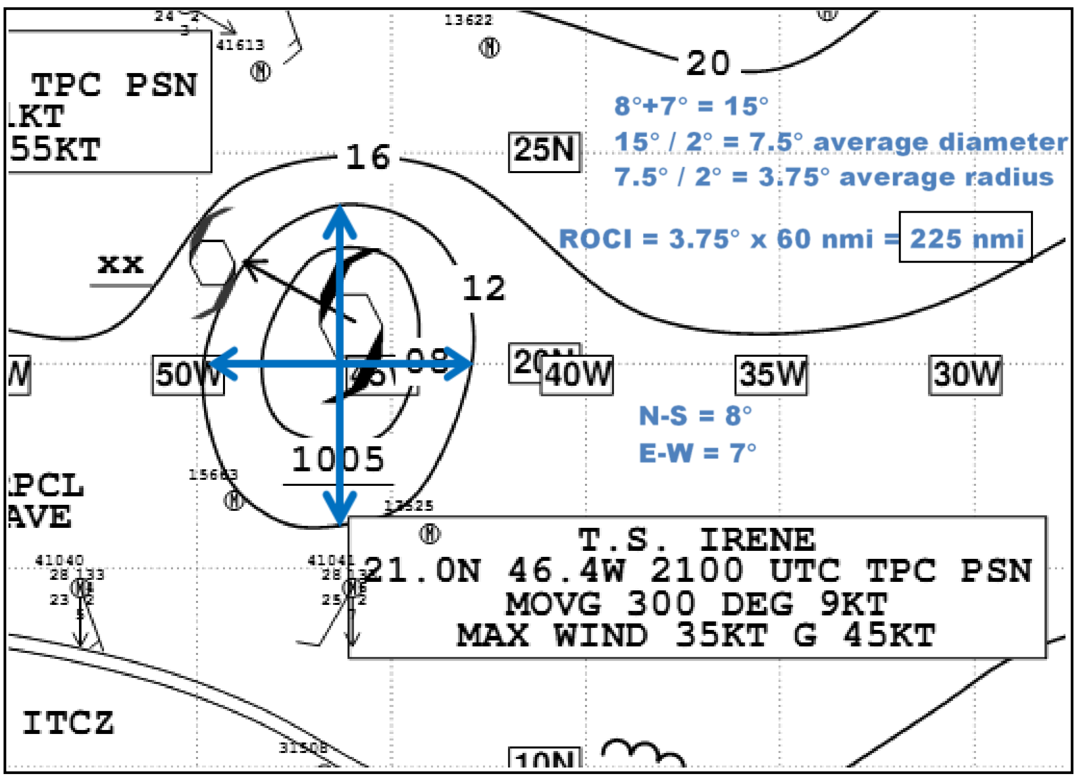


Figure 2.2. Example of how ROCI was measured in this study.

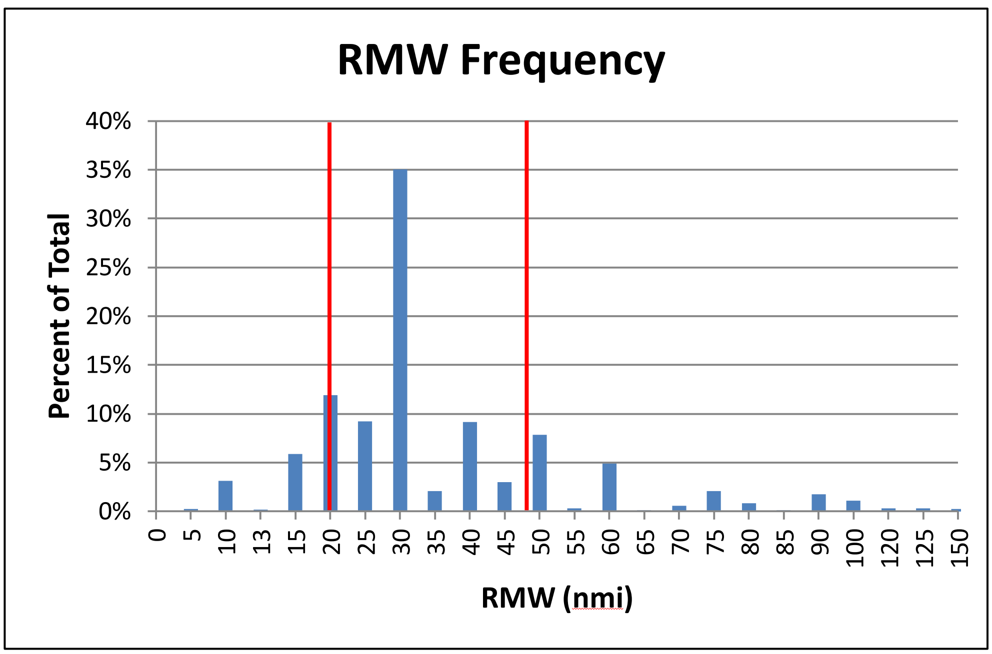
a zoomed in excerpt of a surface analysis map from TAFB and it demonstrates the process of how the ROCI is measured.

In some instances where the ROCI is missing from the data and the surface analysis maps do not show a closed low (even though the storm was officially considered a closed system), an outer most closed isobar has to be drawn in order to calculate the ROCI at that particular time. In order to close an isobar, the synoptic map is carefully scrutinized for low pressures around the tropical cyclone. The buoy, ship and/or station observations around the system are also inspected to see if the winds circulate in the counter-clockwise motion as they should be around a tropical cyclone in the northern hemisphere. If the winds are circulating around the low pressure system and the observations show an equal low pressure, an isobar is drawn around the low.

The areal extent of a cyclone circulation is measured by forecasters as the extent of winds above a certain speed, usually gale force (17.5 ms^{-1} or 34 kt) (Merrill, 1984). The radius of the 34 kt winds, also described as the outer-wind radii (Kimball and Mulekar, 2004), is documented for all four quadrants every 6 hours for each storm and expressed in nautical miles in the EBT database. As mentioned earlier, the ROCI is averaged from north-south and east-west in order to get one value. The RMW is also presented as a symmetric value in the EBT database. Since the radius of the 34 kt winds is documented for each quadrant, therefore giving four values, the four quadrants are averaged in order to have one symmetric value like the other two parameters. If one of the quadrants has 0 as its value, it is not included in the average. For example if the values are 50, 30, 0, and 50 nmi (northeast, southeast, northwest, and southwest respectively) then the average radius of 34 kt winds would be 43 nmi instead of 33 nmi.

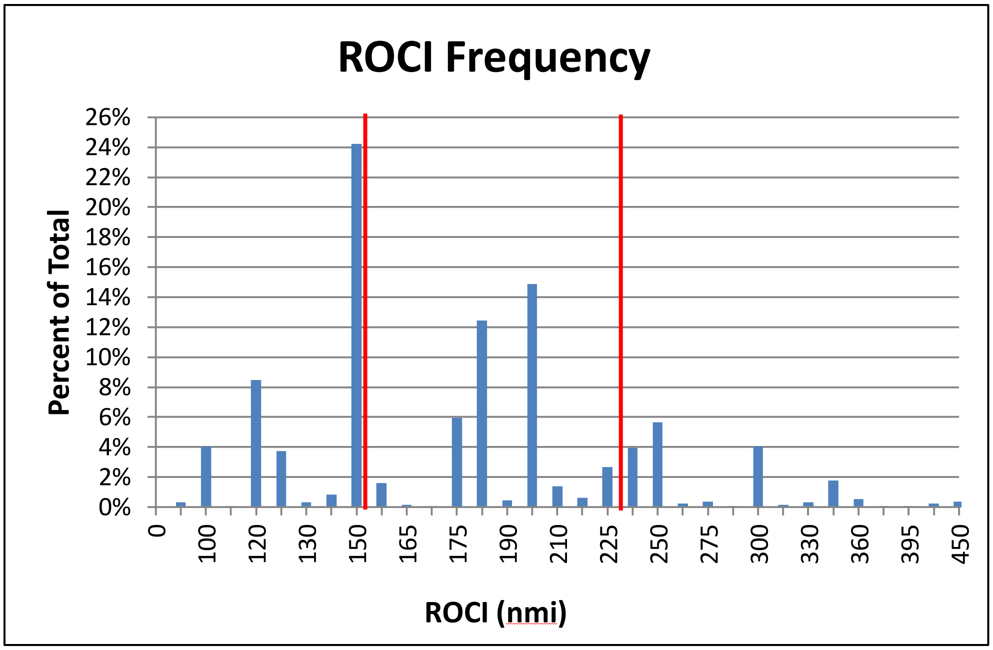
Figures 2.3a-c show the frequency breakdown of every nautical mile of every size parameter (RMW, ROCI, average 34 kt radii) for all cases (RI and non-RI) during 1990-2010. For example, in Figure 2.3a, 35% of all 1,312 twenty-four-hour periods have an RMW of 30 nmi. The reason why there are certain peaks in the RMW figure, 20, 30, 40, 50, and 60 nmi for instance, is because all these parameters are operational estimates and the forecasters are rounding to the nearest 10 nmi most of the time. The ROCI shows a noisy distribution; this is due to the fact that forecasters round to the nearest degree or half degree latitude when estimating the ROCI. Because of this, there are peaks in the 120 nmi (2° latitude), 150 nmi (2 ½ ° latitude), 180 nmi (3° latitude), 200, 250 and 300 nmi. When the storm is really big, they tend to round to the nearest 50 nmi. Not only are the forecasters estimating and rounding, but the RMW and ROCI are not best tracked; the only parameter out of the three that they do quality control on after the storm is the 34 kt radii. This is partly why Figures 2.3a and 2.3b do not show a smooth distribution like Figure 2.3c.

Forecasters at NHC obtain and estimate these parameters from data sources such as ship and surface reports, aircraft reconnaissance data and satellite imagery. Because all the parameters



(a)

Figure 2.3. (a) Percent breakdown of RMW for all cases (RI and non-RI), (b) Percent breakdown of ROCI for all cases (RI and non-RI), (c) Percent breakdown of Ave 34 kt Radii for all cases (RI and non-RI). Red lines separate the small, medium and large boundaries.



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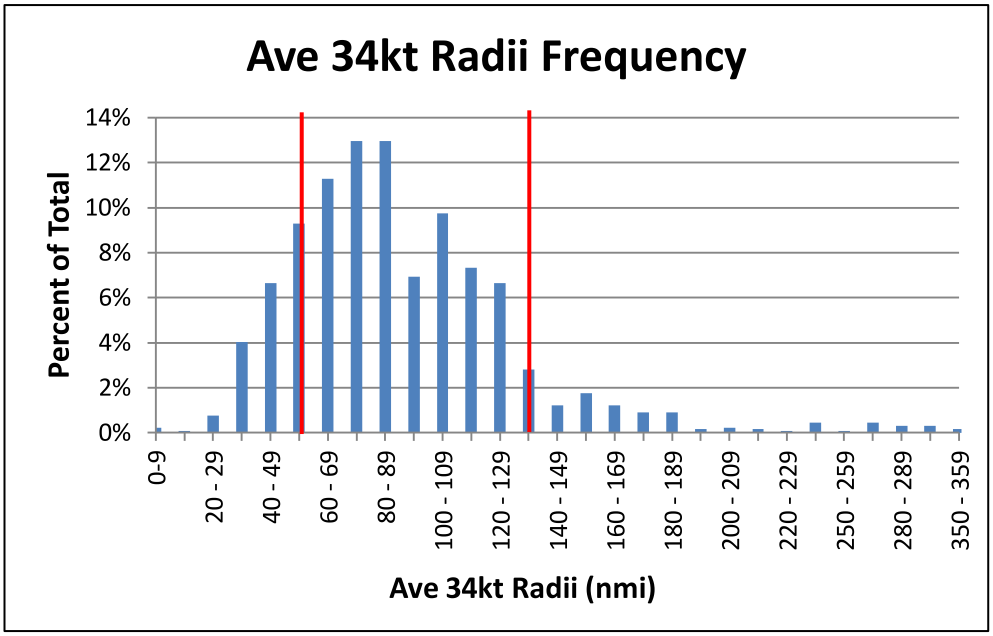


(c)

Figure 2.3. (cont).

are estimates and the data is operational, there is no guarantee that all of the parameters are consistent and "at present, there are no error estimates for these variables" (DeMaria et al. 2011).

2.5 Data Organization

A series of excel files were produced in order to organize the data from the EBT database. Originally, two datasets were created with all the original parameters contained in the EBT database for the Atlantic Basin between the years of 1990 to 2010: one with all the rapid intensifying storms (RI storms) and one with all the storms that did not have rapid intensification periods (non-RI storms). Subsequently, the datasets were edited and reduced to include only the parameters being used in this study (RMW, ROCI, and the 34 kt wind radius of all four quadrants) along with the averaged 34 kt radii and the maximum wind speed (kt) of every 6 hour interval. In addition, all biases were taken out of each dataset; this is explained in the following section.

Because this study is aimed to determine if the size of the storm plays any significant role at the onset of rapid intensification, then the data was reduced to 24-h periods and a change of intensity parameter was included. The change of intensity parameter shows what the intensity change (in knots) was during the 24 hours.

Both the RI and non-RI storms were rearranged into 24 hour periods. For the storms containing RI periods, anything that was not in the RI period was taken out and only the values at the onset of a rapid intensification period were kept. Some storms had intensification periods that lasted more than 24 hours. For example, Hurricane Andrew intensified for 54 hours from 08/21 12Z to 08/23 18Z. In these cases, 24 hours were counted starting from each 6 hour interval that was inside the intensification period and every 24-h period was considered a separate RI period. Therefore, Hurricane Andrew has six RI periods: first [08/21 12Z – 08/22 12/Z], second [08/21 18Z – 08/22 18Z], etc. An excerpt of the 24-h dataset can be seen in Table 2.2. For the storms that did not have any rapid intensification periods (non-RI cases), the only 24-h periods included were the ones in which the intensity either increased slowly or remained the same. Hence, any decrease of intensity was not included.

Table 2.2

Tropical Cyclones of 2008 That Underwent RI

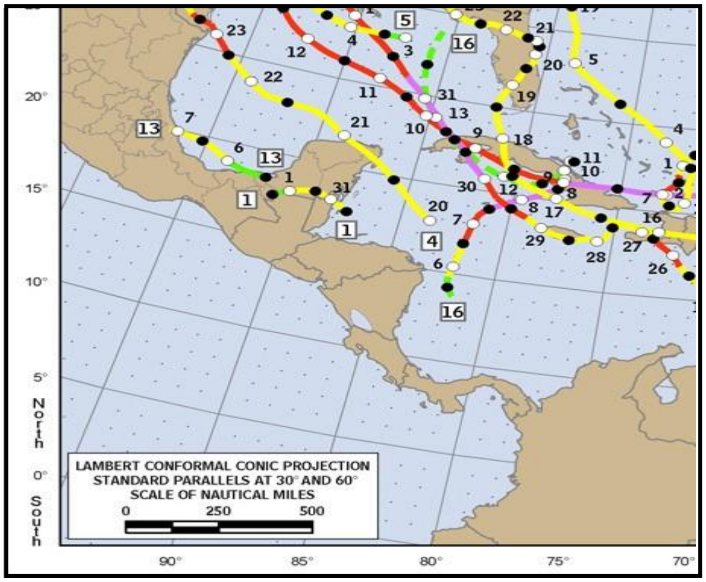
Name	**initial max wind speed (kt)**	**RMW (nmi)**	**ROCI (nmi)**	**radii 34kt NE (nmi)**	**34kt SE (nmi)**	**34kt SW (nmi)**	**34kt NW (nmi)**	**Ave 34kt radii (nmi)**	**subsequent change of intensity 24 hours (kt)**
BERTHA	45	30	180	75	30	0	75	60	35
	45	30	180	75	30	0	75	60	55
	55	30	180	75	30	0	75	60	50
	65	20	200	100	60	45	100	76	40
DOLLY	55	45	240	140	120	60	120	110	30
GUSTAV	55	20	225	120	120	40	60	85	30
	50	25	225	120	120	40	60	85	60
	65	25	225	130	120	70	100	105	60
	75	20	250	140	120	90	120	118	45
HANNA	40	75	220	100	100	75	100	94	30
	45	50	220	100	100	75	100	94	30
IKE	55	90	250	150	115	45	120	108	50
	55	50	200	145	110	45	120	105	70
	60	45	200	135	105	50	120	103	60
	75	30	200	130	100	60	120	103	40
OMAR	35	45	150	40	40	0	0	40	30
	40	45	180	45	45	45	0	45	30
	65	15	180	60	75	105	25	66	30
	70	10	240	60	105	135	30	83	45
PALOMA	35	35	210	0	0	0	20	20	30
	40	30	210	30	30	20	20	25	35
	65	15	180	60	60	40	40	50	35
	65	10	180	65	65	40	40	53	45
	75	10	180	85	70	45	55	64	50
	80	10	210	110	80	50	70	78	45

Note. RI segment of the 24-h dataset. These are the storms of 2008 that underwent rapid intensification that are included in this study.

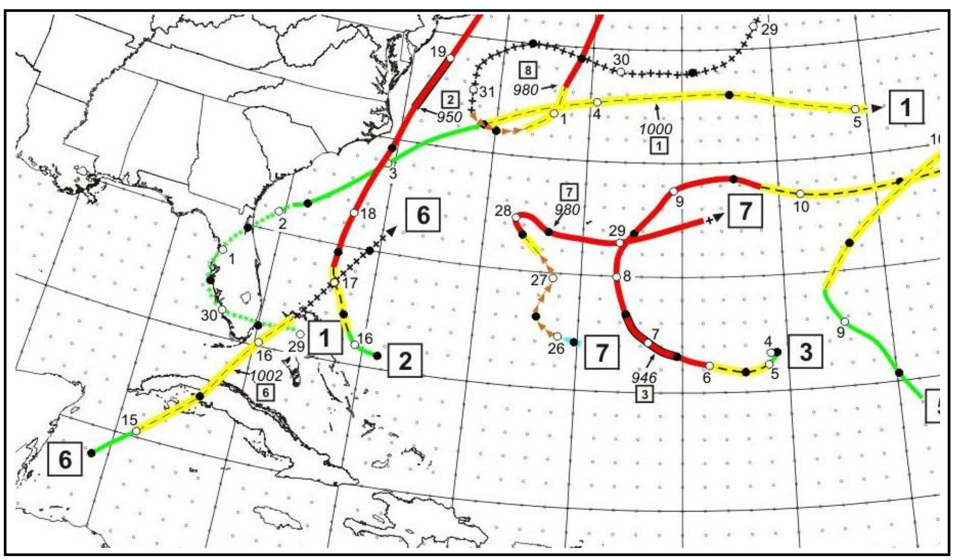
2.6 Biases

In order for this study to be more accurate, biases were taken out from the datasets. Seeing as this study wanted to observe the intensification of tropical storms and hurricanes, all extra-tropical storms, sub-tropical storms and depressions were removed from both the RI and non-RI cases. Sometimes the RI period began during the depression stage but this implied that the 34 kt radii would be 0 since a depression has maximum sustained wind speeds of 33 kt or less. For this reason, anything 30 kt or less at the initial time was removed. Other RI cases were also deleted because of lack of data (expressed as a -99 in the EBT database) at the beginning of the RI periods. Typically, the 34 kt radii was the size parameter that had the most about of missing data. Some storms, as mentioned before, had many RI periods and therefore only one of the intensification periods was removed because of lack of data. If the data of the rest of the intensification periods was complete, then only the period that lacks data was removed, not the entire storm. A total of 25 tropical cyclones that underwent rapid intensification were removed because of lack of data.

Tropical cyclones that made landfall within 24 hours of their genesis were also removed because there is no possibility for intensification once the cyclone is over land. However, if the tropical cyclone made landfall and then continued its course eventually going over water again, it was kept in the database if it survived at least another 24 hours over water. Tropical Storm Arthur in 2008 (Figure 2.4a) is an example of a storm that was taken out of the dataset because it made landfall within a few hours of its genesis. Tropical Storms Ana and Fabian in 1991 (Figure 2.4b) are good examples of two storms that were not removed because they both made landfall within 24 hours of genesis, yet they both went back over water and survived a longer period of time. In total, 13 tropical cyclones were removed from the non-RI cases because of their landfall within the first 24 hours.



(a)



(b)

Figure 2.4. (a) Tropical Storm Arthur in 2008 (storm 1) was taken out of the dataset because it made landfall in Belize less than 24 hours after its genesis, (b) Tropical Storms Ana and Fabian in 1991 (storms 1 and 6, respectively) were not removed because they made landfall and went back over water.

Once all these biases were taken out, the dataset of 24-h periods was created. As mentioned before, the only 24-h periods of non-RI cases included in this dataset were the ones in which the maximum sustained wind increased gradually or remained the same during each 24-hour period. One of the main comparisons made of this study was between RI and non-RI cases and how their sizes differed from each other. Given that the RI cases only included the periods of rapid intensification, in order to accurately compare them with the rest of the tropical cyclones, the periods in which the maximum sustained winds intensified or remained the same in the non-RI cases had to be included. Therefore, decaying parts of the tropical cyclones in the non-RI cases were removed. Lastly, as previously stated in the size parameters section, only none zero numbers were averaged when finding the mean of the four quadrants of 34 kt radii.

After removing all the biases, out of the 280 tropical cyclones from that occurred from 1990 to 2010, a total of 205 tropical cyclones were used in this study (120 non-RI and 85 RI). The 24 hour dataset contains 1,312 twenty-four hour periods: 1,016 non-RI cases and 296 RI cases.

2.7 Size Climatology

In his 1984 paper, Merrill formulates size categories for ROCI in the Atlantic Basin; he concludes that small/medium tropical cyclones are ≤ 3° latitude (180 nmi) and large tropical cyclones are ≥ 4° latitude (240 nmi). Given that three different size parameters are being used and compared in this study, a size classification is defined for each of the parameters.

In order to accurately assess the different sizes of the tropical cyclones being used, the size climatology is calculated using only the storms being investigated in this study: 205 out of the 280 total tropical cyclones during 1990-2010. The data used in the size classification is from the excel spreadsheet that contains the entire life cycle of each tropical cyclone in 6-hour intervals. The 24-hour dataset is not used because it only contains the size of each parameter at the beginning of an intensification (RI and non-RI) or stable period (non-RI) therefore missing the rest of each storm's life cycle. The data consists of 5,132, 5,239 and 5,264 six hour intervals of RMW, ROCI and Ave 34 kt radii, respectively.

For each size parameter (RMW, ROCI, and Ave 34 kt radii) the small and large sizes are categorized using the 25^{th} and 75^{th} percentile of the size distribution. Hence, tropical cyclones are considered small if the RMW ≤ 20 nmi, medium if > 20 and < 48 nmi, and large if ≥ 48 nmi (Table 2.3). When using ROCI as the size parameter a tropical cyclone is classified as small if the size ≤ 151 nmi, medium if > 151 and < 235 nmi, and large if ≥ 235 nmi (Table 2.4). And

Table 2.3

Size Climatology Based on RMW

Size of Tropical Cyclone	**Size (nmi)**	**Size (°lat)**
Small	≤ 20	≤ 0.33°
Medium	20 < med < 48	0.33° < med < 0.8°
Large	≥ 48	≥ 0.8°

Table 2.4

Size Climatology Based on ROCI

Size of Tropical Cyclone	**Size (nmi)**	**Size (°lat)**
Small	≤ 151	≤ 2.52°
Medium	151 < med < 235	2.52° < med < 3.92°
Large	≥ 235	≥ 3.92°

Note. The 25^{th} and 75^{th} percentile of the size distribution are used to categorize small and large tropical cyclones in Tables 2.3 and 2.4.

lastly if the average 34 kt radius is being used as the size parameter, a tropical cyclone is categorized as small if ≤ 59 nmi, medium if > 59 and < 135 nmi, and large if ≥ 135 nmi (Table 2.5).

Table 2.5

Size Climatology Based on Average 34 kt Radii

Size of Tropical Cyclone	**Size (nmi)**	**Size (°lat)**
Small	≤ 59	≤ 0.98°
Medium	59 < med < 135	0.98° < med < 2.25°
Large	≥ 135	≥ 2.25°

Note. The 25th and 75th percentile of the size distribution are used to categorize small and large tropical cyclones in Table 2.5.

Liu and Chan (2002) also use the 25th and 75th percentile of size distribution but it is employed on tropical cyclones of the western North Pacific. Since Merrill's (1984) climatology tropical cyclone size (Table 2.6) confirms that tropical cyclones of the western North Pacific are

Table 2.6

Comparison of Size Climatology of Merrill (1984) and This Study

Size of Tropical Cyclone	**Merrill (1984)**	**This study**
	Size (°lat)	
Small[a]	≤ 3°	≤ 2.52°
Medium		2.52° < med < 3.92°
Large	≥ 4°	≥ 3.92°

Note. This table compares the size categories for the ROCI size parameter made by Merrill (1984) and the ones made in this study.

[a]Refers to small/medium for the Merrill study. He did not specify a medium range; he grouped small and medium together.

characteristically twice as large as their Atlantic counterparts, a comparison of Liu and Chan's findings will not be made. Table 2.6 shows how the ROCI size categories developed by Merrill (1984) are comparable to the ROCI size categories used in this study.

2.8 Interpreting Results Using the T-Test

The T-Test is used in this research in order to clarify some of the results. Because some of the results will be comparing the difference between the RI and non-RI tropical cyclones and the difference between the small and the large tropical cyclones, then the T-Test is the most appropriate to use. The T-Test assesses whether the means of the two groups being compared are statistically different from each other (Trochim, 2006). For example, when looking at the differences between the average RMW for RI and non-RI storms, the T-Test will help determine the difference between their means relative to the spread or variability of the RMW.

The "TTEST" function in excel is used in this study. When using this function in excel, it asks to input the following: Array 1, Array 2, tails, type. Array 1 is the first data set and Array 2 is the second data set being compared. For example, when comparing the average RMW for RI and non-RI tropical cyclones, Array 1 is the RI data set and Array 2 is the non-RI data set. Tails specifies the number of distribution tails. For this study, the two-tailed distribution is used (tails = 2). Type is the kind of T-Test that is performed. The two-sample unequal variance test is performed in this research (type = 3).

Once the "TTEST" function is performed in excel, the program returns a P-value. A P-value below 0.05 is generally considered statistically significant, while one of 0.05 or greater indicates the distribution is random (Burton, 2002).

CHAPTER 3

Analysis and Results

The rapid intensification process of a tropical cyclone continues to baffle many hurricane researchers and specialists. Every so often a case like Hurricane Humberto of 2007 comes along and adds to the confusion and amazement of how unpredictable the rapid intensification of a tropical cyclone can be. Hurricane Humberto was only a depression when it was 60 miles off the coast of Texas. During the short period of time it had over water before reaching land and with barely any warning, Humberto intensified to a Category 1 hurricane as it was about to make landfall. This goes to show that even with all the research being done on rapid intensification and the process that may cause it occur, it is still very difficult to forecast such an intensification in such a short period of time.

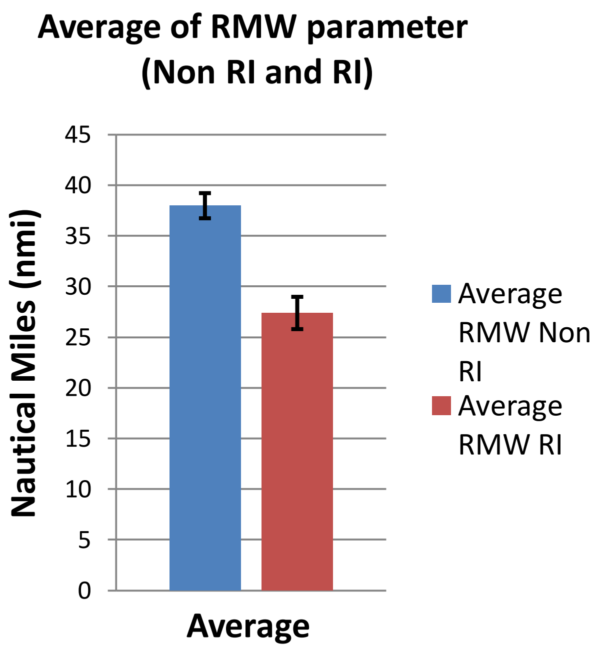
Storms like Hurricane Humberto are the main inspiration for this research. The major concern with tropical cyclones like Humberto is the fact that they could be so close to land and still undergo a rapid intensification cycle and cause a lot more damage than anticipated. Interactions with warm ocean waters and low vertical shear have been studied and have shown correlation with the rapid intensification of tropical cyclones. This research was conducted in hopes of finding out if something as simple as the size of the tropical cyclone could play any role in the intensification process. A correlation with size and intensification could help hurricane specialists possibly identify and anticipate a rapid intensification period just by knowing the size of the tropical cyclone.

The pivotal questions this research aims to answer are: Does the overall size of a tropical cyclone matter for allowing rapid intensification to occur, do different size parameters show different tendencies and if so, what would be the most reliable size parameter to use in order to detect a rapid intensification period. The main hypothesis is that smaller tropical cyclones will be more prone to rapid intensification. It is also hypothesized that the ROCI will be the best parameter to use when trying to identify if the tropical cyclone will undergo a period of rapid intensification since the ROCI measures the outer core or overall size of the tropical cyclone.

A series of comparisons are done in order to find any correlation between the size of a tropical cyclone and its ability to undergo rapid intensification. The data is distributed in various charts to show the relationship between the RI and non-RI storms, the change of intensity of each size parameter for RI and non-RI cases, and the frequency and distribution of the three different size parameters in RI cases. All are analyzed and discussed in the following sections.

3.1 RI vs. Non-RI

One of the objectives of this research was to compare the difference in size between the tropical cyclones that underwent rapid intensification with those that did not in order to see if there was any correlation between the two. Therefore, an average of the RMW, ROCI and 34 kt Radii was found and compared between the RI and non-RI cases (Figures 3.1a-c). When comparing the averages of all three size parameters in Figures 3.1a-c, it can be seen that non-RI storms have a tendency to be larger than the RI storms. However, Figure 3.1b shows that there is only a slight difference of about 2 nmi between the RI and non-RI cases for the ROCI parameter. In order to see if there was any significance in the difference between RI and non-RI storms, a T-Test was performed (Table 3.1). As previously mentioned, a P-value below 0.05 is considered to be statistically significant while a P-value of 0.05 or greater is not. The comparison between the RMW RI cases and the RMW non-RI cases results in a P-value of 4.76561E-23, or < 0.001. Hence, this shows that there is a statistical difference between storms that undergo rapid intensification and those that do not. A similar statistical significance (P-value = 1.11556E-07 or



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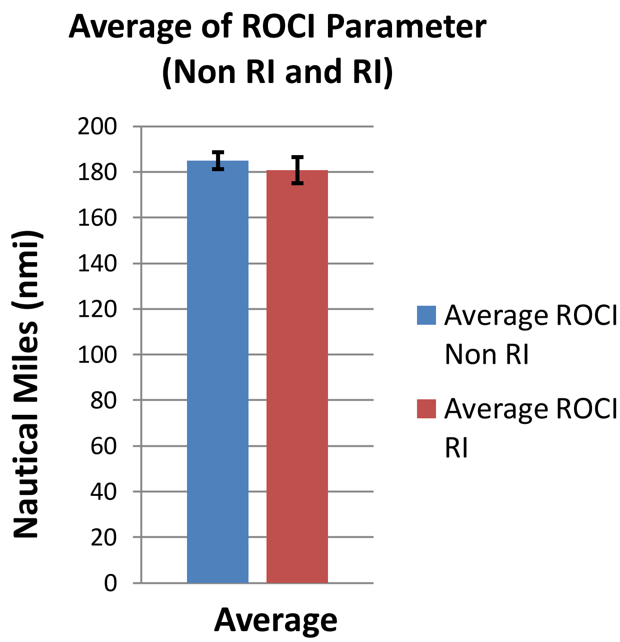

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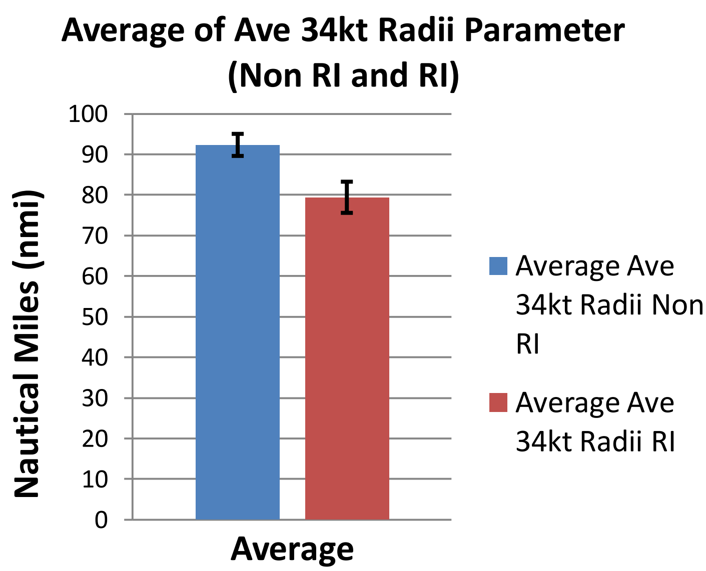


(c)

Figure 3.1. (a) Average of RMW parameter (RI and non-RI cases), (b) Average of ROCI parameter (RI and non-RI cases), (c) Average of Ave 34 kt radii parameter (RI and non-RI cases). 95% confidence intervals are also shown in each chart.

< 0.001) is seen with the average 34 kt radii parameter. However, the T-Test for ROCI parameter shows no statistical significance between the difference of RI and non-RI cases because the P-value found is 0.233739081 which is greater than 0.05.

Table 3.1

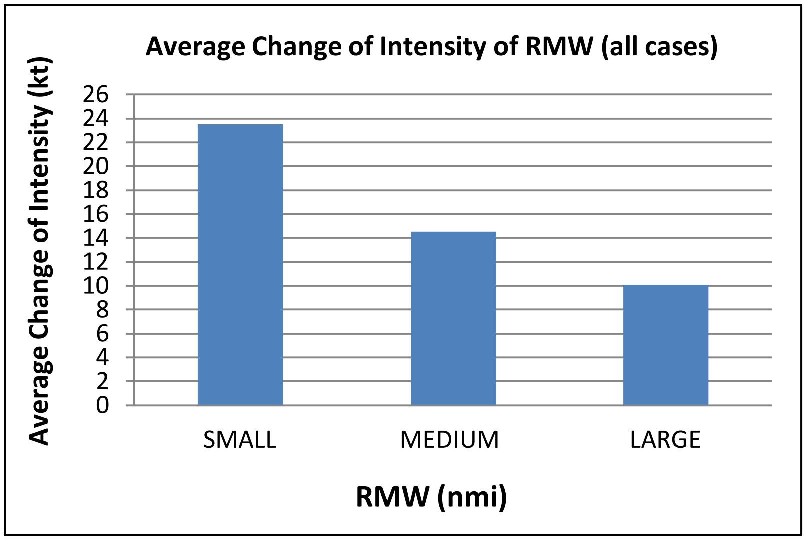
T-Test of RI vs. Non-RI

Size Parameter	**P-value**
RMW	< 0.000000001
ROCI	0.233739081
Ave 34kt Radii	0.000000111

Note. T-Test done for RI vs. non-RI for the average of each parameter in Figures 3.1a-c.

3.2 Size Parameters vs. Change of Intensity

Using the size climatology that was created for this study (Tables 2.3-2.5), each size parameter was divided into small, medium and large sizes for all cases (RI and non-RI). Figures 3.2a-c compare the amount of intensity change that occurs when the three size parameters are stratified into small, medium, and large. A strong correlation between the small tropical cyclones, measure by the RMW, and the change of intensity can be seen in Figure 3.2a. This trend that small tropical cyclones have a higher average change of intensity is also seen in Figure 3.2c, where the tropical cyclones are measured using the average 34 kt radii. The average 34 kt radii trend is not as distinct as the RMW trend as the medium sized storms have a very similar average change of intensity as the smaller storms. Nonetheless, both small and medium sized tropical cyclones measured by RMW and average 34 kt radii have a distinct greater intensity change than the larger sized tropical cyclones for both size parameters. On the other hand, Figure 3.2b shows how the ROCI parameter tends to have a bias towards larger sized storms, even though it shows that overall when combining non-RI and RI cases, the medium sized tropical



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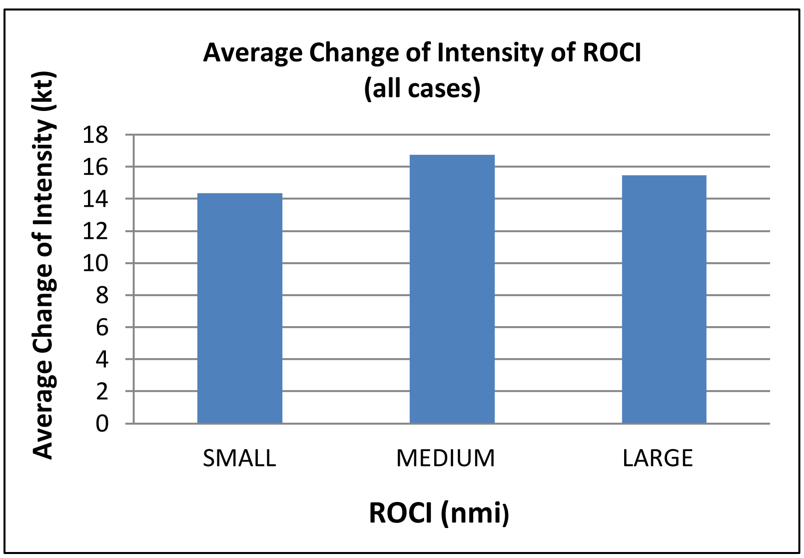
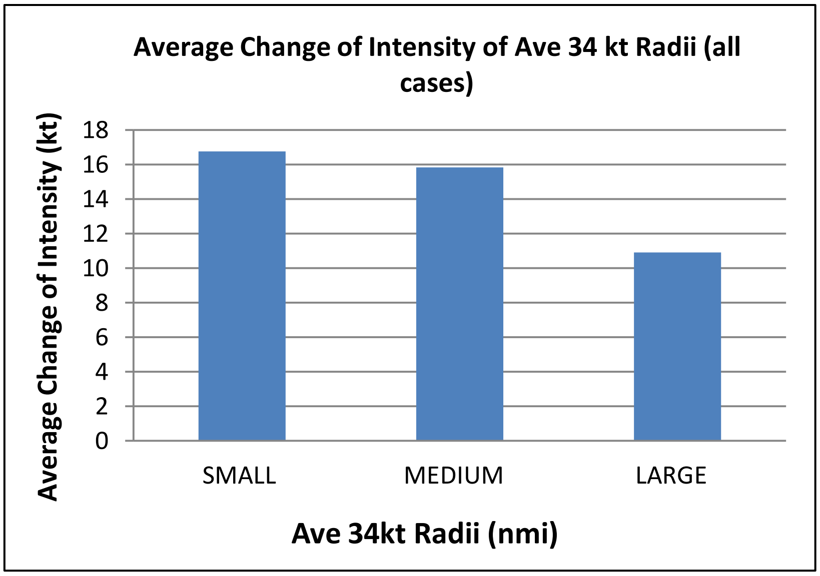


(b)

Figure 3.2. (a) Average change of intensity of small, medium, and large for all cases of RMW, (b) Average change of intensity of small, medium, and large for all cases of ROCI, (c) Average change of intensity of small, medium, and large for all cases of average 34 kt radii.



(c)

Figure 3.2. (cont).

cyclones seem to have a higher change of intensity. Yet, the larger storms are very close to the medium storms and still have a higher change of intensity than the smaller sized storms. A T-Test was performed for Figures 3.2a-c and it can be seen that the RMW and average 34 kt radii are statistically significant (Table 3.2). However, Table 3.2 shows that the ROCI size parameter again does not appear to be significant function for intensity change.

Table 3.2

T-Test of Small vs. Large

Size Parameter	P-value
RMW	< 0.00000001
ROCI	0.34836936
Ave 34kt Radii	0.00000732

Note. This table shows a T-Test of small vs. large for each size parameter in Figures 3.2a-c.

Scatter plots were created to show the overall distribution of each individual size of every parameter (RMW, ROCI and average 34 kt radii) and the 24-hour change of intensity it had when the tropical cyclone was that specific size (Figures 3.3-3.5). These plots contain both RI and non-RI cases (all 1,312 twenty-four-hour periods) and the red lines show the breakdown of small, medium, and large sizes for each size parameter. Right away it can be clearly seen that the

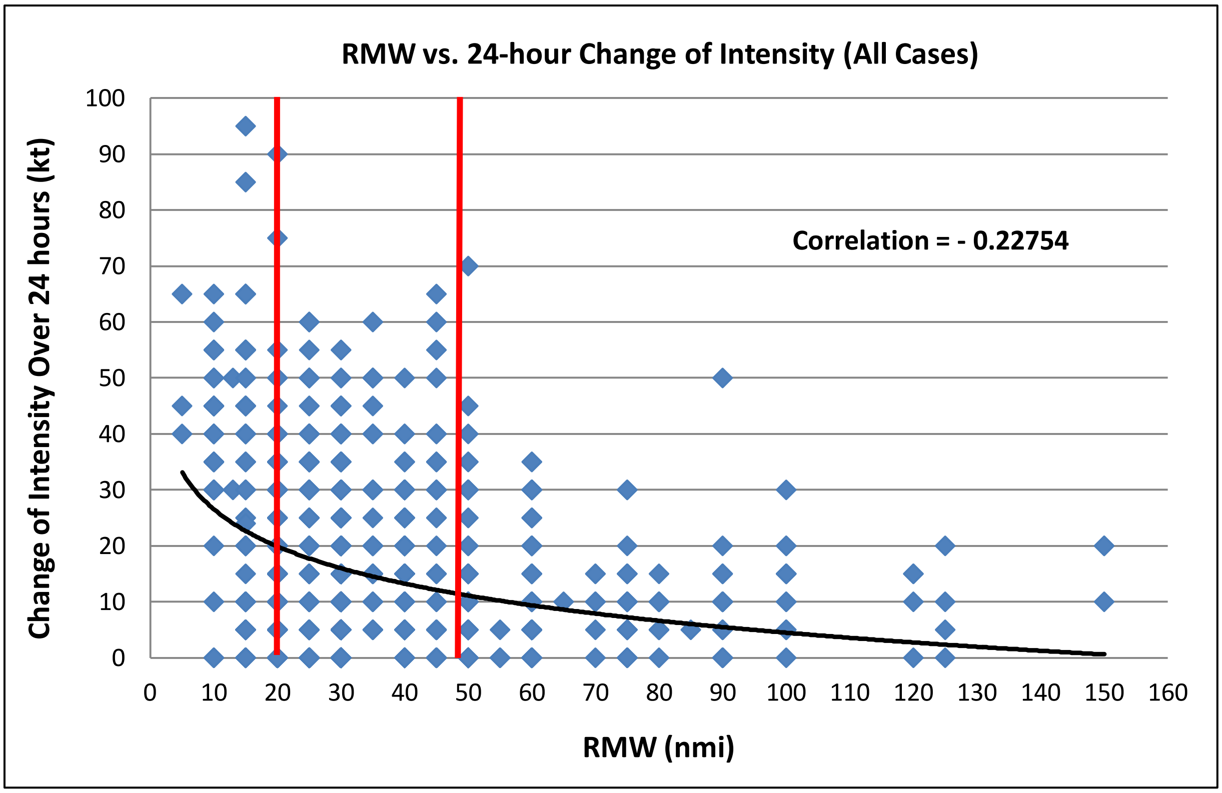


Figure 3.3. Change of intensity over 24 hours of all cases using RMW size parameter. The two red lines separate the small, medium and large boundaries. The black line represents the logarithmic trend line.

greatest change of intensity happens within the smaller storms when using RMW as a size parameter (Figure 3.3). Also, most of the data points appear to be within the small and medium boundaries. Furthermore, this figure shows that there is a negative correlation between the change of intensity and the RMW. This negative correlation suggests that as the RMW increases (or the tropical cyclone becomes larger), overall the subsequent intensity change is not as great or decreases.

Conversely, Figure 3.4 shows basically no correlation between the change of intensity and the ROCI size parameter. All data points are especially scattered and all appear to be equally scattered within the small, medium and large boundaries.

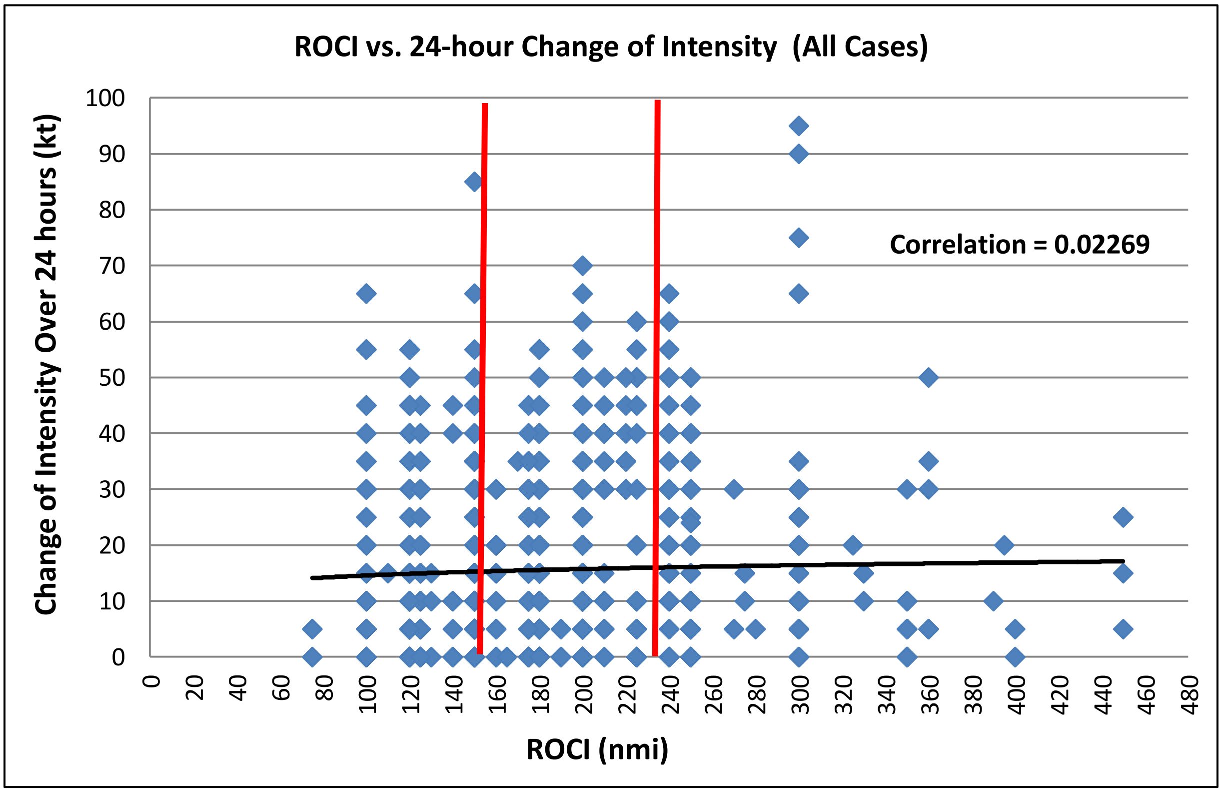


Figure 3.4. Change of intensity over 24 hours of all cases using ROCI size parameter. The two red lines separate the small, medium and large boundaries. The black line represents the logarithmic trend line.

However, when looking at Figure 3.5, a similar correlation to the one seen in Figure 3.3 can be observed. Figure 3.5 illustrates a negative correlation between the change of intensity and the average 34 kt radius. Comparable to Figure 3.3, Figure 3.5 also shows that the majority of the data points are located with the small and medium size boundaries. Yet, this distribution is more apparent in Figure 3.5. In addition, the data is more unified or less scattered than the other two figures. This is due to the fact that the average 34 kt radius is best-tracked by NHC and the RMW and ROCI are not.

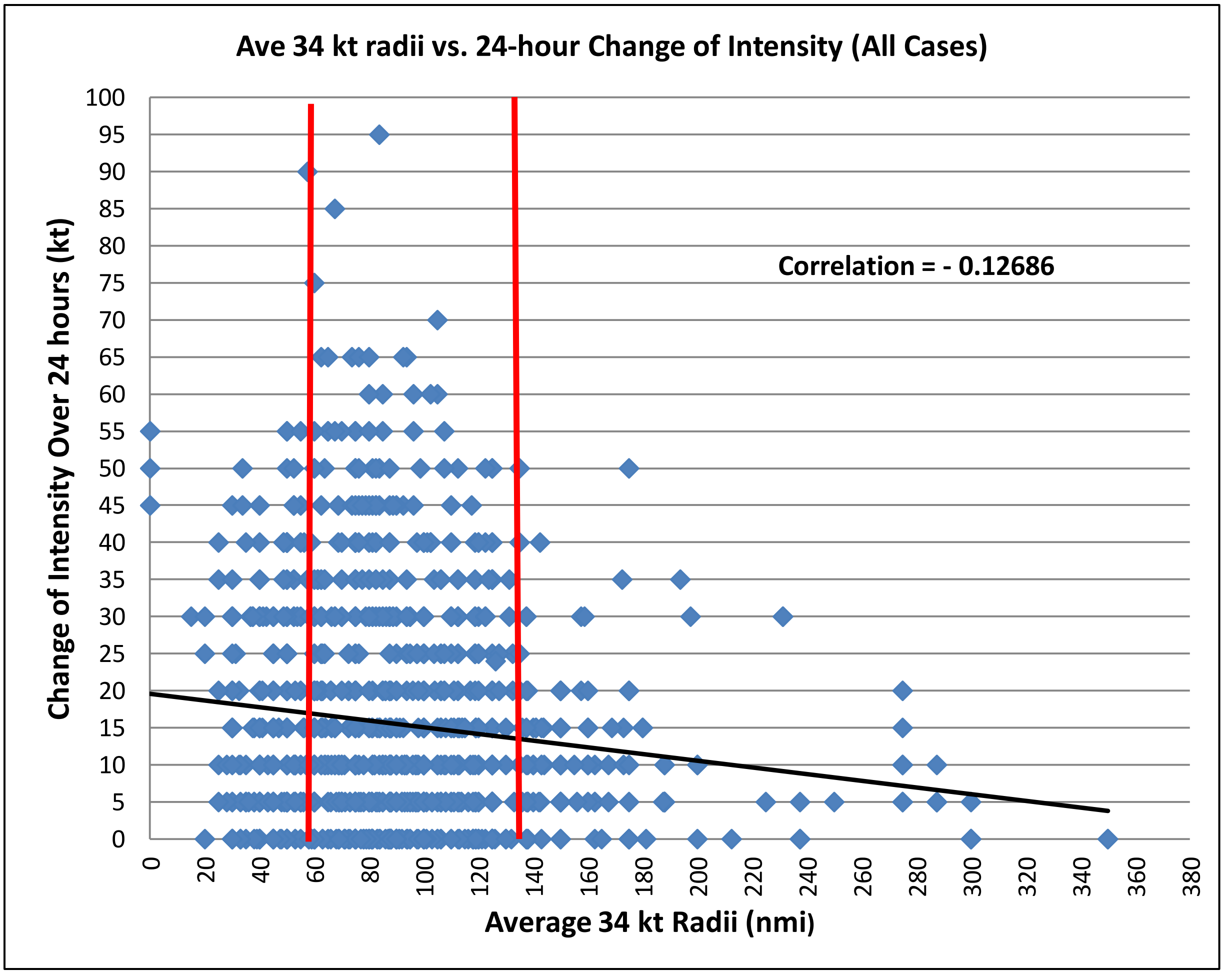
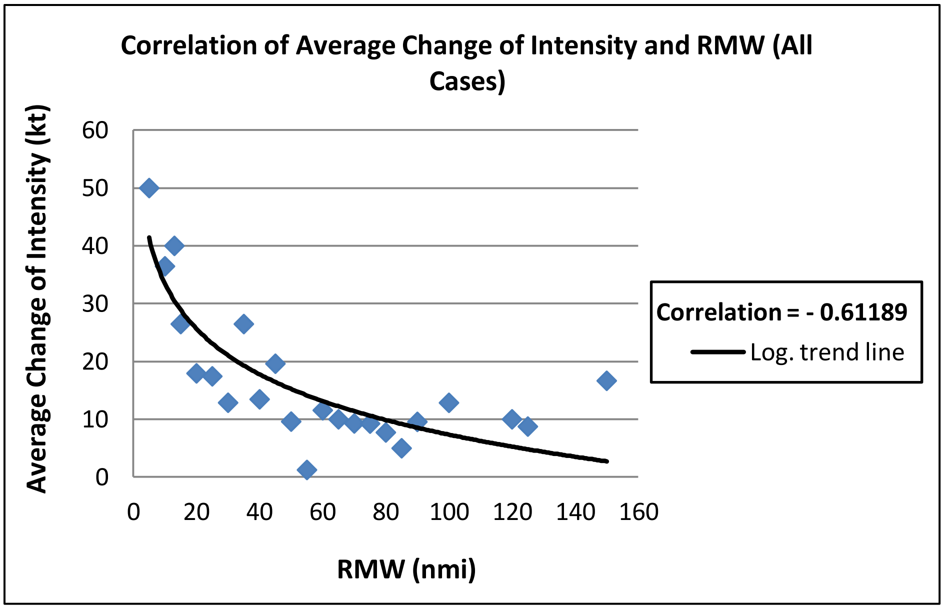
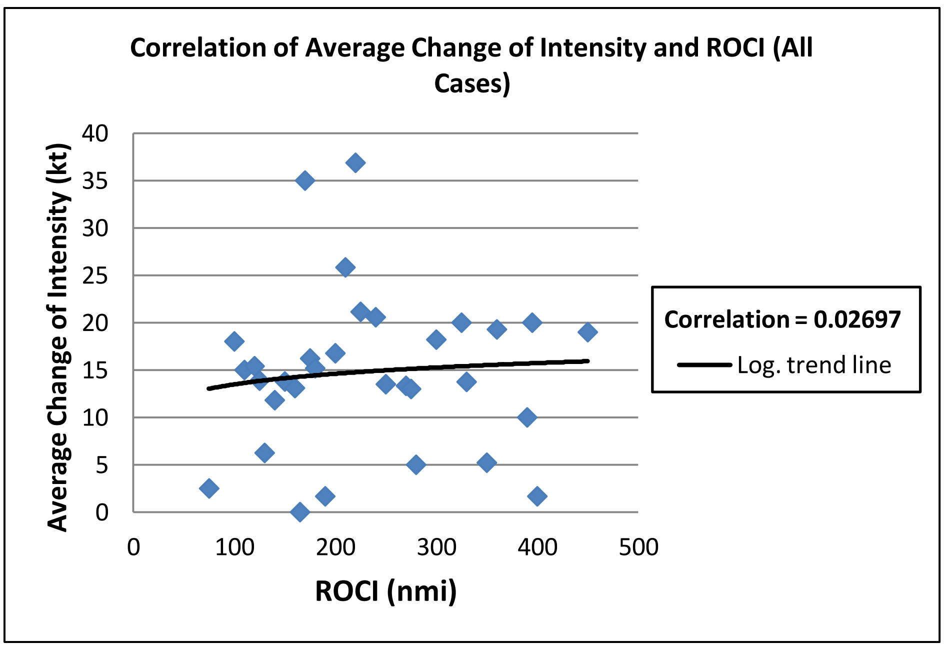


Figure 3.5. Change of intensity over 24 hours of all cases using average 34 kt radii size parameter. The two red lines separate the small, medium and large boundaries. The black line represents the logarithmic trend line.

To better demonstrate a correlation, the average change of intensity was calculated for each individual radius of the RMW, ROCI, and average 34kt radii parameters. These plots can be seen in Figures 3.6a-c. A very nice relationship is seen in Figures 3.6a and 3.6c with the greatest

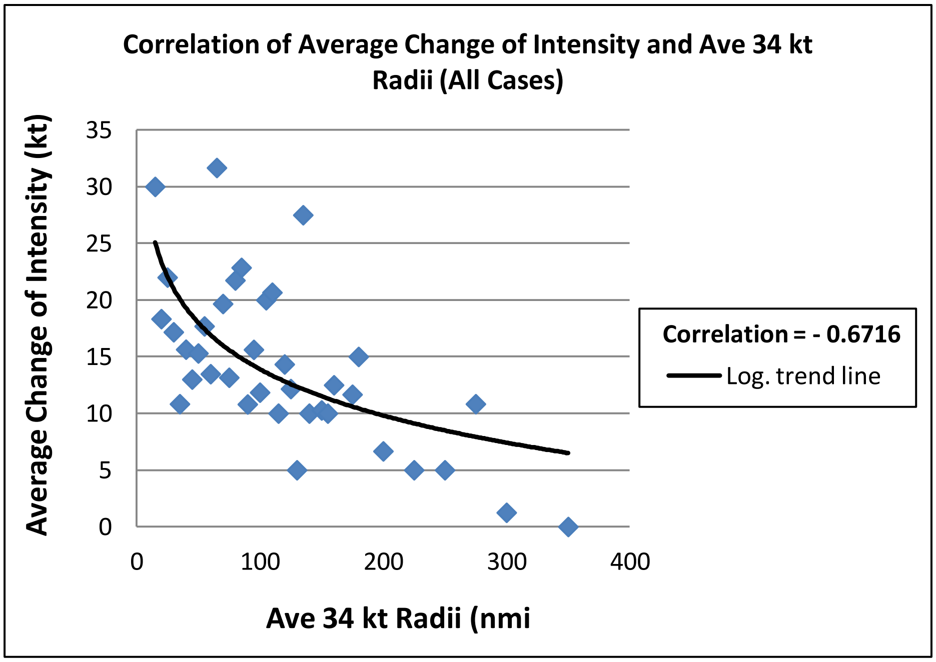


(a)



(b)

Figure 3.6. (a) Correlation of average change of intensity and RMW (all cases), (b) Correlation of average change of intensity and ROCI, (c) Correlation of average change of intensity and average 34kt radii. Black line is the logarithmic trend line.



(c)

Figure 3.6. (cont).

correlation shown in Figure 3.6c with the average 34 kt radii, followed by Figure 3.6a with the RMW. This data shows a tendency for the smaller tropical cyclones to have a greater average change in intensity for the RMW and average 34 kt radii parameters, where as in the ROCI case it is close to no tendency. Moreover, it can be deduced that based on ROCI measurements, tropical cyclone size does not matter or matter much less to the average change of intensity.

In order to see what happens during the rapid intensification cases, the same sets of scatter plots as the ones seen in Figure 3.3-3.5 were produced but only for the RI cases (Figures 3.7-3.9). Figure 3.7 is even more obvious than Figure 3.3 in showing that most of the data points are located within the small and medium categories. The difference between these two scatter plots is that Figure 3.3 includes all cases (RI and non-RI) and Figure 3.7 only contains the RI cases. Therefore, Figure 3.7 indicates that most of the RI cases occur when the tropical cyclone is small or medium. The fact that the data points are mostly in the small and medium boundaries is so noticeable that it gives the impression that there is a threshold for RI. It can be seen that once the RMW is past 50 nmi, it is very difficult for a tropical cyclone to undergo RI.

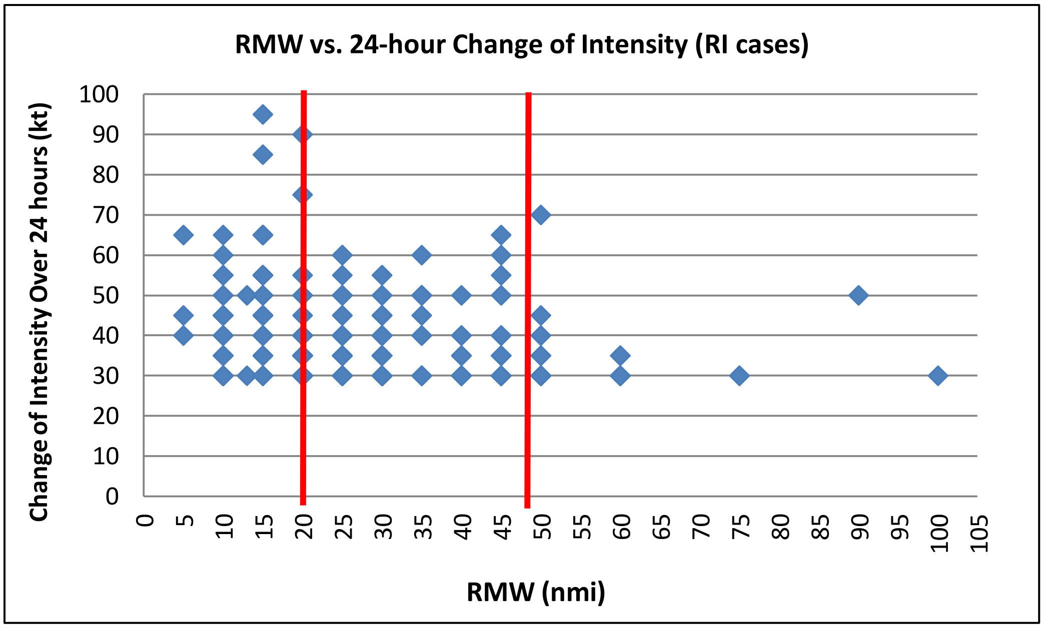


Figure 3.7. Change of intensity over 24 hours of RI cases (296 cases) using RMW.

In contrast, Figure 3.8 shows an equal distribution of data points amongst all three

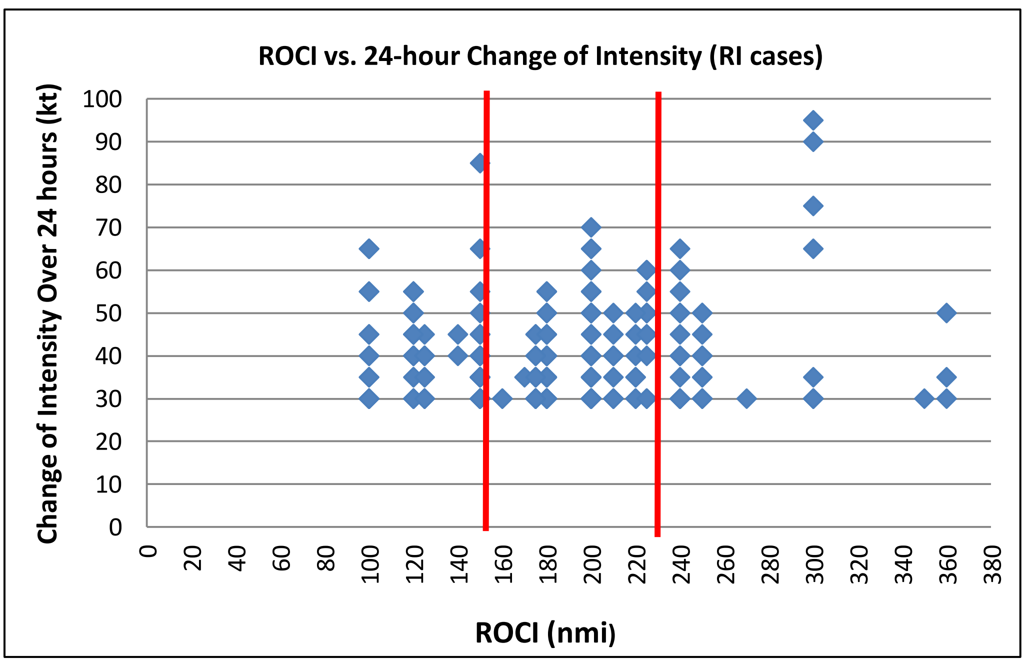


Figure 3.8. Change of intensity over 24 hours of RI cases (296 cases) using ROCI.

sizes (small, medium, and large). It also does not show a threshold for RI like the RMW parameter.

Similar to the RMW, the average 34 kt radii parameter also shows that there is a threshold for RI (Figure 3.9). It can be seen that a minimum amount of cases underwent RI when the tropical cyclone had an average 34 kt radius greater than 140 nmi.

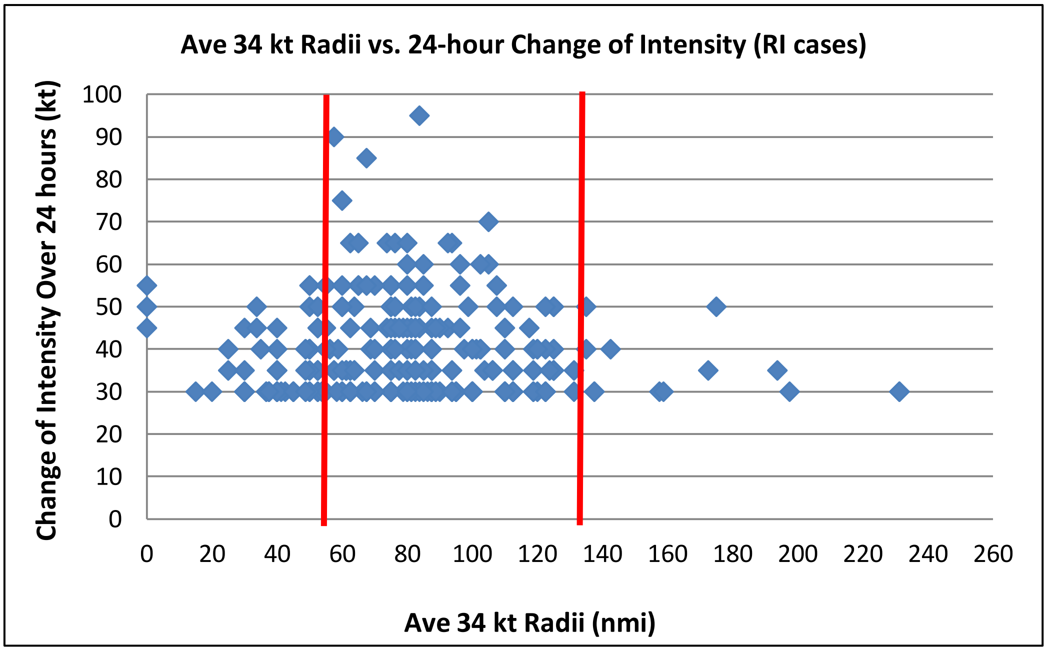
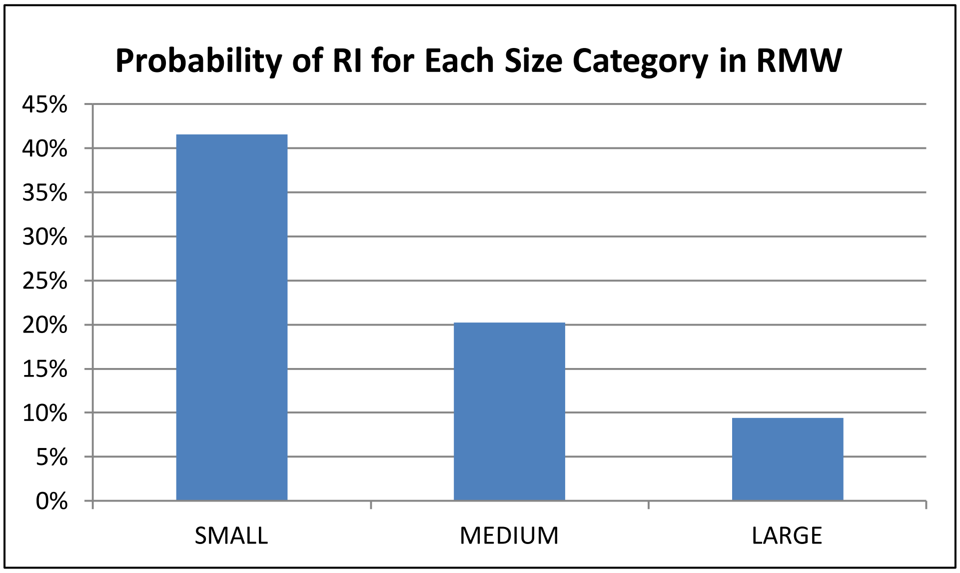


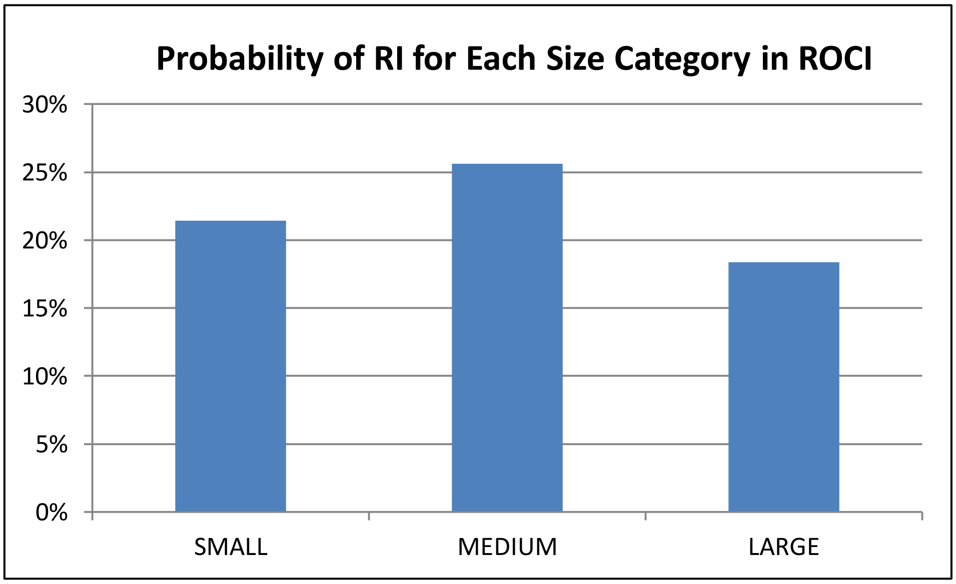
Figure 3.9. Change of intensity over 24 hours of RI cases (296 cases) using average 34 kt radii size parameter. The two red lines separate the small, medium, and large boundaries.

3.3 Frequency and Distribution of Size Parameters in RI Cases

Lastly, three charts were made to show the probability of RI for each size category (small, medium, large) for RMW, ROCI, and average 34 kt radii parameters (Figures 3.10a-c). These figures basically demonstrate the percent of small (medium or large) cases that underwent RI out of the total number of small (medium or large) cases. Figure 3.10a illustrates that in the past two decades, a small tropical cyclone is four times more likely to go through rapid intensification than a large tropical cyclone, when using the RMW parameter. Figure 3.10c shows that when using the average 34 kt radii parameter, it is three times more likely for a small tropical cyclone to have a rapid intensification period than a large tropical cyclone. Finally, in

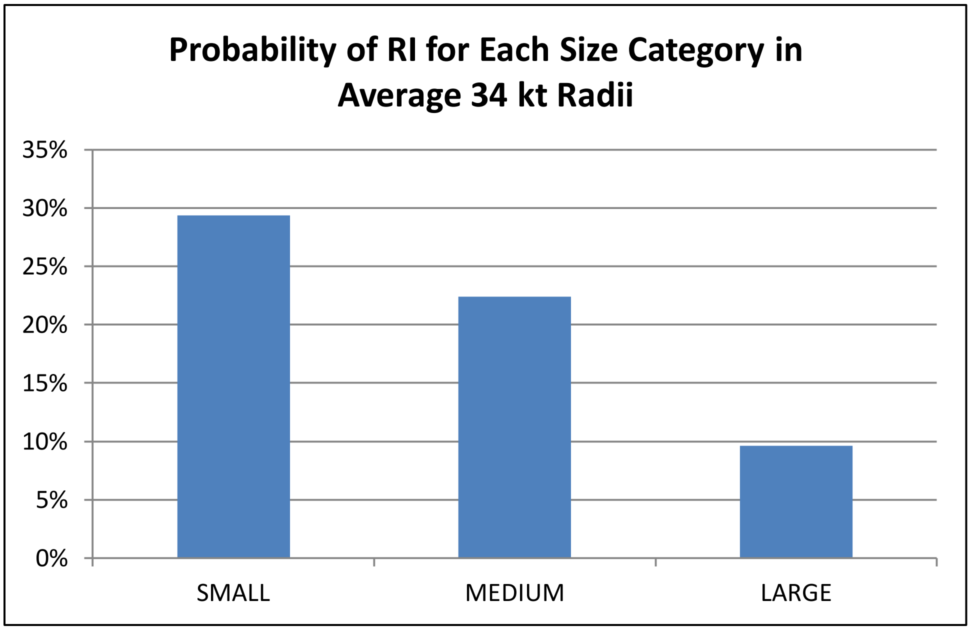


(a)



(b)

Figure 3.10. (a) Probability of RI for each size category in RMW, (b) Probability of RI for each size category in ROCI, (c) Probability of RI for each size category in average 34 kt radii.



(c)

Figure 3.10. (cont).

the case of the ROCI parameter, the probability of a tropical cyclone to undergo rapid intensification is essentially the same for small, medium, and large storms. There is less than a 10% difference between each size category, thus showing that ROCI is not a good size parameter to use when looking for potential RI cases.

CHAPTER 4

Conclusions

When regarding rapidly intensifying storms, there seems to be some sort of sensitivity to the initial size. As indicated by Figures 3.1a-c, in average for the years between 1990 and 2010, rapidly intensifying tropical cyclones appear to be smaller than the tropical cyclones that did not have any rapid intensification periods. Non-RI storms are approximately 10 nmi larger than the RI storms when using RMW and average 34 kt radius as the size parameters and the findings are statistically significant. This parallels DeMaria's findings in 1994 when describing the SHIPS model; it is mentioned that the size variable was smaller than average for rapidly intensifying cases. In contrast, when using ROCI as the size parameter, there is only a 2 nmi difference between the non-RI and RI tropical cyclones. The T-Test (Table 3.1) performed for Figures 3.1a-c confirms that the difference between the non-RI and RI storms is not statistically significant when using the ROCI parameter.

When comparing the three size parameters with the subsequent change of intensity, it showed that the initial RMW and the initial average 34 kt radius have a strong negative correlation with the change of intensity. When using RMW as a size parameter, there is a tendency for smaller tropical cyclones to have a higher subsequent change of intensity. This is also seen when using the average 34 kt radius as a size parameter, but it is not as distinct. Nonetheless, both small and medium tropical cyclones have a noticeably greater intensity change than the larger tropical cyclones.

The scatter plots depicting the RMW and average 34 kt radii versus the change of intensity for RI cases interestingly show that most of the RI cases fall between the small and medium size boundaries. Figures 3.7 and 3.9 give the impression that a threshold for RI exists:

about 50 nmi for RMW and 135 nmi for the average 34 kt radius size parameter. For both size parameters, the thresholds lie at the boundary separating the medium and large storms, suggesting that once the tropical cyclone is larger than the thresholds it is very difficult for it to undergo rapid intensification.

There is a higher correlation between the size parameters (average 34 kt radii and RMW) and the change of intensity for the RI cases. However, no correlation was found between the ROCI and the subsequent change of intensity when comparing all cases or just RI cases. The T-Tests performed and this finding help conclude that the ROCI may not be a good measure to use when trying to predict possible RI periods in tropical cyclones. This is probably due to the way the ROCI is measured. The ROCI measures the outermost core of the tropical cyclone. However, the outer-most closed isobar can sometimes be located outside the main energy of the storm therefore not really being a good measure of the actual size of the storm. On the other hand, the RMW and 34 kt wind radii are both wind measurements and maximum winds and gale winds are always located within the core or the main energy of the tropical cyclone.

The frequency charts demonstrate that the highest percentage of RI occurrences come from the medium and small tropical cyclones. This, along with the other results, appear to demonstrate a pattern that RMW and average 34 kt radii are the best size parameters to use when seeing if the tropical cyclones will undergo RI. Overall, there is a consistent signal that smaller storms have a larger change of intensity. Finally, when looking at all the RI storms used in this study (of the past two decades), a tropical cyclone is 3 and 4 times (when using average 34 kt radii and RMW as parameters, respectively) more likely to undergo rapid intensification if it is small rather than large (Figures 3.10a-c).

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