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A Case Study of Hurricane Katrina: Rapid Intensification in the Gulf of Mexico

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Abstract

On August 28, 2005, Hurricane Katrina encountered the Gulf Loop Current in the Gulf of Mexico and, over the next 18 hours, experienced a strong period of rapid intensification (RI). Katrina intensified overnight from a Category 3 to a Category 5 hurricane on the Saffir-Simpson scale and, with a central pressure of 902-hPa, became the fourth most intense Atlantic Hurricane on record as of that time. This paper examines Katrina's RI phase by examining five factors considered to be important in predicting RI: previous 12-hour intensity change, sea surface temperature, low-level relative humidity, vertical shear, and the difference between the current intensity and maximum potential tropical cyclone intensity. In analyzing Katrina, the values for these five variables were calculated for every six hours of the 18-hour RI period. The values of these five variables were compared to a database of both RI and non-RI cases. The results show that 4 out of 5 of Katrina's conditions agreed with those present in the majority of other RI tropical cyclones.
Keywords: Katrina, Hurricane, Rapid Intensification

1. Introduction

There are many factors that influence hurricane development and intensification. The most well-known and perhaps most important of these factors is sea surface temperature (SST). Through the interaction between the ocean and the atmosphere, heat is transferred from the water to the hurricane, allowing it to become more intense. The higher the SST, the more heat flux there is and the stronger the hurricane can become. The passage of tropical cyclones (TCs) over the ocean also causes upwelling, however, which mixes the colder, deeper water with the warm water at the surface. If the layer of warm water is shallow, this upwelling can work against the TC by bringing the cool water to the surface and lowering the heat flux. Therefore the ocean water ought to be warm at depth as well as the surface to support RI. This dynamic relationship between TC intensity and SST has been documented in many observational studies, including the study of Hurricane Opal by Hong et al.[1] and the study of the interaction between TCs and the ocean by Chang and Anthes[2].

In addition to the conditions present in the ocean, the vertical structure of the atmosphere is also important in TC intensification. If high vertical wind shear is present, it can tear apart the structure of the TC before it has a chance to strengthen. Therefore, low vertical wind shear is ideal. Kaplan and DeMaria[3] have also shown that low-level relative humidity plays an important role in TC intensification. In observed TC cases, relative humidity has generally been higher in cases where RI has occurred than those where it did not.

In order to explore Kaplan and DeMaria's RI predictors in more detail, Hurricane Katrina (2005) has been selected for this study. Out of all of the TCs from the 2005 season, Hurricane Katrina is perhaps the most ideal to study the causes of RI because of its unusually strong intensification. In this study, RI is defined as a 30 kt or more increase in intensity over a 24-hour period. Upon entering the Gulf of Mexico on August 26 of last year, Katrina experienced two such periods of RI. The first began at 0600 UTC on August 26, just after passing over the tip of Florida, and lasted 24 hours before being disrupted by an eyewall replacement cycle[4]. In an eyewall replacement cycle, the inner eyewall deteriorates while a larger, outer eyewall forms around it. This temporarily prevents the storm from becoming any stronger. The second instance of RI started at 0000 UTC on August 28 and continued until 1800 UTC on that same day. This second period of RI, which caused Katrina to intensify from a Category 3 to a Category 5 hurricane overnight, is analyzed in this paper.

In their paper on large-scale characteristics of tropical cyclones with RI, Kaplan and DeMaria[3] looked at all Atlantic basin TCs that developed from 1989 to 2000 and determined five factors important in RI. These factors were the previous 12-hour intensity change (DVMX), SST, low-level relative humidity (RHLO), vertical shear (SHR), and the difference between current intensity and the maximum potential TC intensity (POT). The exact meaning of these variables will be discussed later. Kaplan and DeMaria's conclusion was that these five variables were the most important factors in determining if TCs will undergo RI or not. They assert that the chances of RI go up from 1% to 41% when all five of these factors fall within their optimal RI ranges.

The goal of this paper is to compare the values of these five variables in Hurricane Katrina at all four times that it was undergoing its second period of RI – 0000, 0600, 1200, and 1800 UTC on August 28, 2005 – and comparing these to the means calculated by Kaplan and DeMaria[3]. Because Hurricane Katrina had such a impressive period of RI, it is expected that the values of these variables will have a strong correlation to those in the Kaplan study that underwent RI. This study is important because, if the correlation is a strong one, it will further support Kaplan's conclusions and show that these factors have a significant influence on whether a TC will undergo RI or not.

2. Synoptic History of Hurricane Katrina

Hurricane Katrina began as Tropical Depression Twelve over the southeastern Bahamas. It was formed by the merging of the remains of Tropical Depression Ten, a tropical wave, and an upper-level trough on August 21, 2005. Two days later, on August 23, the National Hurricane Center (NHC) reported the formation of a tropical depression and from then on it was monitored as it began its journey toward the United States. On August 24 it was upgraded to a tropical storm and a day later, on August 25, it was named the fifth hurricane of the 2005 season. Two hours later, at 2230 UTC, it made landfall on the southern tip of Florida, near Miami, as a Category 1 hurricane. Katrina weakened over land but emerged into the Gulf of Mexico at 0600 UTC on August 26 with its well-defined eye still intact and visible.

Hurricane Katrina's "best track"[5] path over the Gulf of Mexico is shone in Figure 1. Initially, the NHC forecast predicted that it would curve northward soon after entering the Gulf and make for the panhandle of Florida. Rather than doing this, however, Katrina maintained a more southwesterly path, maintaining that track over the Gulf for another day before turning to the northwest and heading towards New Orleans. The maximum sustained wind speed upon first emerging over water again was 65 kt, but soon, due in large part to the warm waters of the Gulf Loop Current, it began its first period of RI. Beginning at 0600 UTC on August 26, Katrina increased 30 kt over the next 24 hours. At 1200 UTC on the next day maximum winds increased to 100 kt, making Katrina a Category 3 hurricane. At this time Katrina was 365 nautical miles southeast of the opening of the Mississippi River. After this RI period Katrina underwent an eyewall replacement cycle, limiting any further intensification. In Katrina's case,

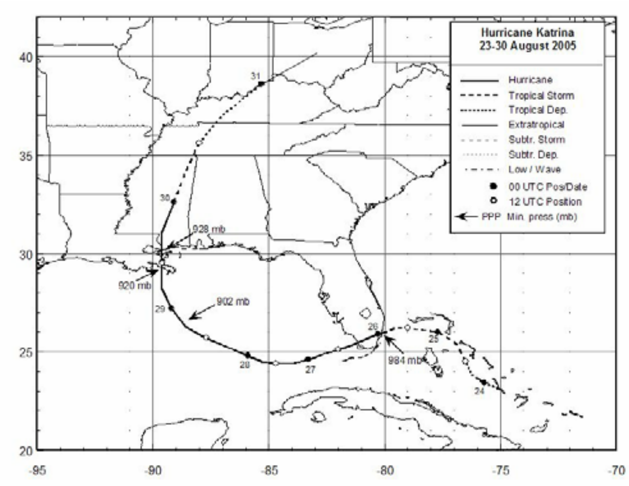

Figure 1. National Oceanic and Atmospheric Administration's (NOAA) best track positions for Hurricane Katrina. Reprinted courtesy of NOAA.

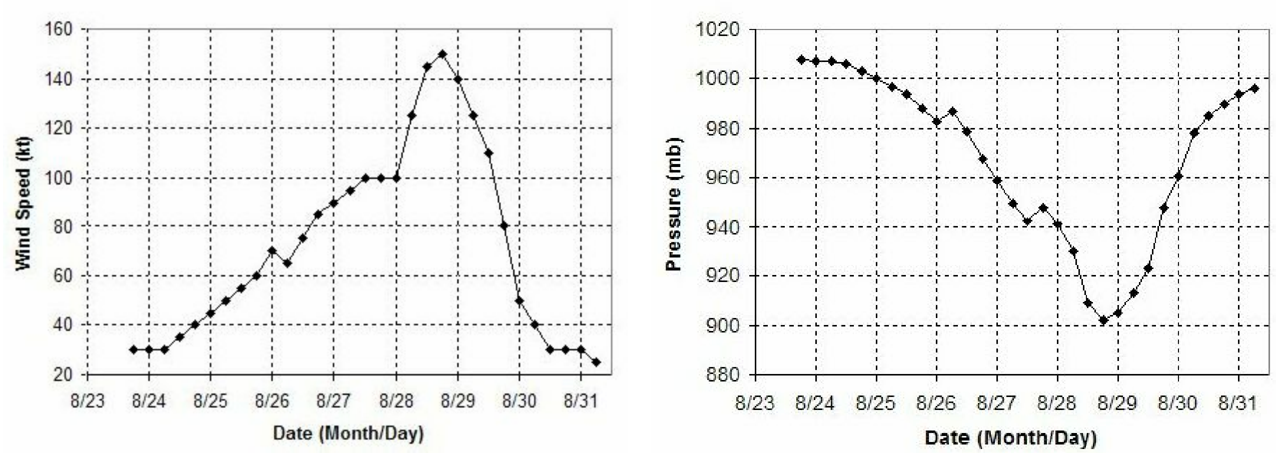

Figure 2. Best track maximum sustained surface wind speed curve [left] and minimum central pressure curve [right] for Hurricane Katrina, August 23-31, 2005.

this also led to an almost doubling of the size of the storm. By August 27, tropical storm force winds extended 140 nautical miles out from its center.

The steering current during this time had been defined by a strong troposphere ridge on the middle and upper levels. During the day of August 27, this ridge began to shift eastward, allowing Katrina to turn to the northwest.

The second period of RI, and the focus of this paper, began at 0000 UTC on August 28. By 1200 UTC, Katrina had become a Category 5 storm. By 1800 UTC it reached its peak intensity, with sustained winds as high as 150 kt. At this time it also reached its minimum central pressure of 902-hPa. Figure 2 shows the time series of maximum sustained surface wind and minimum central pressure over the lifetime of the storm.

At the beginning of August 29, Katrina was about 170 nautical miles south of the mouth of the Mississippi River. It soon entered another eyewall replacement cycle and, as the inner eyewall deteriorated, it quickly began to weaken. This decrease of intensity might have also been caused by a slight increase in wind shear and cooler SSTs[5]. By the time it made landfall on August 29, Katrina had weakened to a Category 3 hurricane with sustained winds of 110 kt. Katrina did extensive damage to much of Louisiana and Alabama before finally being down-graded to a tropical depression and then being absorbed into a frontal boundary in southeastern Canada on September 1.

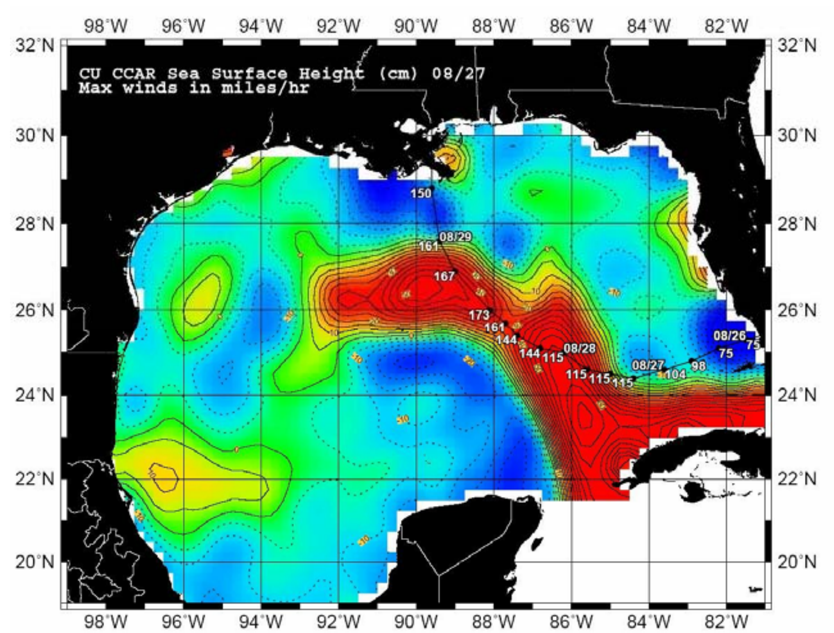

Figure 3. Sea surface height (cm) for the Gulf of Mexico on August 27. Katrina's track is superimposed on top of this. Reprinted courtesy of the Colorado Center for Astrodynamics Research (CCAR).

Table 1. Definitions of variables used in this study.

Variable	*Units*	*Definition*
VMX	m s^{-1}	Maximum sustained surface wind speed
LAT	°N	Latitude
LON	°W	Longitude
DVMX	m s^{-1}	Intensity change during the previous 12 hours
SST	°C	Sea surface temperature
MPI	m s^{-1}	Maximum potential intensity
POT	m s^{-1}	Storm potential; MPI – VMX
UGRD	m s^{-1}	Zonal component of wind
VGRD	m s^{-1}	Meridional component of wind
SHR	m s^{-1}	850–200-hPa vertical shear averaged from r = 200-800 km
RHLO	%	850–200-hPa relative humidity averaged from r = 200-800 km

3. Data and Methodology

At the beginning of the second period of RI, at 0000 UTC on August 28, Katrina was located at 24.8°N, 85.9°W. It had entered the Gulf of Mexico 42 hours earlier and was passing over an area of unusually warm water. This warm water, over 30°C at its center, was caused by gulf stream current, which frequently warms the water in the gulf basin. Figure 3 shows the sea surface height, which is used to illustrate SST. The red and yellow areas show warm areas of water while the blue areas stand for water that is cooler. This figure also illustrates the fact that Katrina remained over warm water throughout all 18 hours of its RI.

In collecting data to analyze in this study, several different sources were looked at. The main source of data was the Global Forecast System (GFS) archive located on the NOAA National Model Archive and Distribution System (NOMADS)[6]. GFS is a computer forecast model that generates weather forecasts from a databank of observed climatological values. For this study, the analysis (observational) field is being analyzed. NOMADS keeps GFS records at 1 degree resolution for every 6 hours going back to July 6, 2005. Data for August 28, 2005, at 0000, 0600, 1200, and 1800 UTC was acquired and, from this, the following variables were extracted: the relative humidity (RH) at 700, 750, 800, and 850-hPa, and the zonal (UGRD) and meridional component of wind (VGRD) at 200 and 850-hPa.

The SST information was downloaded from the Remote Sensing Systems (RSS) website[7]. RSS uses a blend of Advanced Microwave Scanning Radiometer (AMSR) and Tropical Rainfall Measurement Mission (TRMM) Microwave Imager (TMI) observations to record the temperature at the surface of the ocean. It stores daily SST values at a 0.25 degree resolution. The daily data for August 28 was used in this study.

Another source of data was the NOAA "best track" plot for Katrina[5]. The latitude (LAT), longitude (LON), and maximum sustained wind speed (VMX) was taken from this data every 6 hours. Table 1 defines all of the variables used in this study. This table is borrowed, in part, from Kaplan and DeMaria[3].

Using the gathered data, values for DVMX, SST, RHLO, SHR, and POT were calculated for the four time periods specified above. The variables were calculated as follows:

3.1. previous 12-hour change in maximum wind speed (DVMX)

DVMX is defined as the difference between the maximum wind speed at t = 0 and the maximum wind speed twelve hours earlier. The NOAA "best track" data is used for this because it gives the maximum surface wind speed in knots for every 6-hour period of time. Starting with 0000 UTC on August 28, the DVMX was calculated for all four of the times during which Katrina was undergoing its second period of RI.

Statistically, storms that underwent RI were intensifying faster than non-RI storms in the 12 hours before the start of RI. Therefore a higher DVMX indicates a higher likelihood of RI.

3.2. observed sea surface temperature (SST)

The SST data was decoded and used in an averaging program to determine the mean SST near the center of Katrina at all four times. The averaging program looks at all points within a certain radius of the center of the storm and averages them. This average is preferable to a single point because it reflects the most important area of water that

Katrina is interacting with rather than just the centermost temperature. It also reduces any noise that might occur in the data.

The averaging radius was initially chosen to be 50 km. After this, three more tests were run, increasing the size of the radius by 50 km each time. Because there was little difference between these values, the initial 50 km radius calculations were used for each point. This is reflective of the approximate size of the eye at that time. For each calculation there were 12 data points within the 50 km radius.

In the study by Kaplan and DeMaria[3], systems with RI typically had a higher SST than those without RI. This is because the transfer of heat through the ocean-atmosphere interface is what gives a TC its fuel.

3.3. 850–700-hPa relative humidity (RHLO)

The low-level RH was calculated by averaging the RH at the 850, 800, 750, and 700-hPa levels for all points within 200 and 800 km of the center of Katrina for each of the 4 time periods. This averaging includes 170 data points for 0600 and 1200 UTC, 167 points for 0000 UTC, and 168 points for 1800 UTC. The number of included data points for the first and last case is lower because some of the points were over land during those periods. The outputted value represents RH in the level where it is critical to hurricane intensification. Higher RH values are more favorable for RI because low-level moisture is a key requirement in maintaining the energy flow for the TC.

3.4. vertical shear (SHR)

The GFS data is once again used to calculate the SHR. In this situation, shear is calculated by subtracting the wind speed at 200-hPa from the one at 800-hPa for both the UGRD and VGRD. As in the Kaplan and DeMaria study, both the UGRD and the VGRD were averaged from r = 200 to r = 800 km. The same number of data points are included in these calculations as were in the calculations for RHLO, due to the reasons listed above. The last step in determining the average SHR is to calculate the magnitude of the wind vector produced by UGRD and VGRD. This is done by using the Pythagorean Theorem, which is illustrated in the equation

$$\mathrm{SHR} = (\mathrm{avgUGRD}^2 + \mathrm{avgVGRD}^2)^{1/2} \quad (1)$$

where avgUGRD and avgVGRD are the u and v wind shear components averaged from r = 200 to r = 800km. With this done, SHR represents the average wind shear in the area surrounding the eye of the hurricane.

Kaplan and DeMaria[3] note that the SHR was previously computed from r = 0 to r = 600km. They changed this in order to exclude the eye of the hurricane from calculations.

Low SHR is an important factor for RI because high shear breaks apart the vertical structure of the storm, disrupting it and keeping it from being able to intensify.

3.5. storm potential variable (POT)

The POT is determined by subtracting VMX at t = 0 from the maximum potential intensity (MPI). VMX was determined from NOAA “best track” data[5]. MPI was calculated according to the following equation, as in Kaplan and DeMaria:

$$\mathrm{MPI} = \min[X, 85] \quad (2)$$

where

$$X = A + B(\exp)[C(\mathrm{SST} - \mathrm{SST}_0)]$$

$A = 34.2\ \mathrm{m\ s^{-1}}$, $B = 55.8\ \mathrm{m\ s^{-1}}$, $C = 0.1813°\mathrm{C}$, and $\mathrm{SST}_0 = 30°\mathrm{C}$.

The calculation of X, as well as the values of the constants, comes from the study of the interaction between SST and MPI of Atlantic TCs by DeMaria and Kaplan[8]. $6\ \mathrm{m\ s^{-1}}$ was added to the constant A to account for the mean translational speed of Atlantic TCs. The MPI is also maxed out at 85 kt in equation (1) because DeMaria and Kaplan[8] could not confirm the relationship of MPI to SST when the SST was above 30°C. Once the MPI was calculated for each of the four time periods, the VMX at t = 0 was subtracted from it. This resulted in the value of the POT.

A high POT is beneficial for RI because it means the storm still has plenty of room to grow. A system that has a low POT is already near its maximum intensity and therefore does not have a large chance of RI.

4. Results and Discussion

Once the values for these five variables was calculated, they were compared to the mean values for RI and non-RI cases found by Kaplan and DeMaria[3] in their study. Table 2 shows the values found for the five selected variables for all four time periods. Table 3 shows the mean for the RI and non-RI TC cases found by Kaplan and DeMaria[3].

Starting with DVMX, it can be seen that the values for all but the 0000 UTC time fall in line with what is expected for a case of RI. The reason for the complete lack of intensification before the 0000 UTC time can be attributed to the eyewall replacement cycle the hurricane underwent during that time, keeping VMX at exactly the same magnitude. Despite this, the values for the other three periods are all well above the mean for RI cases.

As expected, the SST values for Hurricane Katrina are much higher than the average for RI cases. All four of the values are above 30°C, which is very warm for waters in the Gulf of Mexico. This is due to the Gulf Loop Current, which was discussed earlier. The sea surface heights, which are representative of SST, can be seen in Figure 3. This clearly outlines the shape of the warm water, which Katrina was over the entire time.

Likewise, the values for RHLO are well above the values expected for RI with the exception of 0600 UTC. Even the 0600 UTC value is still above mean for non-RI cases. It is approximately halfway between the two, and does not say much either way. The reason for the temporary drop in RHLO is unknown. Still, since three of the four values of RHLO are above the mean for TC cases with RI, it can be said that RH conditions in the lower atmosphere were optimal for RI.

The results for SHR are not quite so clear-cut as some of the other variables. The values computed for 0000 and 1800 UTC were below the mean RI mean of 4.9 m s^{-1}, meaning they were good for RI, but the values for the other two times sat squarely between the RI and non-RI means. This does not necessarily mean that conditions were detrimental to RI during this 6 hour time period, but simply that they were not particularly beneficial. Still, since two of the time periods had optimal conditions for RI and the other two were simply marginal, it may be said that conditions were overall fairly good for RI.

The last variable that was examined in this study, POT, had by far the least ideal values for RI. In fact, it is the only one with values that did not clearly signal RI. These values range from 33.56 m s^{-1} at 0000 UTC to 7.83 m s^{-1} at 1800 UTC. All of these are far below what would be expected for RI cases, and it is also below the mean for non-RI cases. This means that the conditions for POT were not ideal for RI. Because Katrina's period of RI was such an intense one, it was anticipated that all five of the variables would be favorable for RI, instead of just four. A possible reason for why the values for the POT are not as high as expected is because Katrina was already such a strong storm when it began its period of RI. Most TCs in the Kaplan and DeMaria study were weaker systems.

Table 2. Calculated values for the five selected variables at 0000, 0600, 1200, and 1800 UTC.

Time (UTC)	*DVMX (m s^{-1})*	*SST (°C)*	*RHLO (%)*	*SHR (m s^{-1})*	*POT (m s^{-1})*
0000	0.000	30.16	71.65	3.69	33.56
0600	12.861	30.46	67.84	6.63	20.70
1200	23.150	30.49	71.00	5.66	10.41
1800	12.861	30.56	75.86	2.46	7.83

Table 3. Mean values for variables in RI and non-RI TC cases, found by Kaplan and DeMaria[3] in their study of 163 Atlantic basin TCs from 1989 to 2000. Also included are the differences between these mean values.

Variable	*Units*	*RI (N = 159, N_e = 92)*	*Non-RI (N = 2462, N_e = 705)*	*D = RI – Non-RI*
DVMX	m s^{-1}	4.6	1.0	3.6
SST	°C	28.4	27.5	0.9
RHLO	%	69.7	65.4	4.3
SHR	m s^{-1}	4.9	8.5	-3.6
POT	m s^{-1}	47.6	40.3	7.3

Therefore Katrina did not have as much room to intensify as a weaker storm might. Another reason why the values are so low was the very high SSTs. In the study done by DeMaria and Kaplan[8], none of the TCs they looked at passed over waters higher than 30°C, so they did not know how storms would react. In Katrina's case, however, the SST at all four times was above 30°C. Since the interaction at those temperatures is unknown, it was decided to cap the MPI at 85 kt, which is was the maximum value possible in Kaplan and DeMaria[3]. Since that is what was done in this current study, the MPI is kept lower than it otherwise might have been. If this cap had not been employed, POT values likely would have been more favorable for RI.

Despite the low values for POT, all four of the other variables were favorable for RI. This lends further evidence to Kaplan's conclusions that these five variables are the most influential in predicting whether a TC will undergo RI or not. Further comparison of the calculated results to the means of RI and non-RI TCs is shown in Figure 4. The bar on the left, in black, is the mean of the data from cases with RI; the bar on the right, in gray, is the mean of the data from cases without RI; and the four bars in the middle, all in white, are the values from 0000, 0600, 1200, and 1800 UTC on August 28. Recall that low values are ideal for the SHR parameter, while high values are ideal for the other four.

5. Conclusion and Final Remarks

In analyzing the period of RI that occurred between 0000 and 1800 UTC on August 28, the values of five RI predictors were calculated for Hurricane Katrina. In their 2003 paper, Kaplan and DeMaria[3] determined that these were the five most important factors in determining if a TC will undergo RI or not. In this study it was hypothesized that, since Katrina underwent such a profound period of RI, it would certainly have optimal values for all, or almost all, of these five variables. If this proved true it would further support Kaplan and DeMaria's conclusions and provide hope toward predicting RI in the future.

Hurricane Katrina had values in the optimal range for 4 of the these 5 parameters, lending some support for Kaplan's hypothesis. The unexpected lowness of the POT variable was most likely found because Katrina was already such a powerful storm when it began its second period of RI, and therefore was already quite near to its MPI. As such, this should not be a problem with weaker storms over warm SSTs, which should have plenty of room to grow and will have a much larger POT. It is hoped that more studies like this will further support these conclusions and lead to a more complete understanding of the process of RI.

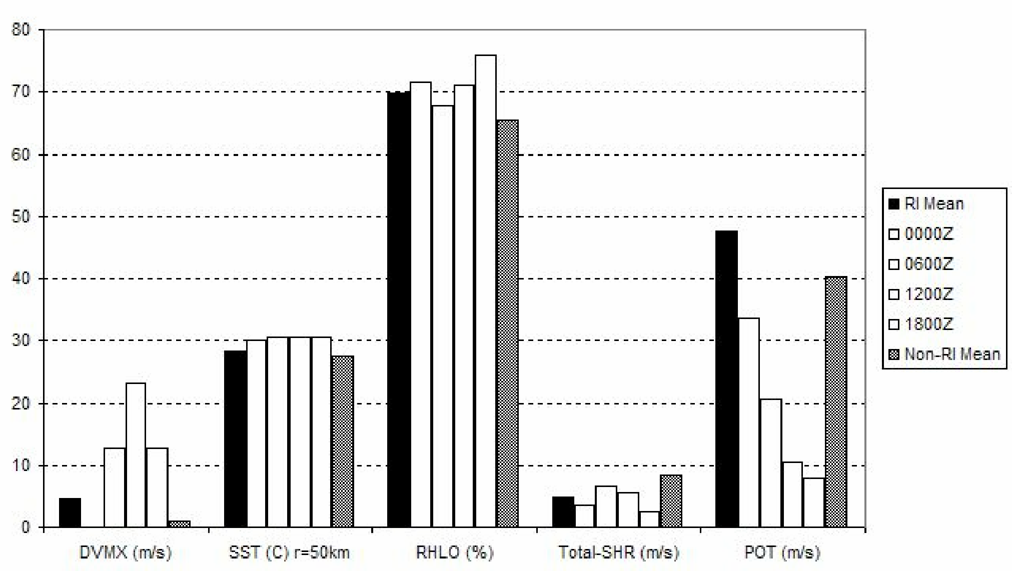

Figure 4. Comparison of the calculated values in this study to the means of RI and Non-RI cases as calculated by DeMaria and Kaplan[3].

Future studies in this area should accomplish several things: first, they should expand the scope of variables to include a larger variety of parameters and, secondly, they should analyze storms that did not undergo RI and attempt to offer explanations for their behavior as well. While this current study has been a case study based on the pioneering work done by Kaplan and DeMaria[3], further studies are planned to examine more cases with new RI predictors. The results presented here look promising and suggest that there is indeed a correlation between these five variables and RI. Perhaps in the future the relationship between RI and environment forcings can be defined more completely.

6. Acknowledgements

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7. References

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