6C2 **Estimating Tropical Cyclone Intensity at Low Wind Speeds**

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I. INTRODUCTION

Tropical Cyclones form over warm ocean waters where direct measurements of its intensity are scarce due to limited resources, meaning that existing best track data of observed Tropical Cyclones (TCs) lack validation, especially at low wind speeds. Additionally, current methods of estimating the intensity of weak tropical cyclones leave much to be desired. Therefore, this study began with creating an ever-growing database of simulated storms using the Weather Research and Forecasting (WRF) model.

In studying each simulated TC, the technique I use is called the Deviation Angle Variance (DAV) technique, and utilizes satellite imagery to determine a value that represents how symmetric a storm is. Intuitively, the more organized a TC is, the more intense it can be; thus, the focus of this study is to investigate the dependence of a storm's axisymmetric nature on its observed intensity.

The main issue in examining tropical cyclones is that current techniques provide only a subjective analysis. Nevertheless, these methods are still utilized heavily today.

The Dvorak technique, developed in the 80s by Vernon Dvorak, is still widely used today for estimating the intensity of TCs despite its subjective nature. The technique utilizes a complicated recognition and analysis of 4 basic patterns as seen from satellite imagery: Curved Band, Shear, Central Dense Overcast, and an observed Eye. These patterns, however, can only be seen by the human eye, and are thus a subjective measurement of the intensity (Dvoark 1975).

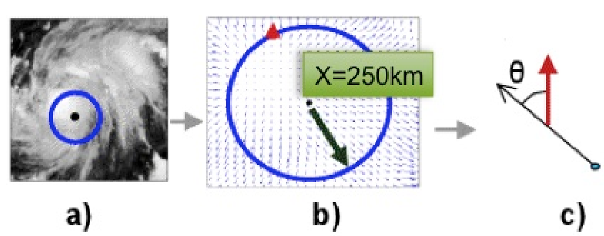
To oppose the Dvorak technique and other subjective methods, the DAV technique was created to propose an objective way to estimate the intensity of a given TC.

II. DAV THEORY

The DAV can be used for a variety of purposes throughout the lifetime of a TC, but has not been researched greatly for weaker storms. It has primarily been utilized in concurrence with satellite imaging on real tropical cyclone cases. Miguel Pineros developed and tested the DAV on both the intensity and genesis of existent TCs (Pineros 2008, 2011).

In this study, the DAV is calculated for eleven simulated storms using the WRF model, which conveniently implies that all of the variables associated with TCs are readily available and easy to access. The values of interest are the outgoing long wave radiations fields since they are similar to the cloud top temperatures obtained by satellite.

Figure 1: Steps of the DAV Technique (Pineros 2011). a) The center and gradient of the OLR field is represented; b) radial vectors are displayed, and c) the difference in gradient and radial angles is shown.

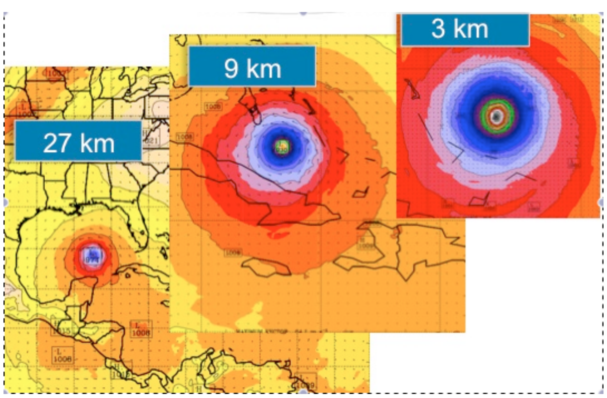


The idea of the DAV technique is to quantify the organization of a given TC and is displayed in *Figure 1*. Given the WRF Model variable fields, one must first calculate the gradient of the OLR values that the WRF model spits out, as shown in figure 1a. Then an average over 9 pixels is necessary to obtain a center for the storm. With this center point, one can draw a radial vector at each pixel (figure 1b). The angle between these two vectors is called the Deviation Angle (figure 1c) and is calculated at all pixels within 250 km of the storm center. Finally, the variance of these values is determined at each time step and the behavior in reference to intensity is examined.

III. WRF MODEL

All of the TC simulations are performed using the WRF-ARW Model version 3.2 with the vortex following option as provided by the National Center for Atmospheric Research. This model incorporates multiple nested grids and includes both explicit moist physical processes and a variety of cumulus parameterization and boundary layer schemes. It solves the nonlinear, primitive equations using Cartesian coordinates in the horizontal and a terrain-following coordinate in the vertical. The model has been adapted for use with idealized initial conditions to permit careful control of initial value experiments.

Figure 2: A visual representation of the WRF Model. The plots are created using RIP4.



The use of a model of this type is necessary to accomplish the scientific goals of the paper by supplying the database with simulated storms. The model is configured with 42 vertical levels, seven of which are below 850 mbar, and the simulations have a temporal resolution of one hour. The outer domain is square with 200 grid points on each side and a horizontal resolution of 27 km. There are also two nested inner domains of (spatial sizes) 9 km and 3 km resolution, as shown in figure 2. The use of three grids is important because numerical simulations designed to follow the entire lifecycle of a tropical cyclone require a model with a very large domain to ensure that the storm does not move too close to any boundary. Additionally, a high-resolution innermost domain is needed capable of resolving the small, intense core of the storm. Therefore, there is one nest to cover the lifespan of the TC, one to resolve smaller scale processes, and a third nest to connect the two together. All the nests interact with each other, allowing for the large range of TC scales in the simulation. Both inner nests are vortex-following which ensures that the inner-core of the TC is always well-resolved; ideally, the model should resolve moist processes explicitly in the eye and eyewall region in order to properly simulate the intensity of the tropical cyclone and the associated cloud fields.

The boundary layer is parameterized using the Mellor-Yamada-Janjic scheme (Janjic, 1990; 2002) where the lower boundary is an ocean surface at a constant temperature of 302 K, and the upper limit depends on buoyancy and shear of the driving flow. For the two outer domains, the Kain-Fritsch cumulus parameterization is applied (Kain and Fritsch, 1993). The convection, described by microphysics, is explicitly resolved on all domains using the WRF single-moment 6-class scheme, which has ice, snow, and graupel, processes (Hong and Lim, 2006) suitable for high-resolution processes. Radiation processes are handled via a Rapid Radiative Transfer Model (Mlawer et al. 1997), which account for multiple bands, trace gases, and microphysics schemes for long wave radiation; and the Dudhia scheme for shortwave radiation (Dudhia, 1989), which is a simple downward integration allowing for absorption and scattering for clouds and clear sky.

Once WRF has created a file containing all of the variable fields of a given TC, two post-processing tools are used to view and use the output. The RIP4 software is used to check if a model run is indeed a TC. The sea level pressure (SLP), wind speed, and wind direction are plotted, as shown in figure 2, to ensure the storm is usable for the study. Due to complications in obtaining binary files of WRF output fields using RIP4, the NCAR Command Language (NCL) tool is used to acquire the necessary OLR fields, which can then be fed into the DAV code. I also use NCL to plot the OLR fields in order to check that the DAV is functioning properly.

A total of 11 tropical cyclone cases were simulated for the study, and this database continuously grows. The initial and boundary conditions are provided by the NCEP Final Analysis (FNL from GFS) using one-degree resolution analysis downloaded from: http://dss.ucar.edu/datasets/ds083.2. Each case is integrated beginning 24-48 hours before the first position in the National Hurricane Center best track archive (http://www.nhc.noaa.gov/pastall.html) and ending either after landfall (not including islands) or at the end of the NHC best track.

IV. PROCEDURE

From beginning to end, the procedure is as follows. The real data from the FNL files are used to define boundary conditions in the WRF model. The model runs over the life cycle of the storm or until landfall and outputs the corresponding intensity and OLR fields. These files are put through post processing to determine whether or not the model run can be used for the database of tropical cyclones. Once the tropical cyclone is established in the database, the OLR fields for domain 3 (the smallest domain) are used to determine the DAV. For this study, the DAV value of the TCs symmetry is analyzed in reference to the model's determined intensity, and plotted in both a time series and a direct relationship. There are many more applications that are mentioned in my future research later on in the conclusion.

V. RESULTS

Once the DAV is calculated, I create time series plots of the DAV verses the intensity in domain 3 on each storm. In the sample displayed in Figure 3 of Hurricane Rita, note the obvious inverse relationship implying that a more axisymmetric storm corresponds to a greater intensity. This is a great result as the features of the storm display a similar relationship achieved in observational research by Pineros (Pineros 2008, 2011). Time Series Plots were performed for each TC in the database, and OLR plots were output every 6 hours to ensure that the DAV was behaving correctly.

Figure 3: (Top) Time Series Plot of DAV and intensity of Simulated Hurricane Rita. (Bottom) Corresponding Simulated Hurricane Rita OLR images at developing and maximum intensity times: made using NCL graphics.

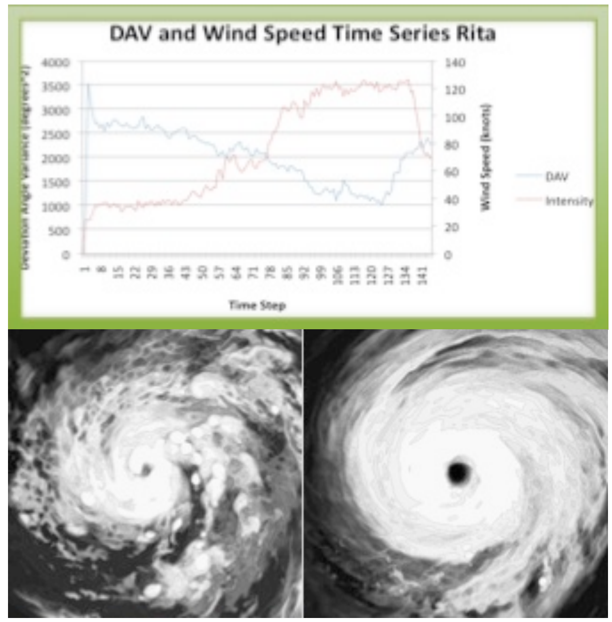


Figure 4: Updated table of simulated tropical cyclones and their respective DAV-Intensity correlation values.

Storm	Domain 3
Simulated Rita	-0.87
Simulated Beryl	-0.18
Simulated Vince	-0.83
Simulated Harvey	-0.44
Simulated Dennis	-0.81
Simulated Epsilon	-0.80
Simulated Gamma	-0.96
Simulated Katrina	-0.22
Simulated Nate	-0.16
Simulated Wilma	-0.11
Simulated Zeta	-0.12

Each tropical cyclone was also added to the overall database and the storm's specific correlation value was determined for domain 3. These values are shown in the above table in Figure 4; please note that the table is updated when a new storm is analyzed. It is also important to keep in mind that the simulated storms may not accurately depict the real case scenario. Despite the fact that the average correlation fits well, not all of the values are within the expected range. The observational data also exhibits this feature and, interestingly, is not displayed in only weak storms. There are a few possible explanations for this, but none are supported by significant evidence at this time, so supplementary examination of the DAV is clearly required for some of the irregular storms.

Figure 5a: Intensity vs. DAV using data from all simulated storms. Correlation Value = -0.71

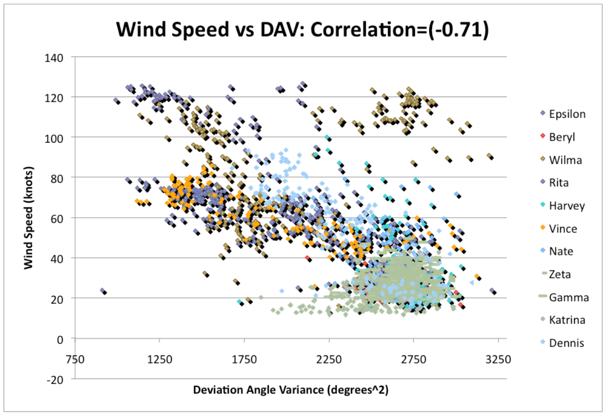
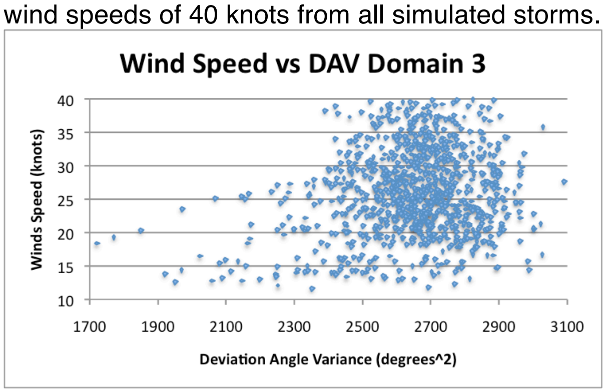


Figure 5b: Intensity vs. DAV using data below wind speeds of 40 knots from all simulated storms.



Additionally, a general correlation value was calculated for the dataset exhibited in figure 5a. Using data from all 11 simulated storms, I expect a correlation value close to (-1.0), but accepted values can range from (-0.7 to -1.0) to support the observational results concluded by Pineros (Pineros 2008, 2011). I obtained a correlation value of -0.71, which is not as linear as expected, most likely due to the higher spatial resolution of the data. However, it is still in the range expected and the structure of the plot seems to follow the sigmoid, which reinforces the analysis performed on observational data by Pineros (Pineros 2008, 2011). The interesting part of this plot is actually the chunk of data in the upper right. These points correspond to Hurricane Wilma at her most intense phase and are extremely different from what is anticipated. This encourages the need for a closer look at the simulation to really determine what is going on with this cyclone.

Zooming in on only the low wind speeds, namely those data points whose wind speed is less than 40 knots (~46mph), the data are very intriguing. It may be difficult to see that the trend in this data is actually just the lower end of the sigmoid curve because the sigmoid trend is a fit for all intensities, as seen in Figure 5a. In Figure 5b, however, the more fascinating characteristic is that data seem to be constrained to DAV values between 2400 and 3000. The reasons for this are unknown but provide great motivation for further analysis on the DAV in reference to the TCs Intensity at low wind speeds.

VI. CONCLUSION

By creating a cumulative database of tropical cyclones, this study supplies the ability to study all variables that govern the behavior of such great storms--variables that cannot be measured for real observational data using satellite imagery. This investigation can therefore be utilized to support observational research performed on the DAV even though the research is in its early stages. The results in this investigation do, in fact, support the observational research with an overall correlation value of (-0.71) between the DAV and intensity of tropical cyclones. Time series plots depict the expected inverse relationship of a storm's organization to its intensity, and the relationship plots follow the sigmoid trend as in observational analysis. More research is necessary, however, for specific simulated storms and for low speed DAV values in general. In addition to a further investigation of the constraints of the Deviation Angle Variance values at low wind speeds, other variables are of future interest to the DAV study. These include relationships of the DAV with vertical wind shear, sea surface temperature, size of TC (radius of maximum winds, radius of 35 knot winds), and a storm's preferred DAV radius calculation. These will be studied and presented at a later date.

VII. REFERENCES

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