4.4 The Vertical Structure of Tangential Winds in Tropical Cyclones: Theory vs. Observations

Daniel P. Stern* and David S. Nolan
Rosenstiel School of Marine and Atmospheric Science
University of Miami

1. Introduction:

While the direct impacts of tropical cyclones are generally manifested at and just above the surface, the necessity of understanding TC structure and dynamics is not limited to this region. The importance of the radial structure of the primary circulation has been thoroughly examined in recent years (e.g. Mallen et al. 2006, Willoughby et al. 2006); the vertical structure has received relatively less attention. This is likely due to the dearth of quality observational data of axisymmetric wind fields above aircraft flight level. It is unreasonable to assume that the dynamics of TCs are insensitive to vertical structure, in numerical models or in reality. In most modeling studies, a baroclinic vortex is specified, with the particular structure arbitrarily chosen. The baroclinic structure of TCs influences dynamics in several ways, notably by altering the efficiency with which unbalanced heat energy is converted to balanced mean kinetic energy (Nolan et al., 2007). In this study, three-dimensional Doppler wind analyses of several intense hurricanes are examined in an effort to gain some insight into observed vertical structure. In particular, the slope of the Radius of Maximum Winds (RMW) and angular momentum (*M*) surfaces are examined as a comparison to existing theoretical predictions. The relationships between these two slopes and the cyclone intensity, the RMW, and each other, are also examined. Finally, composites are made of the normalized tangential wind along the RMW.

2. Previous Studies of Vertical Structure:

Several case studies of TC wind structure were performed in the 1960's and 70's, using flight level data from aircraft (e.g. Hawkins and Imbembo 1976). The RMW was found to often have a significant outward slope, especially above 500mb. A comprehensive composite study of flight level winds was performed by Shea and Gray in 1973. They found that RMW slope was small, and was a function of intensity. In particular they found that the RMWs of strong storms were essentially vertical.

Jorgensen (1984) studied the structure of 4 intense hurricanes. Eyewall slope as diagnosed from radar reflectivity was found to vary between 45 and 60 degrees from the vertical. From a detailed analysis of Hurricane Allen, Jorgensen found a mean RMW slope of 60 degrees from the vertical on August 5. Three days later, the diagnosed slope was 45 degrees, and the RMW was much smaller. Jorgensen found that both the updraft axis and the RMW were surfaces of constant absolute angular momentum.

An objective analysis of Hurricane Gloria was constructed from dropsondes and Doppler radar by Franklin et al. (1993). They found that the RMW was nearly vertical below 500mb, with even a slight inward slope at mid-levels. The peak V_{MAX} was found at 550-600mb, and the RMW was an *M* surface.

There have been numerous additional studies utilizing Doppler radar winds in the last 20 years (e.g. Marks et al., 1992). RMW slope is generally found to be 30-60 degrees from vertical, but there is large variation between and within storms. Most studies find that the RMW and updraft axis are both close to being along *M* surfaces.

The Maximum Potential Intensity (MPI) theory of Emanuel (e.g. Emanuel 1986) predicts an exact axisymmetric structure of tangential winds, which is completely determined by SST, outflow temperature, and vorticity along the tropopause. The analytical model is based on the assumptions of a steady state, thermal wind balance, and slantwise moist neutrality. This constrains surfaces of absolute angular momentum and saturated equivalent potential temperature to be congruent. Furthermore, the RMW is itself an *M* surface, which will always slope outward with height in a baroclinic vortex. While thermal wind balance is generally accepted to be a good approximation in the free atmosphere for tropical cyclones, the general validity of slantwise moist neutrality is still debated.

3. Data and Methods:

The primary sources of data in this research are 3D Doppler analyses acquired from the Hurricane Research Division online data archive at http://www.aoml.noaa.gov/hrd/data_sub/radar.html. The data as acquired consisted of *u* and *v* wind components in storm centered, earth relative, Cartesian coordinates at 2km horizontal resolution, and 37 vertical levels at 500m resolution, and had already been automatically quality controlled. In order to maximize data coverage and minimize biases from the asymmetric sampling that is often present in individual legs, the radar winds from all available legs within about 6 hours were added

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[*] Corresponding author address: Daniel P. Stern, RSMAS/MPO, 4600 Rickenbacker Causeway, Miami, FL 33149. dstern@rsmas.miami.edu

together, and the average over the legs was taken at each grid point. The number of samples used in each grid point average is therefore spatially variable. Even after compositing multiple legs of radar data, regions of missing data usually remained, which can have deleterious effects on interpolation to finer resolution and can introduce biases in azimuthal averages. To mitigate these concerns, all missing data at each level were filled in with a two-dimensional interpolation/extrapolation scheme. Note that this step leaves all existing data points unchanged. The data were then interpolated to 500m horizontal resolution with cubic splines. To construct radius-height plots of azimuthal mean tangential winds, the data were binned and averaged in 500m radial increments. Finally, a 1:2:1 horizontal smoother was applied to all azimuthally averaged fields.

There are several assumptions made about the data, namely that the structure was not evolving too rapidly between consecutive legs, and that asymmetric features have not been significantly aliased onto the symmetric structure in the process of compositing. The filling in of missing data was felt to be the best solution to a number of problems, but it obviously leads to the added concern of utilizing what is purely interpolated data. The resultant fields do appear quite realistic however, and their azimuthal averages are not very different from a previous method where we didn't use filling. Furthermore, the azimuthal coverage of the raw data was examined, and it is generally better than 80% in the vicinity of the RMW for most storms utilized in this study. Finally, it was decided to only use data at and below 10 km height, based on data coverage considerations.

4. Results:

Figure 1(a-b) shows the tangential wind field of Hurricane Ivan on two days, a week apart. Immediately evident is the fact that the RMW is nearly vertical on the 7th, while there is a large slope (slope is defined such that a vertical RMW has zero slope) of ~1.5:1 on the 14th. Note that Ivan on the 14th is much more intense, so the differences in slope are counter to what one would expect from previous studies. On the other hand, the RMW is located further from the center on the 14th, which is consistent with the expected relationship between RMW and slope. This would suggest that radius may be the dominant control on slope. Figure 2 shows scatter plots of RMW and V_{MAX} vs. the slope of the RMW, using data from 7 storms on 19 days. The slope has been objectively determined from the best-fit line to the RMW between 1 and (in most cases) 10 km height. The RMW and V_{MAX} are taken at 1 km. A clear relationship emerges between RMW and slope, whereas there is apparently no relationship between V_{MAX} and slope.

Another question that can be addressed with this dataset is the degree to which angular momentum is conserved along the RMW. One way to look at this is to plot the RMW along with the M contour which originates at the RMW at 1 km. This is shown in Figure 3 for Hurricane Dennis on the 7th and on the 10th. On the 10th, the M contour is nearly congruent with the RMW throughout, indicating that the RMW can be very well approximated as a surface of constant absolute angular momentum. On the 7th, the M contour diverges significantly from the RMW, especially between 1 and 7 km. In this case, the tangential wind speed is decaying with height faster than implied by the slope of the RMW, and the RMW does not well approximate an M surface. Indeed, the RMW is nearly vertical and the wind speed would be nearly constant with height if the RMW and M surface were congruent. The degree to which an RMW approximates an M surface can be examined in the aggregate with a scatter plot of the slope of RMW vs. the slope of the angular momentum contour, which is shown in Figure 4. It is seen that quite a few data points are a large distance from the 1:1 line, and therefore most RMWs lose angular momentum with height.

One of the primary motivations of this research is to determine a "typical" vertical structure for use in the parameterization of vortices in numerical modeling. Towards that goal, the normalized tangential winds along the RMW are shown in Figure 5a, and a composite stratified by RMW is shown in 5b. While there is some spread, most storms retain 75-85% of their maximum 1 km tangential winds at 8 km height. There is also a dependence on radius; the rate of decay along the RMW increases with increasing RMW. This is consistent with the relationship between RMW and its slope.

5. Summary and Future Work:

In this study, the vertical structure of the tangential wind fields of several tropical cyclones were examined, and compared to the results of previous observational studies as well as theoretical predictions. The RMW was found in some cases to be approximately a surface of constant absolute angular momentum. This is consistent with MPI theory and in accord with previous observations. However, there are also many cases where the RMW appears to not be well approximated by constant angular momentum. Some of these cases are of cyclones undergoing steady or even rapid intensification, such as Dennis on the 7th, which deepened from 989mb to 972mb over the 12 hours centered on the data. However, some others which don't conserve angular momentum along the RMW are apparently near steady state. It also seems that the degree of slope of the RMW is generally well correlated with RMW, but not with V_{MAX}. The slope of angular momentum contours originating from the low-level RMW are very well correlated with RMW (not shown). A composite of vertical structure of tangential winds along the RMW has been presented, which indicates a generally slow, approximately linear rate of decay with height in the low and mid-troposphere. Since the tangential winds must go to zero at some height, the decay rate must increase substantially in the upper troposphere.

It is premature to draw any firm conclusions from this research, as it is still preliminary, and there are still some possible biases in the data. It is also unclear whether statistical significance can be shown in the suggested correlations, due to small sample size and questions of independence. Further work is necessary, and the acquisition of additional and higher quality datasets is anticipated. It is hoped that it will be possible to further determine the generalized vertical structure of tropical cyclones, in much the same way as has been done for the radial structure. It will then be possible to more objectively parameterize the structure of vortices to be used in idealized modeling studies.

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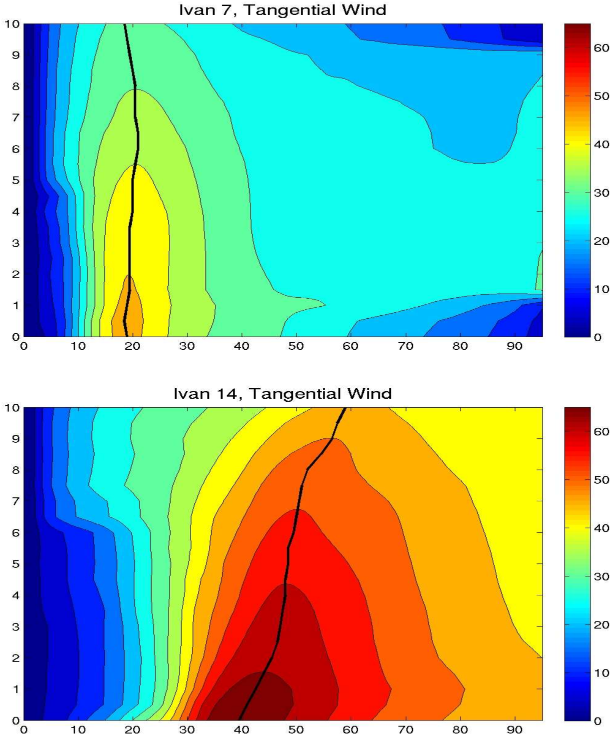

Figure 1: Tangential Winds, Ivan 7th (a), 14th (b). Black line is the RMW. Contour interval is 5 m/s.

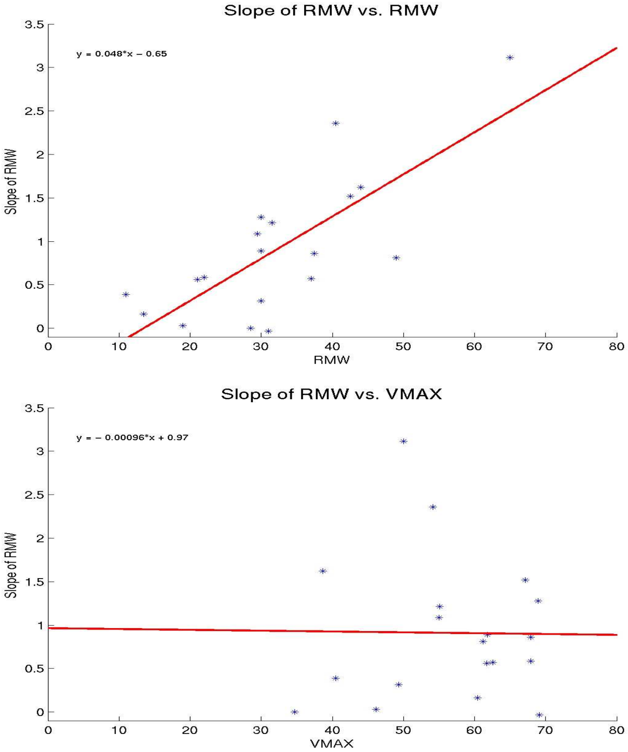

Figure 2: Slope of RMW vs. RMW (a), VMAX (b). Best fit line is in red.

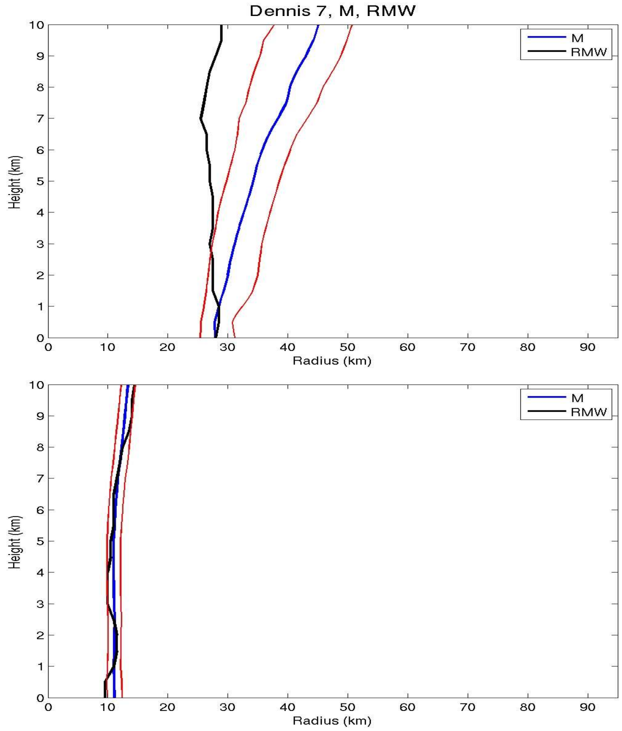

Figure 3: M contour originating at the RMW at 1 km height (blue), RMW (black) for Dennis 7th (a), 10th (b). Red lines are contours of M at 90% and 110% of that at the 1 km RMW.

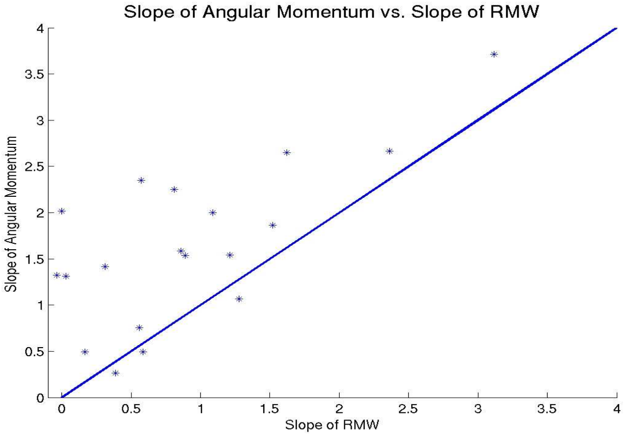

Figure 4: Slope of Angular Momentum vs. Slope of RMW. Line of equal slope is in blue.

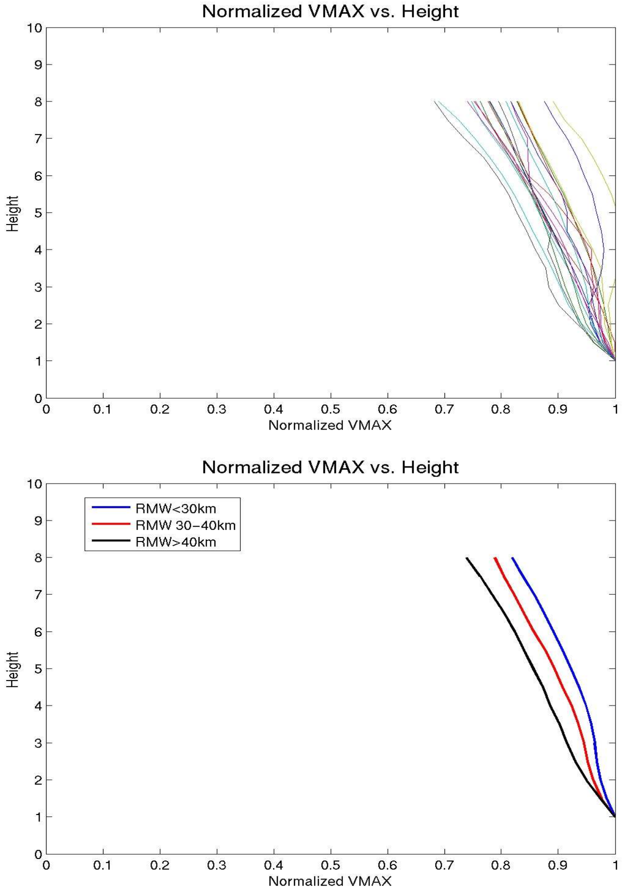

Figure 5: Normalized VMAX vs. Height along the RMW for all storms (a). Composite normalized VMAX (b).