10D.6 TROPICAL CYCLONE NEAR-CORE RADIAL STRUCTURE FROM AIRCRAFT OBSERVATIONS: IMPLICATIONS FOR VORTEX RESILENCY

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1. INTRODUCTION

Recent theoretical studies, based on vortex Rossby wave (VRW) dynamics, have established the importance of the radial structure in the response of tropical cyclone (TC)-like vortices to ambient vertical wind shear (Reasor et al. 2004, hereafter R; Schecter and Montgomery 2003, hereafter SM). Linear VRW theory predicts that in the near-core region beyond the *radius of maximum azimuthal-mean tangential wind* (RMW), the degree of *vortex broadness* determines whether a tilted TC vortex will realign and resist vertical shear or tend to tilt over and shear apart. Fully nonlinear numerical simulations have demonstrated that the vortex resiliency is indeed sensitive to the initial specification of the idealized vortex. This brings into question how well the "true" nature of TC structure is represented by commonly used idealized vortices and motivates the re-examination of the radial structure of TCs.

2. DATA AND METHODOLOGY

The National Oceanic and Atmospheric Administration (NOAA) Hurricane Research Division (HRD) archive of flight-level aircraft observations collected from 63 Atlantic and Eastern Pacific tropical cyclones (1977-1999) is utilized for this study. Out of 560 flight missions, sufficient radial and azimuthal data coverage was available in 450 cases for the estimation of *azimuthal-mean* radial profiles of tangential wind and relative vorticity, the latter of which serves as a proxy for potential vorticity (PV).

The 450 resultant pairs of observed profiles are categorized into three TC intensity classes, defined by ranges in the *maximum azimuthal-mean tangential wind*, Vmax: *pre-hurricane* (< 30 ms^{-1}), *minimal hurricane* (30-50 ms^{-1}), and *major hurricane* (≥ 50 ms^{-1}). To facilitate comparison with idealized profiles, *normalized* composites are constructed that beneficially preserve the underlying tangential wind and relative vorticity structure: Prior to averaging, each individual profile is expressed in non-dimensional form utilizing the typical scales, RMW and Vmax.

To further facilitate comparison with idealized profiles, a modified Rankine vortex ($Vr^{\alpha} = const.$, $0 < \alpha < 1$) is fit to each individual and composite profile for the purpose of quantifying the observed vortex behavior beyond the RMW. Although many past studies (see Mallen et al. 2004 for exhaustive references) have shown that the outer TC structure deviates significantly from a pure Rankine structure ($\alpha = 1$), the Rankine profile (or smoothed counterpart) still serves as a useful starting point for obtaining analytical insight in theoretical studies.

3. RESULTS

As an illustration, the composite structure of a subset of the *minimal hurricane* class (96 cases) is compared with the idealized profiles in Figures 1 and 2. This subset consists of the individual profiles that extend to *at least* three RMW distances from the TC center. Due to the 150 km maximum radial flight leg extent, the RMW is constrained to be at most 50 km. The 1-3 RMW range is emphasized because this near-core region is important in determining the stable or unstable vortex response to vertical wind shear, further discussed in the next section.

The mean tangential wind profile shape within roughly 1.5 RMW is broader than a Rankine vortex, yet narrower than the Gaussian and similar "S" vortex (Fig.1). This is manifested in the sharper than Gaussian, yet finite, relative vorticity gradient across the RMW (Fig.2). As a consequence, appreciably non-zero values of relative vorticity exist outside the RMW, in contrast to Rankine vortices.

Most relevant to the TC resiliency problem, however, is the region farther outward from the wind maximum between roughly 1.5 and 3 RMW distances from the center. Here, the mean *minimal hurricane* vortex structure behaves quite differently than all of the ideal vortices. The tangential wind, similar to the equivalent modified Rankine vortex (α=0.34), decreases more slowly with distance than the Gaussian vortex and therefore slower than all other idealizations (Fig.1). This naturally corresponds to the slower monotonic decrease of relative vorticity with radius (Fig.2), and thus overall greater values throughout the near-core region. In striking contrast, the ideal vortices appear to be characterized by exaggerated tangential wind decrease resulting in negligible (Gaussian), zero (Rankine) or even negative (S vortex) relative vorticity.

For this particular class of TCs, the idealized vortices are clearly unrealistic in representing the mean observed vortex structure in the near-core region outside of the RMW. The composite *pre-hurricane* and *major hurricane* structures (not shown) compare with the idealizations in a qualitatively similar fashion (see Mallen et al. 2004 for details).

The variability of the entire sample, in terms of the modified Rankine decay exponent, is relatively small (mean α=0.37, std. dev. σ=0.14) as the majority of individual cases deviate greatly from their idealized counterparts. Not surprisingly, pure Rankine characteristics of rapid tangential wind decay immediately beyond the RMW and associated *zero relative vorticity* are not evident in any of the cases. While a few cases approach the large rate of tangential wind decay of a Gaussian vortex in the 2-3 RMW region, not a single case exhibits the extremely rapid rate of

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tangential wind decrease characteristic of the S vortex and the associated *anticyclonic relative vorticity near the RMW*.

4. DISCUSSION

How then is the vortex broadness, evident in observed TC structure, related to TC resiliency under an impinging vertical wind shear?

According to linear VRW theory, the *tilt decay rate* of a TC-like vortex subject to vertical wind shear is proportional to the *radial gradient of azimuthal-mean PV* at a *critical radius* outside the RMW, where the vortex precession frequency matches the fluid rotation rate of the mean azimuthal flow.

The locations of “dry” critical radii for Rankine, Gaussian and S vortices (see Fig. 1 and 2) have been calculated analytically (SM) and are identified in Fig.2. The tilted Gaussian vortices realigned in the dry-adiabatic simulations in R because of the *monotonically decreasing* radial PV distributions and sufficiently *negative radial PV gradients* at the critical radius (Fig.2). In contrast, the growth of the tilt asymmetry and the eventually shearing apart in the Jones (1995) simulation (using the S vortex) can in a first approximation be explained using linear theory upon noting the *positive* radial vorticity gradient at the critical radius (Fig.2) arising from the extremely rapid (and unrealistic) tangential wind decrease and associated negative relative vorticity near the RMW of the S vortex (R).

This comprehensive analysis *reaffirms* that real TC structure is characterized by a relatively slow decay of tangential wind. In addition, the associated *broad skirt of significant cyclonic relative vorticity* further characterizes TC structure in the near-core region beyond the RMW. The precise location of “moist” critical radii for the observed radial profiles is not yet known, but may be conservatively estimated to be located between 1–3 RMW distances (Mallen et al. 2004). From the perspective of dry-adiabatic dynamics, we thus expect that the broad near-core vortex structure outside the RMW enable TCs to withstand and survive episodes of weak to moderate vertical wind shear, in contrast to the unrealistic Rankine and S vortex idealizations.

These results demonstrate that caution must be used in the type of idealized vortex specified in theoretical and modeling studies of sheared TC vortices. Contrary to past studies, where the use of such idealized vortices may have resulted in erroneous results, their judicious use is recommended in future studies of TC evolution.

ACKNOWLEDGEMENTS

This work was supported in part by the U.S. Office of Naval Research through Grant N00014-021-0532 under Dr. Bin Wang. Special thanks go to Dr. Michael T. Montgomery for constructive comments and to Dr. Hugh Willoughby and the Hurricane Research Division for their efforts in providing the flight-level data.

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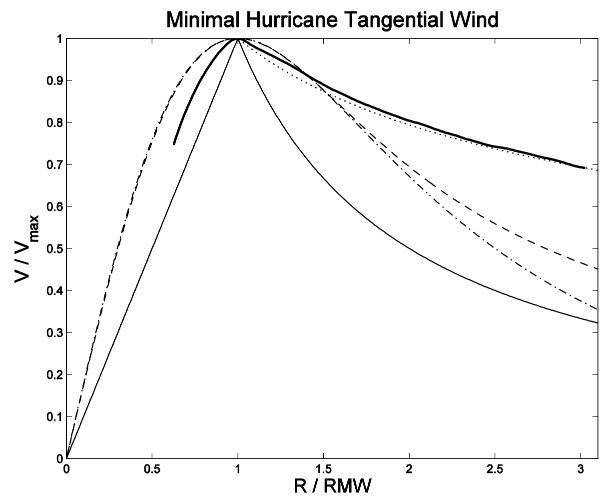

Figure 1. Non-dimensional composite profile of observed *minimal hurricane* tangential velocity (thick solid) and best-fit modified Rankine (dotted) vortex (α=0.34) compared with the equivalent Rankine (thin solid), Gaussian (dashed) and S (dash-dotted) vortices.

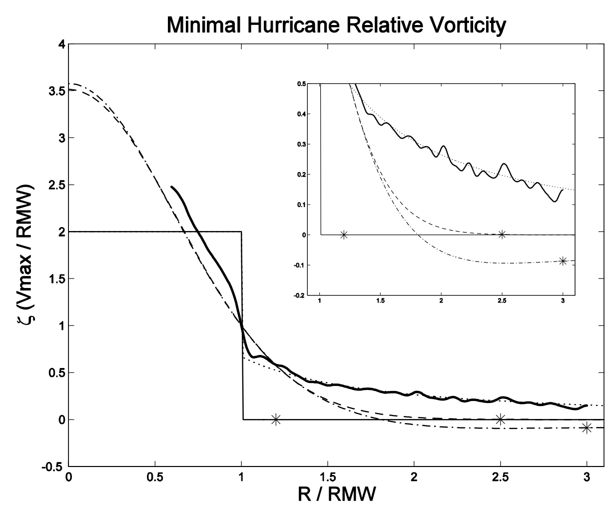

Figure 2. Same as Fig.1, except for relative vorticity. The inset emphasizes the near-core region beyond the RMW where the critical radius resides (denoted by the asterisk).