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UNDERSTANDING THE DYNAMICS OF VERTICALLY SHEARED HURRICANES

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One of the major challenges in forecasting tropical cyclone (TC) intensity is predicting the response of a storm to environmental vertical shear. The recent case of Hurricane Debby (2000) points to deficiencies in the way vertical shear is dealt with in current operational forecast models. Towards remedying this problem, recent theoretical and numerical studies of TCs in shear (Jones 1995; Wang and Holland 1996; Bender 1997; Smith et al. 2000; Frank and Ritchie 2001) have sought to clarify the physical processes that determine the boundary between alignment and irreversible shearing apart of the vortex. In this paper we present a new dynamical understanding of strong vortices in vertical shear, extending the linear quasi-geostrophic (QG) vortex alignment theory of Reasor and Montgomery (2001; RM01) to finite Rossby number with vertical shear forcing.

For a class of QG vortices characteristic of weak TCs, RM01 showed that as long as the upper and lower level potential vorticity (PV) cores overlap, the tilted vortex evolution is captured by linear vortex Rossby wave (VRW) processes. The vortex tilt is viewed as a perturbation to an otherwise aligned vortex, which for simplicity is assumed barotropic here. Whether the tilted vortex precesses or rapidly aligns (on the timescale of the mean vortex circulation) depends only on the ratio of horizontal vortex scale, L, to internal Rossby deformation radius,

$$l_{r,G} = \frac{NH}{m\pi f},$$

where N is the Brunt Vaisala frequency, H the vortex depth, m the vertical wavenumber of the tilt, and f the Coriolis parameter. For small $L/l_{r,G}$ the vortex tilt takes the form of a near-discrete VRW, referred to here as a "quasi mode," causing the vortex to precess. As $L/l_{r,G}$ is increased, RM01 found that the rate of decay of the quasi mode increases and the initial vortex tilt rapidly disperses on the azimuthal mean vortex in the form of sheared VRWs. A complimentary view of this transition to alignment is given by the resonant damping theory of Schecter et al. (2002; SMR02), which predicts the exponential decay of the vortex tilt for $L/l_{r,G} \leq 2$.

If, instead of the QG system, we start with the Asymmetric Balance (AB) model (Shapiro and Montgomery 1993) for rapidly rotating vortices, it is straightforward to extend the above theory to finite Rossby number. The predictive equations for the QG and AB models differ primarily in their definition of Rossby deformation radius. In the AB model the global deformation radius, $l_{r,G}$, is replaced by a local one,

$$l_r = \frac{NH}{m\pi\sqrt{\overline{\eta}\,\overline{\xi}}},$$

where $\overline{\eta} = f+\overline{\zeta}$ and $\overline{\xi} = f+2\overline{\Omega}$ are the mean absolute vertical vorticity and modified Coriolis parameter, respectively. Here $\overline{\Omega} = \overline{v}/r$ and $\overline{\zeta} = r^{-1}d(r\overline{v})/dr$ are the mean angular velocity and relative vorticity, respectively, and $\overline{v}$ is the mean tangential wind. Thus, just as increasing f increases the alignment rate in the QG theory, we anticipate that increasing vortex intensity should have the same effect for more general vortical flows. The question is whether the dynamical mechanisms identified in the QG theory still explain the tilted vortex evolution at finite Rossby number, e.g., is there a quasi mode at small L/l_r and how important are sheared VRWs in promoting alignment at large L/l_r?

The local deformation radius can be expressed as the global value times a function of the Rossby number ($Ro \sim \overline{v}_{\max}/fL$). The parameter space at finite Rossby number is then defined by both $L/l_{r,G}$ and Ro for a vortex of given radial structure. To investigate the parameter space we use a linearized Primitive Equation (PE) model, supplemented by the AB model to demonstrate the balanced nature of the alignment process. In all cases a quasi-balanced tilted vortex (see RM01) is used as an initial condition. When the geopotential amplitude associated with the vortex tilt is plotted over the parameter

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space (after several circulation periods, and normalized by the initial value), we find that small changes in Ro can lead to large changes in the rate of alignment. It is of note that for the range of $L/l_{r,G}$ characteristic of TCs, a clear quasi mode is present at $Ro \sim O(1)$ and accounts for the weak decay of vortex tilt (as discussed in RM01 and SMR02). Since the quasi mode (in this regime) inhibits alignment over physically relevant timescales, vortices are vulnerable to external vertical shear at this stage.

If the Rossby number is increased, the decay of vortex tilt occurs in two ways. Over the first few circulation periods (depending on the magnitude of Ro) the asymmetric PV takes the form of sheared VRWs and the associated geopotential amplitude decays rapidly at a rate similar to a spiral wind-up solution. After this "adjustment," the rate of decay levels off and becomes exponential, consistent with the resonantly damped vortex Rossby core mode of SMR02. In other words, a simple vortex tilt at $Ro \gg 1$ projects onto both the quasi mode and the continuous spectrum of sheared VRWs. Both contribute to the decay of vortex tilt, but the sheared VRWs are responsible for the bulk of the total alignment for meteorologically relevant time scales.

The vortex Rossby wave alignment theory is the basis for a way of viewing the TC in shear problem different from that in recent studies (e.g., Jones 1995; Smith et al. 2000). If we start with an initially aligned vortex and impose a vertical shear flow, based on the behavior of the unforced tilted vortex, the tilt will either project strongly onto sheared VRWs or onto the quasi mode. In the latter case the vortex should irreversibly shear apart if the decay rate of the quasi mode is less than the rate of differential advection by the vertical shear flow. The same should hold true in the former case, but the alignment timescale is set instead by the VRW axisymmetrization rate.

To test this hypothesis we have performed a series of simulations using the linear PE model with a constant zonal vertical shear forcing. In all forced cases the initial vortex is vertically aligned. In the first simulation $H = 10$ km, $f = 3.16 \times 10^{-5}$ s^{-1}, $N^2 = 1.5 \times 10^{-4}$ s^{-2}, $L = 100$ km, $\overline{v}_{\max} = 10$ ms^{-1}, and the vertical shear is 4 ms^{-1} over 10 km. In the unforced simulation the initial tilt projects primarily onto a quasi mode. Over 5 circulation periods the vortex in shear simply tilts over. If we increase $\overline{v}_{\max}$ to 40 ms^{-1}, the unforced vortex exhibits a rapid alignment over the first circulation period as the tilt disperses in the form of sheared VRWs. The vortex in shear remains vertically coherent, increasing in tilt when oriented downshear and then diminishing in tilt when oriented upshear. As the vortex evolves, sheared VRWs are continually generated and symmetrized.

We next consider how these results depend on the radial structure of the mean vortex. In the above simulations the mean radial PV profile is a monotonically decreasing Gaussian. If we redo the second simulation using the benchmark profile of Jones (1995), surprising results are found. While the Gaussian and Jones profiles are similar within the vortex core, the Jones profile exhibits a region of anticyclonic relative vorticity outside the vortex core. The unforced simulation using the Jones profile shows an initial rapid alignment of the vortex in good agreement with the Gaussian case. After this time the vortex tilt rapidly grows, in contrast to the Gaussian simulation. When placed in shear the vortex does precess as in the Gaussian case, but the tilt continually increases. This is in contrast to the Gaussian simulation where the vortex remained vertically coherent.

In the final simulation we use the observed low-level radial profile from Hurricane Olivia (Reasor et al. 2000) at all levels. A vertical shear comparable in magnitude to that observed is imposed. Within one circulation period the unforced vortex nears complete alignment due to axisymmetrization of the initial vortex tilt. The forced vortex begins to tilt, but reaches a small-tilt "equilibrium" after 2 hours. The actual evolution of Olivia reflects this tendency to remain vertically coherent. At low levels Olivia was observed to weaken, although this was partially a consequence of the axisymmetric spin-down of the vortex (Reasor et al. 2000). The greatest decrease in $\overline{v}_{\max}$ occurred at mid to upper levels of the storm after the observed increase in vertical shear. Although the vortex tilt did not increase substantially, a wavenumber one asymmetry in convection did. This evolution is similar to that described by Frank and Ritchie (2001) in their "vortex in shear" simulations. The role of the vortex Rossby wave alignment mechanism in keeping both observed and "full physics simulation" TCs vertically coherent is a subject of ongoing investigation.

P.R. was supported by the National Research Council while a postdoctoral research associate at the Hurricane Research Division and M.M. was supported in part by NSF ATM-0101781.

References available from author upon request.