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CONSTRAINTS ON PARAMETRIC HURRICANE WIND PROFILES

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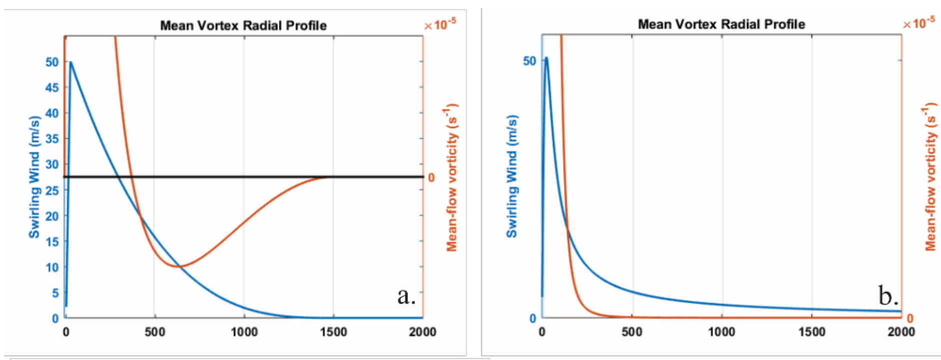
Fundamental fluid dynamics impose physical consistency restraints on parametric tropical cyclone (TC) wind profiles used for idealized theoretical models or full-physics model initialization. A typical TC wind profile exhibits a wind maximum 10-50 km from the storm center surrounded by an initially steep, then gradual, decay with distance away from the center. All profiles share a broad cyclonic vorticity maximum around the center, but differ at large radius. Here, we focus on three types of vortex: asymptotically bounded, finitely bounded, and unbounded.

In bounded profiles, the Circulation Theorem (meteorological version of Stokes' Theorem from vector calculus) requires that the circulation around an area be equal to the integral of the vorticity over the area enclosed, so that the wind either asymptotes to zero at large radius (i.e., asymptotically-bounded vortex, Fig. 1c) or becomes identically zero at some finite radius (i.e., finitely-bounded vortex, Fig. 1a). They both contain cyclonic vorticity near the center surrounded by an equal amount of anticyclonic vorticity. This condition implies the existence of an outer waveguide in which a reversed vorticity gradient (i.e., becoming less anticyclonic outward) can support downstream-propagating vortex Rossby waves (VRWs, Gonzalez *et al*. 2015).



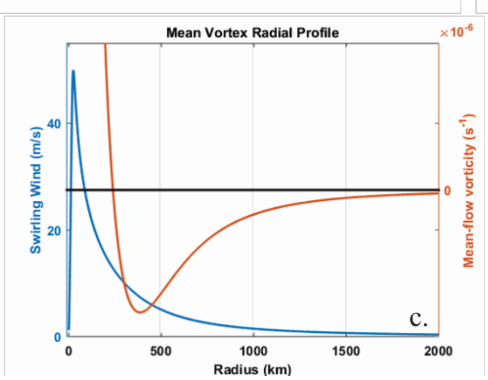


Fig. 1. Radial vorticity/wind profiles for a finitely-bounded vortex (a.), unbounded, Rankine-like vortex (b.), and asymptotically-bounded vortex (c.)

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Unbounded, or Rankine-like, vortices contain cyclonic vorticity only in their inner cores and are irrotational everywhere else (Fig. 1b). This structure means that Rankine vortices are inconsistent with Stokes' Theorem on a spherical Earth (or any closed manifold), because it implies anticyclonic circulation about the antipode of the vortex center. Moreover, unbounded vortices (Montgomery *et al*. 1999) lack outer waveguides and contain both infinite kinetic energy and infinite angular momentum. Therefore, bounded vortices are more logically consistent for modeling large-scale TC dynamics. If one were focused solely on inner core dynamics, then Rankine-like vortices might be reasonable. To better understand the argument for use of bounded vortices, imagine a transparent sphere with no vorticity except for a lone cyclonic patch at some arbitrary location. From the perspective of an observer at the antipode, the circulation would appear to be anticyclonic but with no enclosed vorticity, in apparent contradiction with the Circulation Theorem (Fig.2). To avoid this contradiction, the component of the curl normal to the surface of any closed manifold (e.g., Earth) must integrate to zero.

It is important to emphasize that the antipode of a counterclockwise circulation patch with enclosed cyclonic vorticity in the Northern Hemisphere appears as a clockwise circulation in the Southern Hemisphere. The latter is cyclonic in the Southern Hemispheric sense. However, the interest lies in calculating the component of the curl of the wind perpendicular to the surface of the convex manifold. Here, we integrate over a circular domain. As the domain gets larger, so does the enclosed vorticity until you get to the core's boundary of the "Rankine" vortex. From the Circulation Theorem, the circumference gets larger while no more vorticity is enclosed so that the wind becomes weaker.

In a three-dimensional atmosphere with no rigid lid, vortex tubes must either terminate on the surface or reconnect. Free-slip and no-slip surface boundary conditions yield similar scenarios. In the former, vortex tubes rise upward from the surface in the vortex core, spread at tropopause level, then return to the surface where they end. In the latter, the boundary layer wind is exactly zero at the surface. The resulting strong shear between the surface and top of boundary layer contains horizontal vortex tubes that follow the same pattern as free-slip except that they reconnect in the boundary layer as opposed to

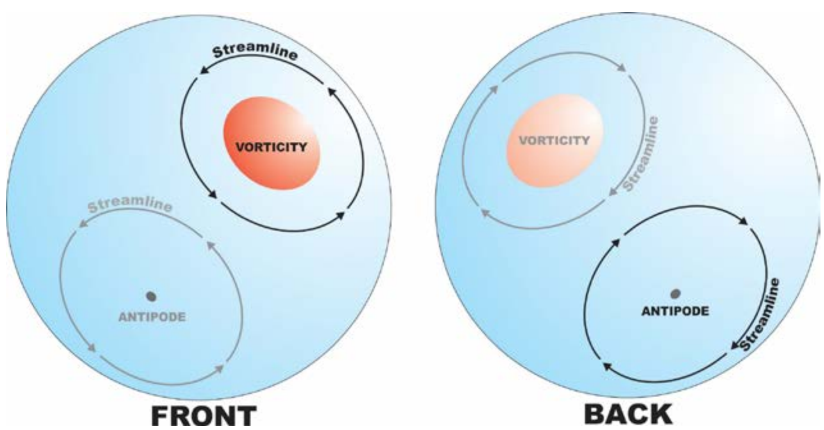

Fig. 2. Cartoon illustrating a closed spherical manifold devoid of vorticity everywhere except a cyclonic patch located in the upper right hand corner of the left panel; the right panel shows the antipode of the patch with anticyclonic circulation, but no enclosed vorticity

terminating at the surface. The region where the vortex tubes rise contains cyclonic vertical vorticity near the center. Anticyclonic vertical vorticity exists where the vortex tubes reconnect with the horizontal tubes in the boundary layer tubes at the vortex periphery. This configuration is consistent with the bounded vortices described earlier.

These vortices have implications for idealized TC motion modeling (e.g., Willoughby 1988, 1992, 1994). Asymptotically-bounded and Rankine vortices in a Barotropic Nondivergent vortex-following model on a beta plane yield northwestward storm motion two to three times faster than the observed beta drift speed. The former consists of two interlocking trailing vorticity spirals that extend to large radius and are likely low-frequency waves forced by beta at their resonance, where strong planetary vorticity advection by the mean flow occurs. The latter vortex exhibits trailing vorticity spirals at the periphery as well despite lacking an outer waveguide because the local change in perturbation vorticity is balanced by merdional advection of planetary vorticity. These spirals wrap around the northern and southern sides of the center where vorticity filamentation occurs. The fast motion and large amplitude are plausibly explained by strong forcing due to advection by the irrotational portion of the vortex (Gonzalez *et al*. 2015).

Finitely-bounded vortices exhibit somewhat slower motion since they are smaller due to their narrow outer waveguides. Beyond some finite radius from the center, the area-integrated symmetric vorticity becomes exactly zero. The propagation speed can vary depending on the shape of the positive radial vorticity gradient profile at the vortex periphery Nevertheless it is important to note that diffusion, vorticity filamentation at a VRW critical radius, and nonlinearity play significant roles in controlling translation speed. High diffusion values ($K \geq 1.5 m^2 s^{-1}$) increase critical radius filamentation thus slowing down the vortex translation speed. Nonlinearity is the dominant mechanism since in semispectral models, wave-wave interactions force wavenumber-one gyres of opposite polarity to the linearly-forced beta gyres, such that the flow between is opposite to the beta-induced relative flow. These “anti-beta gyres” counteract the normal beta gyres’ northwest flow to limit the overall storm motion (Gonzalez *et al*. 2015).

References

Gonzalez, I., III, H.E. Willoughby, and A. Cotto, 2015: Synthesis of Vortex Rossby Waves. Part II: Vortex Motion and Waves in the Outer Waveguide. *J. Atmos Sci*., **72**, 3958-3974.

Montgomery, M.T., D.J., Möller, and C.T. Nicklas, 1999: Linear and Nonlinear Vortex Motion in an Asymmetric Balance Shallow Water Model. *J. Atmos Sci*., **56**, 749-768.

Willoughby, H.E., 1988: Linear Motion of a Shallow-Water, Barotropic Vortex. *J Atmos Sci*., **45**, 1906-1928.

Willoughby, H.E., 1992: Linear Motion of a Shallow-Water Barotropic Vortex as an Initial-Value Problem. *J Atmos Sci*., **49**, 2015-2031.

Willoughby, H.E., 1994: Nonlinear Motion of a Shallow Water Barotropic Vortex. *J Atmos Sci*., **51**, 3722-3744.