P1.21 **STUDIES ON SECONDARY EYEWALL FORMATION**

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1. Introduction

Secondary, or concentric, eyewalls are circular bands of convection located outside the primary eyewall. Secondary eyewalls are commonly observed by radar and other *in situ* studies of intense hurricanes. While their role in the intensity changes of such hurricanes is a frequently studied problem, their formation is not.

A variety of different hypotheses for the formation problem have been suggested. Some authors have suggested that a secondary eyewall is the natural axisymmetrization of the primary convective band, but few have provided a detailed explanation of this phenomenon. Others believe that environmental forcings (upper-level troughs, wind shears, etc.) on the main vortex set up secondary eyewalls. However, many different hurricanes, in many different environments, have been observed to have secondary eyewalls. Another school of thought hypothesizes that internal vortex dynamics play an important role. It is this last school that we focus on here.

At present, few conclusions have been reached with respect to secondary eyewall formation. Modeling studies of intense, non-axisymmetric hurricanes have infrequently produced secondary eyewalls. *In situ* studies have shown only the presence of the secondary eyewall. Modeling studies of axisymmetric hurricanes have shown secondary eyewall formations (Willoughby et al., 1984; Hong and Emanuel, 2002), but, because of their axisymmetric nature, leave possibly important dynamical effects out. Thus, we look first why few full-physics modeling studies have produced secondary eyewall features. In cultivating ideas, we explore the dynamical and thermodynamical phenomena that may play roles in the formation of the secondary eyewall.

2. Modeling Issues

Secondary eyewalls have been observed to form primarily in intense hurricanes. We know this from innumerable radar and *in situ* studies of hurricanes. However, it seems that current full-physics models do not reliably produce secondary eyewalls that look like the observed phenomena. The natural question is to understand why this may be the case.

Since the dynamical cores of the full-physics models currently in use (MM5, RAMS, etc.) are relatively well-known and well-tested, we believe that the central issue comes down to unresolved dynamical processes. The thermodynamics of these models may have an influence, but it seems highly unlikely that secondary eyewalls are strongly thermodynamical entities.

Dynamical features like vortex Rossby waves, critical layers, gravity waves, stagnation regions, etc. can all have scales of less than 5 km in mature hurricane vortices and can all have potentially significant effects on the vortex. Even though many full-physics hurricane simulations are now being run with horizontal resolutions on the order of 1 to 2 km, there is still likely an inability to resolve such small features accurately. If these dynamical features are significant in the formation of secondary eyewalls, then current model runs would have trouble resolving them.

3. Dynamical Conjectures

The fundamental question here is "How do secondary eyewalls form?" This leads to a host of related questions:

- Is environment forcing of a hurricane necessary, or does a hurricane form this phenomenon internally?
- Or is the process an "order out of chaos" problem, akin to two-dimensional turbulence theory?
- What processes dictate their formation and which are the most important?
- Most importantly, can we predict the formation of these new eyewall structures and, thus, improve intensity forecasting of hurricanes?

First instincts suggest that secondary eyewalls are probably not a chaotic-dominated process. After all, these features are not frequently seen in non-intense hurricanes. Only strong and mainly axisymmetric hurricanes tend to have observed and sustained secondary eyewalls. There must be something special about strong, nearly-axisymmetric hurricanes that makes secondary eyewall formation special.

One such idea is the resonance between a perturbation near a critical layer in the flow around a strong vortex. This critical layer theory requires a steep gradient of vorticity in the mean vortex, a phenomenon that intense hurricanes frequently exhibit. We start an analysis of this conjecture in two-dimensional vortex dynamics.

4. Toy Model Results

The essence of this critical layer theory comes from the two-dimensional vorticity equation, linearized around a strong, azimuthally-averaged mean vortex in cylindrical coordinates (, r):

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$$(\frac{\partial}{\partial t}+\frac{\bar{v}}{r}\frac{\partial}{\partial\lambda})\zeta'-\frac{\partial\psi'}{r\partial\lambda}\frac{\partial\bar{\zeta}}{\partial r}=0$$

Here, **v** is the tangential wind, ' is the perturbation streamfunction, ' is the perturbation vorticity, and overbars represent azimuthal averages. If a vorticity perturbation is seeded near the critical radius (the radius at which a particle is advected by the mean flow at the same rotation rate as the discrete vortex Rossby wave on the interface), we see that there should be a resonance between the sheared disturbance and the vortex Rossby wave it excites. By wave-wave interactions and vorticity flux processes, there may be significant mean velocity changes.

To test this idea, we examine a very simple model of a hurricane core: a Rankine vortex. In our numerical model, the mean vortex used has a radius of 40 km and a vorticity of $3x10^{-3}$ s^{-1}, giving a maximum tangential wind of 60 m/s. At the interface, we use a cubic polynomial spline.

If we force this vortex with an azimuthal wavenumber 2 perturbation, the critical radius will be located at 56.57 km. To force it, then, the perturbation we use is a single wavelength of a cos^2 function in radius with half-width of 10 km, centered at 60 km, azimuthal wavenumber 2, and vorticity amplitude of $2x10^{-4}$ s^{-1}.

Figure 1 shows the azimuthal mean vorticity at a later time in this particular run. Initially, the main vortex becomes moderately elliptical due to the strong resonance between the perturbation's forcing and the intrinsic rotation rate of the elliptical vortex. After a few hours, though, the mean vortex has nearly returned to its initial state, but there is a vorticity spinup at 54 km, just inside the critical radius. The nonlinear mixing around the critical radius and the linear dynamics of vortex Rossby waves have forced a significant mean spinup of the vortex near the critical radius.

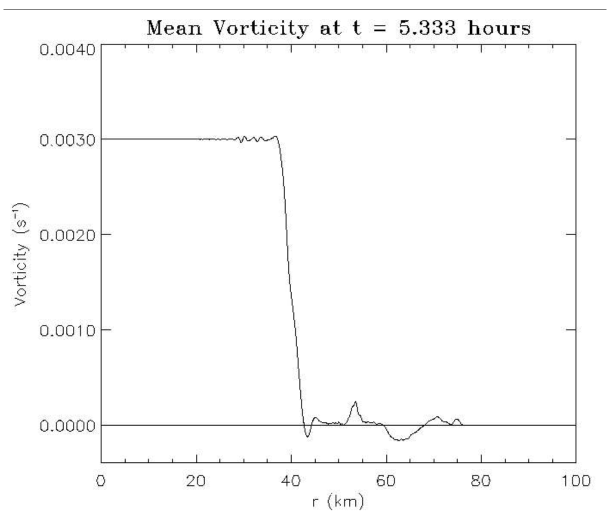

Figure 1: Mean vorticity in the 2-D Rankine vortex simulation at t = 5.333 hours.

If this large vorticity spinup is combined with Ekman pumping theory and convection, this spinup could amplify in a real hurricane vortex via buoyancy-generated vortex tube stretching and related convective processes. In fact, it is our conjecture that this feedback could amplify such a spinup to the creation of a secondary ring of convection.

It is the spatial scale of this phenomenon that may pose a challenge for current full-physics model runs. An adaptation from Killworth and McIntyre's (1985) theory on the nonlinear critical layer theories of Stewartson, Warn, and Warn gives a layer thickness on the order of

$$\delta r \propto \left|\frac{u'}{n(d\bar{\Omega}/dr)}\right|^{\frac{1}{2}}$$

where $\bar{\Omega}$ is the mean angular velocity and u' is the magnitude of the perturbation radial wind at r_c. This is on the order of 5 km in our Rankine vortex case. Although model runs are currently being run with horizontal resolutions of 1 to 2 km, vorticity filamentation and stirring is an important aspect of the critical layer theory and this happens on scales much smaller than the critical layer's thickness. Thus, the resolution requirements may be much more severe.

Similar to the critical layer theory, stagnation radii in more gently-varying mean vortices could act as focal points for vorticity spinup in perturbed vortices (Montgomery and Kallenbach, 1997) and, by the same Ekman pumping and convection mechanisms, may force secondary eyewall formation.

To further research and examine these conjectures as viable secondary eyewall formation processes, we focus on testing these ideas in more complex models, including the three-dimensional quasi-geostrophic and full-physics RAMS models. Some results from these models will be presented.

5. References

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