

## CORRESPONDENCE

### Comments on “Convectively Generated Potential Vorticity in Rainbands and Formation of the Secondary Eyewall in Hurricane Rita of 2005”

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#### ABSTRACT

In a previous paper Judt and Chen propose that secondary eyewall formation can be the result of the accumulation of convectively generated potential vorticity in the rainbands. They argue that secondary potential vorticity maxima precede the development of the secondary wind maximum and conclude that vortex Rossby waves do not contribute to the formation of the secondary eyewall. Amidst examination of their thought-provoking study, some questions arose regarding their methodology, interpretation, and portrayal of previous literature.

Here the authors inquire about aspects of the methodology for diagnosing vortex Rossby waves and assessing their impact on their simulation. Inaccuracies in the literature review are noted and further analysis of existing, three-dimensional, full-physics, numerical hurricane integrations that exhibit canonical secondary eyewalls are encouraged.

#### 1. Introduction

Secondary eyewalls are a relatively common phenomenon in mature hurricanes (Hawkins and Helveston 2008) and are associated with storm intensity change (Willoughby et al. 1982; Kuo et al. 2009) and the growth of damaging winds (Maclay et al. 2008). Despite widespread agreement among tropical meteorologists on the prevalence and importance of the secondary eyewall phenomenon in major tropical cyclones, our understanding of the formation process is still far from complete. The current lack of dynamic understanding of the secondary eyewall formation (SEF) process hinders the development of forecasting tools, which currently rely heavily on empirical relationships (Kossin and Sitkowski

2009). In this context, only a handful of studies have attempted to explain the dynamics of SEF. Some of these studies have relied upon highly idealized numerical integrations of barotropic (Kuo et al. 2004, 2008; Martinez et al. 2010) or axisymmetric models (Willoughby et al. 1984; Nong and Emanuel 2003), which for various reasons may be unfitting for studying the problem (Moon et al. 2010; Abarca 2011). It has not been until recently that full-physics three-dimensional models have been used to examine the dynamics of SEF (Terwey and Montgomery 2008, hereafter TM08; Qiu et al. 2010; Judt and Chen 2010; Martinez et al. 2011; Abarca and Corbosiero 2011; Yi-Hsuan et al. 2012; Menelaou et al. 2012). These studies have furthered our understanding of SEF to the extent that they present a clear and thorough analysis of potential formation mechanisms and factually portray the relevant contributions of the preceding scientific literature.

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## Report Documentation Page

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The study by Judt and Chen (2010, hereafter JC10) has presented a thought-provoking analysis of the SEF phenomenon. Based on an analysis of a realistic numerically simulated hurricane vortex, JC10 propose that SEF can be the result of the accumulation of potential vorticity because of convective activity in rainbands. They argue that secondary potential vorticity maxima precede the secondary wind maximum and conclude that vortex Rossby wave (VRW; Montgomery and Kallenbach 1997) dynamic fluxes are not significant to the formation of the secondary eyewall in their simulation.

Amidst our study of JC10, we have encountered a couple of questions about their analysis and scientific interpretation that may lessen the veracity of some of JC10's conclusions. We communicate these questions here in order to stimulate constructive discussion and encourage continued analysis of the JC10 simulation and other canonical simulations of SEF.

## 2. Scientific concerns

A primary scientific question of JC10 concerns their methodology for diagnosing the existence and impact of postulated VRW activity in the evolution of the mean vortex. We have identified three separate topics within this question that are problematic.

First, JC10 focus only on azimuthal-wavenumber-2 activity and ignore all other azimuthal wavenumbers. The authors argue that the wavenumber-1 asymmetry is related to vertical wind shear and/or storm motion, implicitly implying that wavenumber 1 is not relevant to either VRWs or SEF. However, vertical wind shear has been demonstrated to be a generation mechanism for wavenumber-1 VRWs (Reasor et al. 2004). Since the power of the wavenumber-1 VRW can be a substantial portion of the total perturbation power (Shapiro and Montgomery 1993, their Fig. 1; Reasor et al. 2000, their Fig. 12), it seems questionable to ignore the potential contribution of wavenumber-1 VRWs.

Second, in JC10, the eddy momentum flux divergence used to diagnose the eddy-mean flow interaction is evaluated at just one level—700 hPa. It is unclear to us why the authors made that particular choice. While 700 hPa is typically flight level and that might make the simulation level attractive for comparison with observations, when studying the vortex dynamics, a more robust analysis is needed. The lack of other level data raises the question of whether the results are indeed representative of the impact of VRWs on the mean swirling and overturning circulation in the lower troposphere. Given the results presented in a prior study by TM08 suggesting the importance of an intensifying

low-level jet and more recent results indicating that the secondary tangential wind maximum develops within the boundary layer (Didlake and Houze 2011; Bell et al. 2012; Yi-Hsuan et al. 2012), it seems questionable to study SEF using only 700-hPa-level data.

Finally, although perhaps not fundamentally altering their conclusions, JC10's methodology for identifying VRWs relies heavily on radius–time plots at a specific azimuth (from the center to the east) of the wavenumber-2 Fourier component (JC10, their Figs. 7 and 8). Strictly speaking, such plots are not the ideal diagnostic tool for identifying wave packets that propagate radially. The appropriate quantity to diagnose wave radial propagation of VRW wave packets is the wave amplitude, which is independent of azimuth by its definition [see Montgomery and Kallenbach (1997) and Chen and Yau (2001) for details]. JC10 utilize azimuth-specific cuts through the reconstruction of the Fourier component, which can allow for easy confusion of the radial group velocity and the basic representation of a radially tilted, azimuthally rotating wave.

A second overall question that we have found in our study of JC10 is that the literature review regarding the prior use of high-resolution, full-physics models to study secondary eyewalls presents statements that are unsupported by the referenced work. These statements may potentially mislead young scientists entering the field or more senior researchers desiring an update on the subject. The pertinent text is contained in the third paragraph of the introduction (note that EWRC refers to eyewall replacement cycles) and reads as follows:

“Several studies have used high-resolution, full-physics models with idealized initial and lateral boundary conditions to study secondary eyewalls (Chen and Yau 2001; Wang 2002a,b; Terwey and Montgomery 2008). It is unclear whether there were secondary eyewalls and/or EWRCs in some of these studies since the secondary wind maximum was not shown, such as in Terwey and Montgomery (2008). They used a secondary vertical velocity maximum as a proxy, which may be correlated with convection but is not necessarily representative of a true secondary eyewall with a secondary wind maximum. Another peculiar feature shown in Terwey and Montgomery (2008) is that the simulated storm went through a rapid intensification during an EWRC, which is inconsistent with all existing observations” (p. 3582).

The quoted text reports scientifically inaccurate information in every sentence. It is incorrect that Chen and Yau (2001) and Wang (2002a,b) used high-resolution models to study secondary eyewalls, as those papers focused on VRWs in the primary eyewall and inner-rainband regions and did not mention secondary eyewalls. It is incorrect also that TM08 presented incomplete evidence

of the existence of a secondary eyewall in their simulation study. Moreover, it is untrue that the TM08 simulation is inconsistent with all existing observations. TM08 succinctly summarized the modeled storm evolution (their Fig. 2), including both the maximum azimuthally averaged tangential winds and the radius of maximum tangential winds. In that figure, the maximum tangential wind exhibits a near-sudden increase in the radius of maximum winds expected in a typical eyewall replacement cycle. The authors of TM08 discussed in their text the evolution of the storm and highlighted (their paragraph 25) that such a feature “... is the key signature of a hurricane’s reorganization after the secondary eyewall supplants the inner eyewall...” TM08 offered further evidence of the low-level jet that characterizes the secondary eyewall in their Fig. 10. They presented also quantitative evidence of the convective features associated with the secondary wind maxima in their Figs. 3 and 4. This evidence constitutes ample attestation that the simulation that they studied exhibits a canonical secondary eyewall.

Finally, regarding the suggestion of JC10 in the last sentence cited above: it is incorrect that the rapid intensification during the eyewall replacement cycle indicated in Fig. 2 of TM08 “is inconsistent with all existing observations.” While most observations regarding eyewall replacement cycle lack the spatial-temporal coverage to permit a direct comparison (e.g., Willoughby et al. 1982; Kuo et al. 2009), the storm evolution presented in TM08 is not inconsistent with the observations that detail the inner-core time evolution of a storm undergoing eyewall replacement cycle (e.g., Bell et al. 2012, their Fig. 5). The storm evolution presented in TM08 is consistent also with axisymmetric balance theory, in which intensification is associated with the contraction of the outer eyewall as it becomes the primary eyewall of the storm (Shapiro and Willoughby 1982, their Figs. 15 and 16). The intensification in the TM08 simulation that JC10 make reference to above is also in good agreement with other realistic numerical simulations, including the one analyzed by JC10.

For the completeness of this comment, we present in Fig. 1 radius–time (Hovmöller) plots of the azimuthally averaged tangential wind, with the radius of maximum azimuthally averaged tangential winds<sup>1</sup> superimposed at 149-, 1910-, and 2786-m height. The figure provides further evidence that the simulation of TM08 presents a canonical eyewall replacement cycle, including the

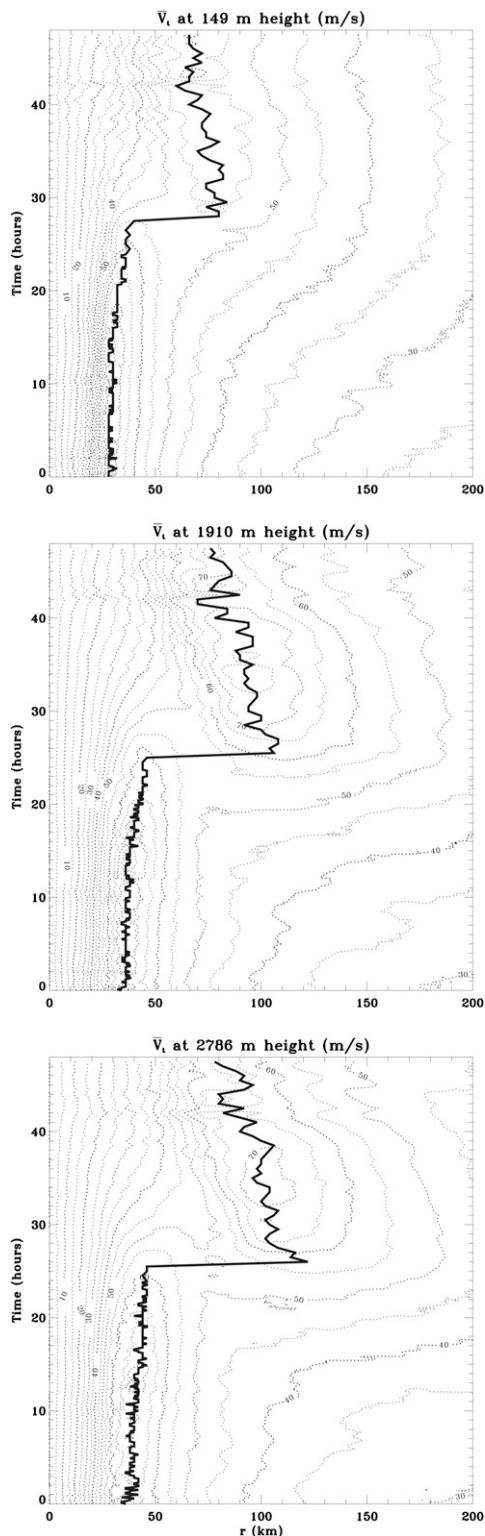


FIG. 1. Radius–time Hovmöller plots of the azimuthally averaged tangential wind (dotted lines) in the TM08 simulation over the time period of the eyewall replacement cycle described in TM08. Contour interval is  $5 \text{ m s}^{-1}$ . Each plot is at a different height: (top) 149, (middle) 1910, and (bottom) 2786 m. The solid black line is the radius of maximum winds in the azimuthal average.

<sup>1</sup> The stepped appearance of the time evolution of the radius of maximum winds is related to the fact that the horizontal grid spacing is 2 km.

weakening (accompanied with radial expansion) of the primary tangential wind maximum and also the intensification of the secondary tangential wind maximum throughout a relatively deep layer as it becomes the primary eyewall of the storm. The figure holds remarkable consistency with the evolution of other idealized (e.g., Zhou and Wang 2011, their Fig. 4) and realistic (Abarca and Corbosiero 2011, their Fig. 2c) numerical simulations, including the one studied by JC10 themselves (see their Fig. 6a).

Careful inspection of Fig. 1 reveals a notable difference between the evolution of the near-surface and interior tangential wind field. At a height of 196 m, the maximum tangential wind near 30-km radius undergoes a slow decay after about hour 15, but the decay is accompanied by a gradual outward expansion of the 40 and 50  $\text{m s}^{-1}$  wind isopleths. Superimposed on this gradually expanding wind field is the emergence at about hour 28 of a distinct secondary tangential wind maximum at approximately 75-km radius. However, at higher levels (1910 and 2786 m), the expansion of the 40 and 50  $\text{m s}^{-1}$  wind isopleths appears relatively sudden, and the secondary wind maximum is located near the 100-km radius, approximately 25 km outside the low-level maximum. Figure 1 shows also the time evolution of the radius of maximum winds. At 1910 m, this parameter remains relatively constant from about hour 0 to hour 15 and then undergoes a gentle increase (of about 10 km) from about hour 15 to about hour 25, when it suddenly increases as a result of the change of location of the strongest winds in the storm to the secondary eyewall. At 149 and 2786 m the evolution of the radius of maximum winds is similar to at 1910 m but consistent with the differences in the evolution of the described wind field in the different levels.

On the basis of the foregoing discussion, the numerical simulation presented by TM08 reproduces all identified observational aspects associated with secondary eyewalls and even suggests the possibility of new avenues of scientific investigation. Continued examination of this simulation has motivated the authors of this article to probe deeper into the dynamics and thermodynamics of SEF using a newly developed paradigm of tropical cyclone intensification proposed by Smith et al. (2009) and Montgomery and Smith (2012, manuscript submitted to *Quart. J. Roy. Meteor. Soc.*). The results of this work will be reported in due course.

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