Reply to "Comments on 'Convectively Generated Potential Vorticity in Rainbands and Formation of the Secondary Eyewall in Hurricane Rita of 2005'"

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(Manuscript received 28 May 2012, in final form 4 October 2012)

1. Introduction

Terwey et al. (2013, hereafter T13) have posted a few questions regarding the analysis of vortex Rossby waves (VRWs) and the role of VRWs in secondary eyewall formation in Judt and Chen (2010, hereafter JC10). One of the main complaints in T13 is about a point made in JC10 that a numerical simulation of eyewall replacement and related intensity change shown in Terwey and Montgomery (2008, hereafter TM08) is unphysical and inconsistent with observations. We welcome the opportunity to respond to the questions raised by T13 and will further demonstrate the aforementioned inconsistency between the model simulation of TM08 and observations by Willoughby et al. (1982) and, more recently, Bell et al. (2012).

2. Reply to specific comments

a. Azimuthal wavenumber 2

T13 raised the question of why the VRW analysis in JC10 focuses on examining the effect of azimuthal-wavenumber (WN)-2 VRWs, but not WN 1. They argued that the effect of the WN-1 asymmetric component may be important to the secondary eyewall formation and eyewall replacement and should be included in the VRW analysis. However, they missed a main point about the WN-1 asymmetry shown in JC10. The WN-1 asymmetry in Hurricane Rita is stationary, which indicates it is not a VRW. As shown in many previous studies (and also stated in T13), the WN-1 asymmetry is a response to environmental wind shear and storm motion in hurricanes. Extensive studies on shear- and motion-induced asymmetries have shown that the WN-1 asymmetry is associated with the precipitation/diabatic heating forced by shear-induced vortex tilt and/or secondary circulation related to shear and storm motion (e.g., Frank and Ritchie 2001; Black et al. 2002; Rogers et al. 2003; Chen et al. 2006; Braun and Wu 2007). The WN-1 asymmetry is usually stationary relative to shear and/or storm motion as shown in observations in Black et al. (2002) and Chen et al. (2006). Reasor et al. (2004), cited in T13, used an idealized dry model that does not represent the storm environment or convective process in a real hurricane. Figures 4 and 5 in Reasor et al. (2004) depict the WN 1 of potential vorticity (PV) propagating azimuthally around the storm center while being deformed into thin bands. In contrast, the WN-1 component of the PV field in Hurricane Rita is stationary, not deformed into thin spiral bands, and a clear response to the continuous heating asymmetry induced by the environmental shear. Furthermore, the stationary WN-1 asymmetry does not agree with VRW theory that predicts VRWs to be propagating azimuthally relative to the mean flow and/or storm center (Guinn and Schubert 1993; Montgomery and Kallenbach 1997).

b. Analysis at 700-hPa level

The second question raised by T13 is why JC10 focused on VRW activity at the 700-hPa level. One of our objectives was to use the Hurricane Rainband and Intensity Change Experiment (RAINEX) observations to evaluate and validate the model forecasts of secondary eyewall formation in a realistic large-scale environment. We chose 700 hPa for our analysis because it is the flight level of airborne observations in Hurricane Rita. In fact, 700 hPa is the preferred level for aircraft flying in most mature hurricanes, as shown in the observational studies by Willoughby et al. (1982), Bell et al. (2012), and many others. JC10 were able to first verify the model results with the RAINEX aircraft observations in Rita and

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DOI: 10.1175/JAS-D-12-0151.1

decided it was natural to use model fields at this altitude for further analysis. Furthermore, the 700-hPa level is a good representation of the lower troposphere. This is supported by the observational study by Reasor at al. (2000) in which they clearly show that the azimuthal variance of the WN-2 vorticity component does not vary much throughout the lower troposphere (cf. Reasor et al. 2000, their Fig. 12). T13 argue that the effects of VRW on secondary eyewall formation are largest in the lowest part of the troposphere, where, according to Reasor et al. (2000), the WN-1 activity is much weaker than the WN-2 VRW activity. Furthermore, the contributions from WN 3 and higher wavenumbers to the horizontal momentum fluxes are negligible compared to the lower wavenumbers. For these reasons, the analysis at levels below 700 hPa will not change the conclusion of JC10.

c. *Tracking of vortex Rossby waves in numerical models*

T13 argue that the method for tracking VRWs in JC10 is flawed. However, the arguments put forth in T13 are not applicable in this case. The authors suggest that the appropriate quantity to diagnose is the wave packet's wave amplitude as in Chen and Yau (2001). Unfortunately, Chen and Yau (2001) attempted to diagnose radial VRW propagation by calculating the third-order radial derivative of the PV Fourier amplitude and found that this approach failed to produce meaningful results in their full-physics simulation. They stated that ''In this control simulation, latent heat release continually generates PV anomalies, making it difficult to distinguish the individual wave packets. The verification of the group velocity is therefore left for the dry sensitivity test'' (p. 2137). But even the VRW tracking results from their dry sensitivity test are still not convincing, as Chen and Yau (2001) have to rely on subjectively drawn lines to indicate where they think the outward-propagating wave packets may exist (Fig. 14 in their paper). Other modeling studies cited by T13, such as TM08, did not even provide a VRW analysis while speculating about their importance.

It is difficult to track the group velocity of VRWs in full-physics, high-resolution models that simulate fast-evolving convective features in the hurricane inner core and rainbands that are controlled by complex, multiscale factors including the storm environment, which have very little to do with VRWs. JC10's main conclusions are from objective analysis of convectively induced PV in the rainbands and its subsequent axisymmetrization, which ultimately lead to the formation of a secondary wind maximum as a dynamic response to the secondary PV ring.

d. *Questions on the results of Terwey and Montgomery*

Figure 1 shown in T13 is not from the original peer-reviewed TM08. Nevertheless, this additional figure further confirms the statement made in JC10 that the model simulation in TM08 is inconsistent with observations. The issue is that the simulated tropical cyclone (TC) in TM08 was going through rapid intensification while the primary eyewall expanded outward; that is, the radius of maximum wind increases while the maximum wind increases at the same time from 50 to 170 h (TM08, their Fig. 2). This is contrary to the canonical mechanism by which a TC intensifies: conservation of angular momentum. To our knowledge, there are no observational studies supporting a storm evolution as the one shown in TM08. In fact, detailed observations from two hurricanes in Willoughby et al. (1982) clearly show that TCs either intensify while the eye/eyewall contracts, or decrease in intensity while the eye/eyewall expands (Willoughby et al. 1982, their Figs. 6 and 7).

The recent observations by Bell et al. (2012, their Fig. 5) have shown the same coherent dynamic process in Hurricane Rita: the TC intensifies while the eye/eyewall contracts, similar to what was shown in JC10 and Willoughby et al. (1982). Rita's eye/eyewall contracts between 1830 UTC 21 September and 0630 UTC 22 September 2005 and the ''best track'' intensity increases from 145 to 155 kt (from 74.6 to 79.7 m s^{-1}) between 1800 UTC 21 September and 0600 UTC 22 September. Again, this shows that the results from TM08 and T13 are inconsistent with observations. To illustrate these discrepancies, we compare the evolution of the radius of maximum tangential wind (RMW) and azimuthally averaged wind speed from T13 with that of Bell et al. (2012) side by side in Fig. 1. For a fair comparison, the aspect ratio is set to be the same for both panels. The RMWs are marked on both panels. Clearly, the observed RMW in Rita decreases while the hurricane intensifies, whereas the RMW increases while the model-simulated storm intensifies in TM08 and T13. Given this unrealistic behavior in the TM08 simulation, we suspect that the idealized model configuration used in TM08 may have a fundamental problem causing the model-simulated TC to intensify in a way that is unphysical and inconsistent with observations. The overall findings of TM08 have to be treated with caution when applied to real hurricanes.

We have addressed the questions raised in T13. JC10 presented a set of analyses from a high-resolution, full-physics model forecasts in a realistic large-scale environment, which have been evaluated/verified by the RAINEX observations. It shows evidence that convectively

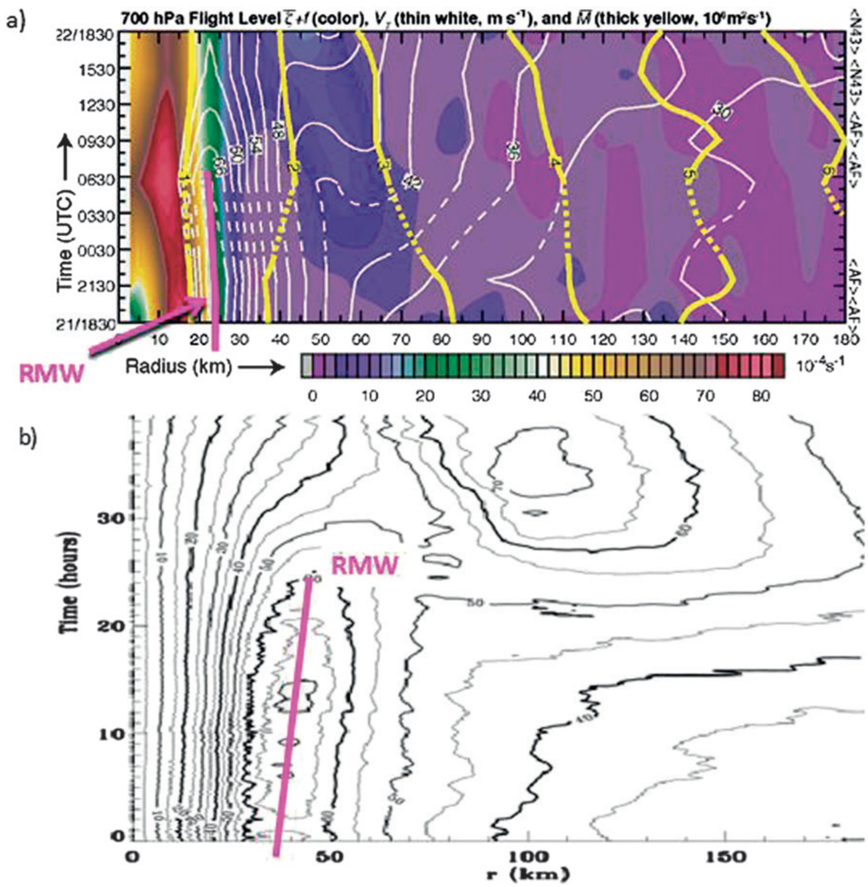

FIG. 1. (a) Azimuthally averaged vorticity (shading; 10^{-4} s^{-1}), tangential wind speed (white lines; m s^{-1}), and absolute angular momentum (yellow lines; 10^6 m^2 s^{-1}) at 700 hPa in Hurricane Rita [adapted from Bell et al. (2012)]. (b) Azimuthally averaged tangential wind speed (m s^{-1}) at 2786-m height (adapted from T13). Magenta lines denote the approximate location of the radius of maximum wind.

coupled VRWs emanating from the primary eyewall in Hurricane Rita were not able to cross the moat region between the primary eyewall and the secondary eyewall and were not responsible for the secondary eyewall formation in Hurricane Rita. The analysis of VRWs using idealized, dry models (e.g., Montgomery and Kallenbach 1997) is very valuable in terms of understanding idealized vortex dynamics in TCs. However, they cannot represent the full physical processes in a real hurricane including convective processes and its interactions with the TC environment. The convective processes are the driving force for TC evolution and the TC–environment interaction can be important for TC rainband structure, which is missing in idealized full-physics model simulations such as in Chen and Yau (2001) and TM08.

Acknowledgments. The authors are supported by research grants from the National Science Foundation (NSF) ATM-0432717 and the National Ocean and Atmospheric Administration (NOAA) NA10NWS4680013.

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