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HIGH RESOLUTION ENSEMBLE SIMULATIONS OF HURRICANE KATRINA: TWO DISTINCT REGIMES OF THE VORTEX INNER CORE STRUCTURE

by

Chi Mai Nguyen[1], Michael Reeder[1], Noel Davidson[2], Michael Montgomery[3] and Roger Smith[4]

[1] ***Department of Mathematical Sciences, Monash University, Melbourne, Australia***

[2] ***Centre for Australian Weather and Climate Research, Bureau of Meteorology, Melbourne, Australia.***

[3]***Naval Postgraduate School, Monterey***

[4] ***University of Munich, Germany***

1. Introduction

In recent years, the role of asymmetries and internal processes in the intensification of tropical cyclones has become an area of active research. Particular areas of focus have included: the relevance of vortex Rossby Waves (Montgomery and Kallenbach, 1997; Montgomery and Enagonio, 1998; Möller and Montgomery, 1999, 2000; Chen and Yau, 2003); the dynamics of eyewall meso-vortices and the mixing of potential vorticity (PV) in the tropical cyclone core (Schubert et al., 1999; Kossin and Schubert, 2001; Kossin et al., 2006); and the role of Vortical Hot Towers (VHTs) in the process of intensification (Hendricks et al., 2004; Montgomery et al., 2006, Nguyen et al., 2008). The present study seeks to understand how these phenomena and processes work in a simulation of a real tropical cyclone by a high resolution, full physics model.

The motivation for this work is to improve our understanding and prediction of rapid intensification with regards to vortex structure and inner core processes. We have studied the evolution of TC inner-region symmetric and asymmetric structure during the intensification process, as indicated in high-resolution ensemble simulations of Hurricane Katrina (2005). Both intensity and track forecasts from TCLAPS (Davidson and Weber, 2000) show encouraging skill for this storm, and for this reason, they have been analyzed in detail to understand the evolution of the vortex structure during the model integration

2. Model and Experimental Design

A high-resolution (5km, 29 vertical levels), full-physics version of operational TCLAPS with vortex specification was used for these numerical experiments. The results presented here are from an ensemble of forecasts for hurricane Katrina, created by running the system with : (i) forecast or analyzed boundary conditions, (ii) different sea surface temperature analyses, (iii) different representations of moist processes, (iv) initial vortices of different sizes, (v) different initialization techniques, and (vi) assimilated observations, perturbed by their estimated error.

3. Intensity and track simulations

The simulations of track and intensity (minimum surface pressure) from a sample of ensemble members are shown in Fig.1. The observed track is plotted in green. The outliers in the track forecasts occur when the global forecasts from 2 to 3 days prior to the base time were used as boundary conditions. Apart from these outliers, members show encouraging behavior in predicting the track and intensity. The general similarity of the member forecasts has encouraged us to examine in detail the processes during rapid intensification. In particular, we have analyzed in detail the simulation closest to the observations, called the Best Member and plotted in red in Fig.1. This forecast was obtained using analyses as the boundary conditions, and a bulk explicit microphysics scheme without the use of a convective parameterization.

[1] Corresponding Author Address: Nguyen Chi Mai.
Email: mai.nguyen@sci.monash.edu.au

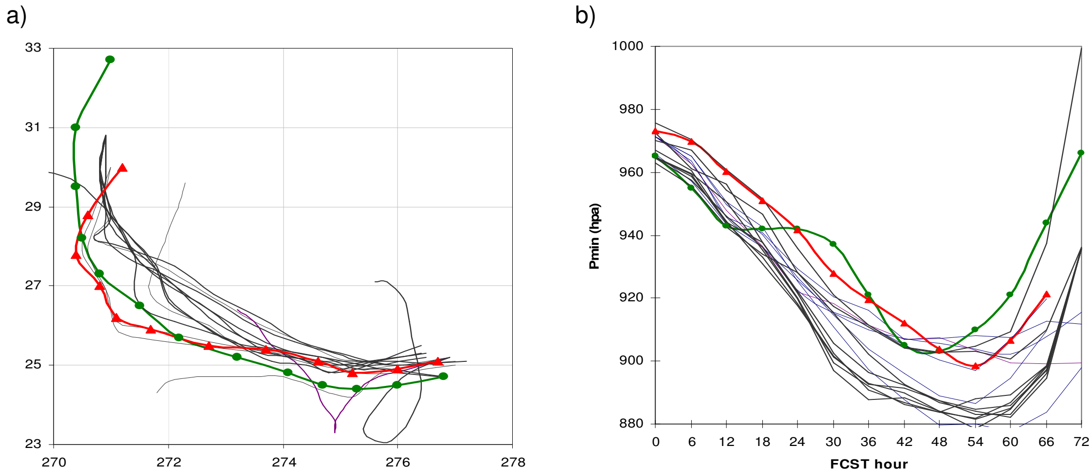

Figure 1: (a) Track and (b) intensity forecasts from high-resolution (5 km) ensemble experiments starting at 0000Z 27 August 2005. Green lines with circles represent best track and red lines with triangles are the Best Member, which is analyzed in detail.

4. Two Distinct Phases of the Vortex Structure During Rapid Intensification

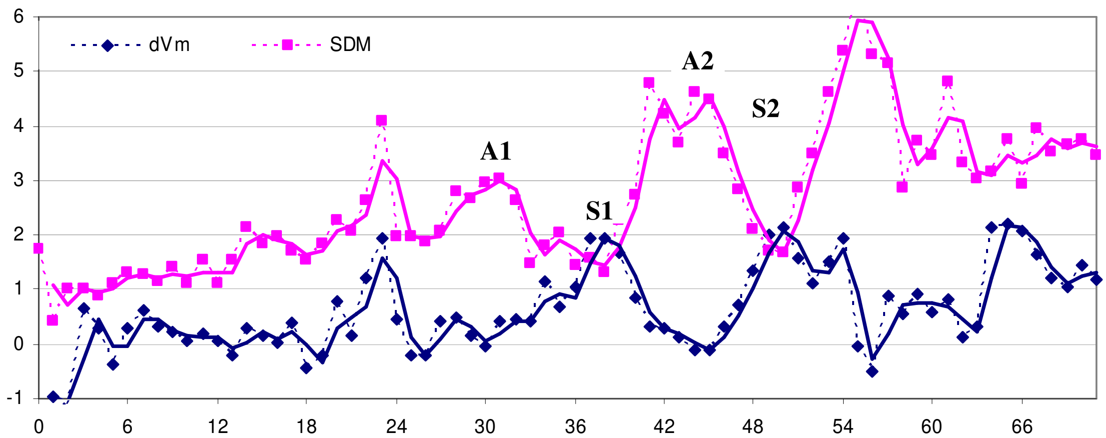

Figure 2: Time evolution of the maximum standard deviation of the PV (the pink line with squares) and tendency of the maximum mean tangential wind (the blue line with diamonds) on the 850 hPa level.

During rapid intensification, the vortex in all ensemble members appears to vacillate between symmetric and asymmetric states. While the amplitude, period and timing of the changes is variable (not shown here for brevity), the alternating pattern is common to all members of the ensemble and stands out as a robust feature of the vortex evolution. For the Best Member (Fig. 2) at hours 30, 31 and 44 of integration time, the Potential Vorticity asymmetry (PVa index defined in the footnote)† attains local maximum values (i.e. high **A**symmetry, denoted by A1 and A2 in Fig. 2). Similarly, the more **S**ymmetric state occurs at hours 39 and 50 (marked with S1 and S2 in Fig. 2). Thus, even though the modeled vortex never becomes completely symmetric (consistent with Nguyen et al., 2008), it is evident that there exists different phases with relatively more/less asymmetry and will be referred to as Asymmetric/Symmetric phases.

† The degree of asymmetry is represented by the standard deviations of the variable of interest within the annuli at different radii. Specifically, the maximum standard deviation of the PV along azimuthal circles to a radius of 300 km (denoted PVa) is used as an index of the PV asymmetry

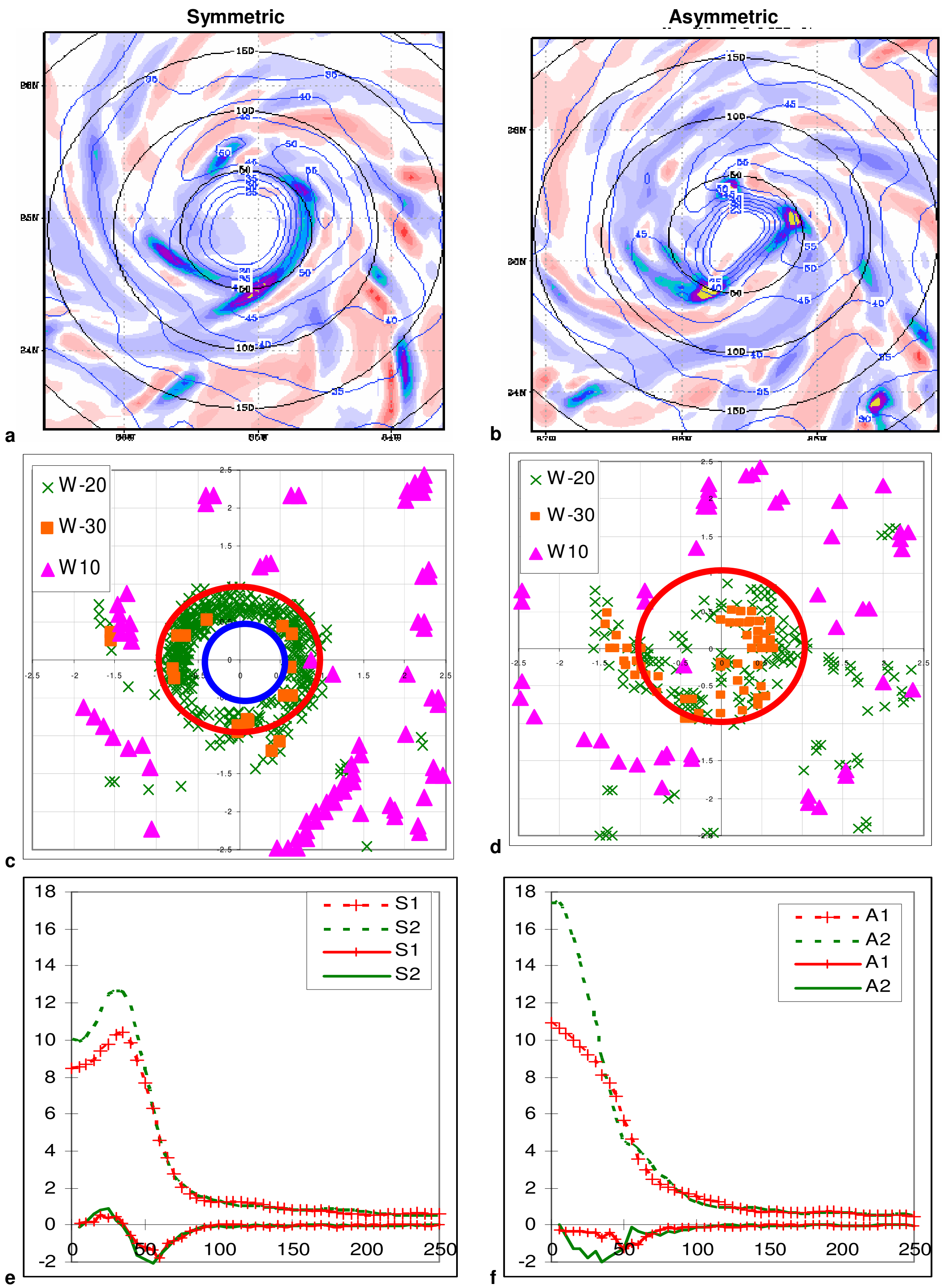

Figure 3. Vortex structure during the Symmetric phase (left panels) and the Asymmetric phase (right panels). *Top row.* Vertical velocity (shaded) and horizontal wind magnitude (contours) for (a) S1, and (b) A2. *Middle row.* Composites of VHT locations during the (c) the Symmetric phase and (d) the Asymmetric phase. Green crosses mark hot towers with vertical motion between -15 to -20 Pa/s; orange squares mark very hot towers with vertical motion less than -20 Pa/s; pink triangles mark downdrafts with vertical motion greater than 10 Pa/s. *Bottom row.* Azimuthal mean PV (dashed lines) and its radial gradient (solid lines) at times (e) S1 and S2, and (f) A1 and A2.

The structure of the vortex during the two phases displays distinct differences. The Asymmetric phase (Fig. 3, right panels) is associated with very strong convection, clustered in the form of 2, 3 or 4 local maxima near the center (to within 10km of the center). These mesoscale structures, which may create their own local circulations, are very similar to VHTs described in Montgomery et al. (2006) and will be interchangeably called VHTs or eye-wall meso-vortices. In contrast, the convective features during the Symmetric phase appear to have smoother structures with fewer VHTs and have the form of stretched bands, wrapping around the eye (Fig. 3a). Thus, in the composite plots of VHT locations, the Symmetric phase appears as a ring, confined between the Radius of Maximum Wind (RMW) and Radius of Maximum PV (Fig. 3c), whereas the Asymmetric phase shows a pattern of scattered strong VHTs at radii much closer to the tropical cyclone center (Fig. 3d).

As can be seen from Fig. 2, the symmetric phase tends to correspond with the times of largest intensification rate of the maximum mean tangential wind at the same level. Conversely, the intensification rate during the Asymmetric phase tends to be smaller. This relationship is seen as an anticorrelation pattern between PVa (pink line with squares) and the intensification rate of the maximal mean tangential wind DV_m/Dt (dark blue line with diamonds). This is consistent with the results of Willoughby (1990), who found that when asymmetric convection erupts near the center of tropical storms or weak hurricanes, it may slow down the intensification rate.

5. Transition between A and S phases.

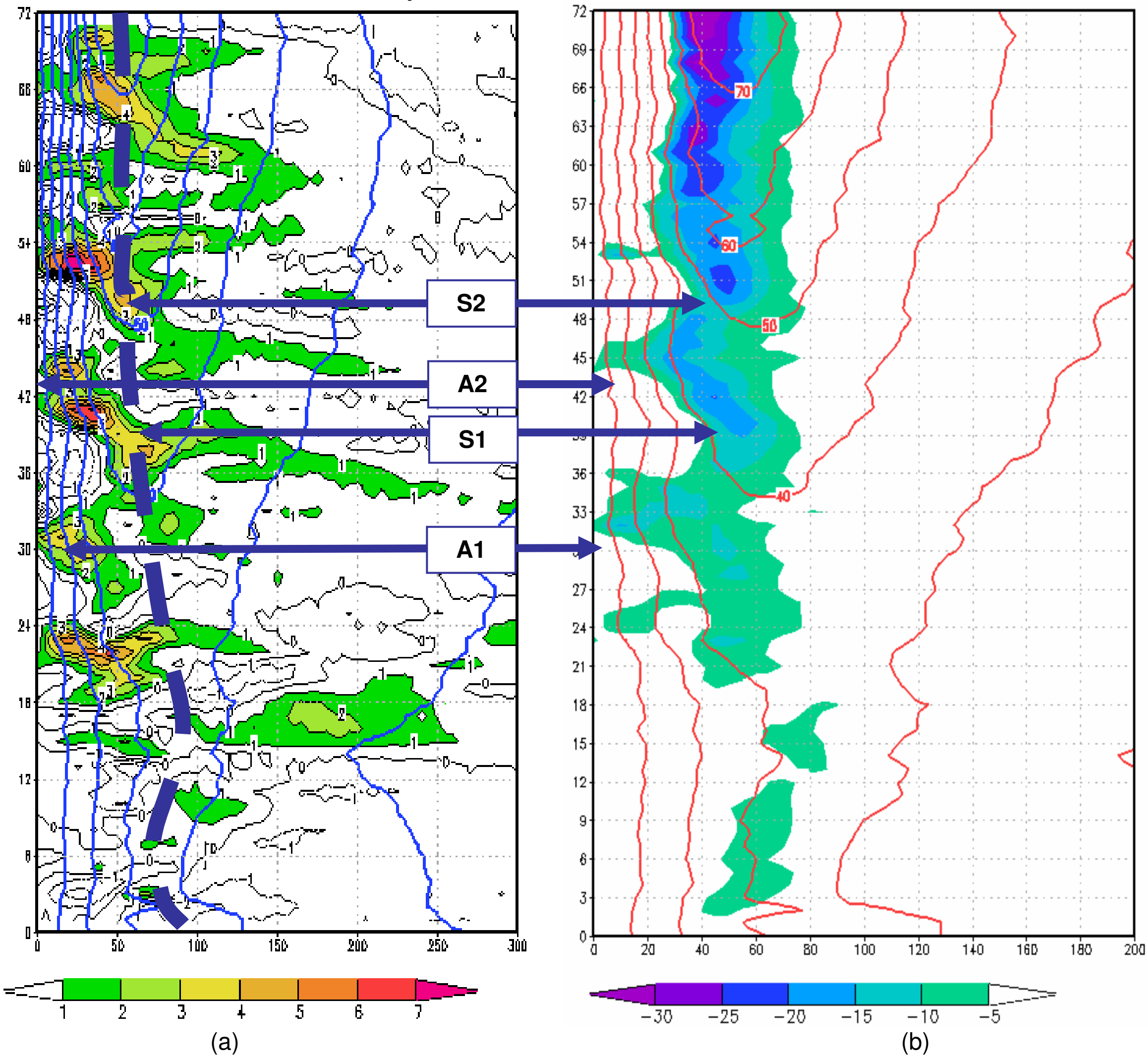

Figure 4: Radius-Time plots of (a) the mean tangential wind tendencies DVt/Dt at 850 hPa(positive tendencies are shaded, contours are the isolines of mean tangential wind Vt, the thick long dashed line represents the RMW); and (b) the radial gradient of mean PV (large negative values are shaded, contours are the isolines of mean tangential wind) at 850 hPa. Note different radial scales.

During rapid intensification, the transitions between Asymmetric and Symmetric phases are reflected in the mean radial gradient of the PV. Figure 4b shows that the vortex goes through a series of changes from the Asymmetric phase, with a negative PV gradient (a monopole PV structure), to the Symmetric phase, with a change in sign of the PV gradient from positive to negative at some small radii (an elevated PV ring structure). An example of the profiles of PV and its gradient at particular times of each phase is shown in Figs. 3e (S1) and 3f (A2). However, later in the integration, e.g. after 54 h, the elevated PV ring persists without transforming back to the monopole structure as occurred during rapid intensification.

It is interesting to note that the change from the PV ring to the monopole structure resembles the PV mixing process described in Schubert et al. (1999), in which the ring structure in the absence of forcing can be barotropically unstable and in such cases vigorous mixing relaxes the ring of PV into a stable monopolar distribution. However, in our simulations, this transition period tends to occur on a much shorter time scale (about 6 h) than that reported in Schubert et al. (1999) (about 48 h), and therefore, dynamical instability may not be the total explanation for the transition. Rather, it is possible that the dynamical instability of the ring structure during the Symmetric phase may contribute to the initiation of the VHT outbreak, apart from the convective instabilities as suggested by Montgomery et al. (2006) and Nguyen et al. (2008). Then, the mixing of air between the eye and the eyewall by VHT meso-circulations will result in the monopole form of the PV profiles in the Asymmetric phase. The mixing effects of VHTs can be seen also in the radial-time plot of the mean tangential tendencies (Fig. 4a), in which the transition from the Symmetric phase to the Asymmetric phase is characterized by a decrease/weak increase of mean tangential wind (blank areas) near the RMW, and strong increase (shaded areas) at inner radii.

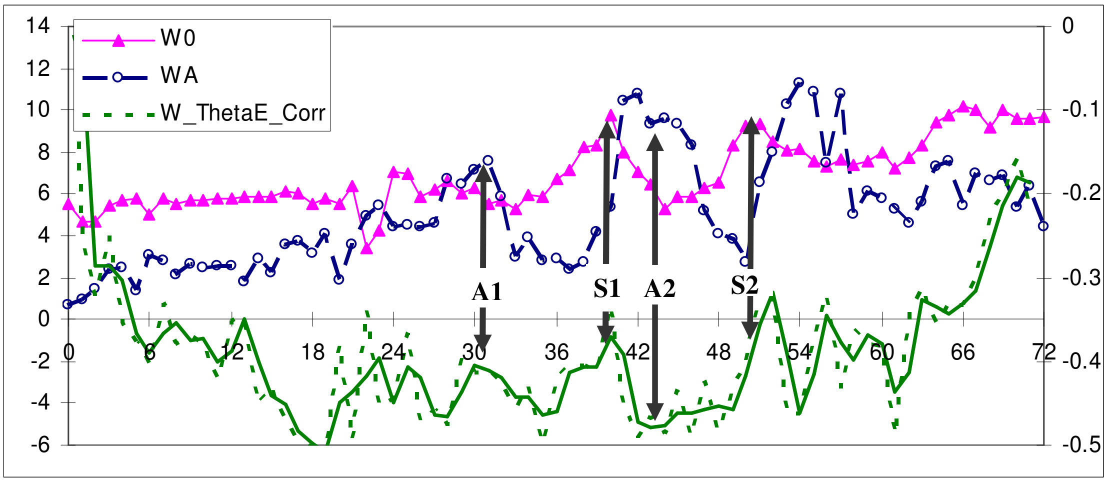

Figure 5: Time evolution of wave amplitudes of PV along the 50 km radius circle at 850 hPa. Pink line with triangles are for wavenumber 0 or symmetric PV. Blue line with circles are for sum of the wavenumbers from 1 to 4. Green dotted line shows spatial correlation coefficients of θ_e anomalies and vertical velocity at 850 hPa. Green solid line is the moving average of the green dotted line, displayed for highlighting the transient trend.

From other perspectives, there is evidence also that the outbreaks of VHTs in the Asymmetric phase may owe their existence to both convective and dynamic instabilities. Figure 5 shows the time evolution of the symmetric (pink) and asymmetric (blue) Fourier components of PV along the 50 km radius circle at 850 hPa. It is evident from this plot that the asymmetry peaks shortly after the symmetric component has reached its maximum. This suggests that the VHTs may be excited by the unstable dynamic configuration in the Symmetric phase. Further, the peak amplitudes of the asymmetric components in the Asymmetric phase (e.g. at A2) appear to be greater than that of the earlier symmetric component in the Symmetric phase (e.g at S1). Therefore, it follows that at least some energy of the Asymmetric phase must come from sources other than that being released from the disruption of the mean flow (i.e. wave number 0). As an alternative, convective instabilities may well play a part here. This is supported by the fact that the spatial correlation coefficients of the updrafts and θ_e anomalies at 850 hPa increase significantly (negatively correlated) in the Asymmetric phase (A2) compared with the Symmetric phase (S1, S2) (green line in Fig. 5). Then, if we use θ_e anomalies as a measure of convective instability, the increase of the correlation coefficient during the Asymmetric phase implies that VHTs are tied to the convectively unstable regions in the inner core, and thus, highlight the role of convective instability.

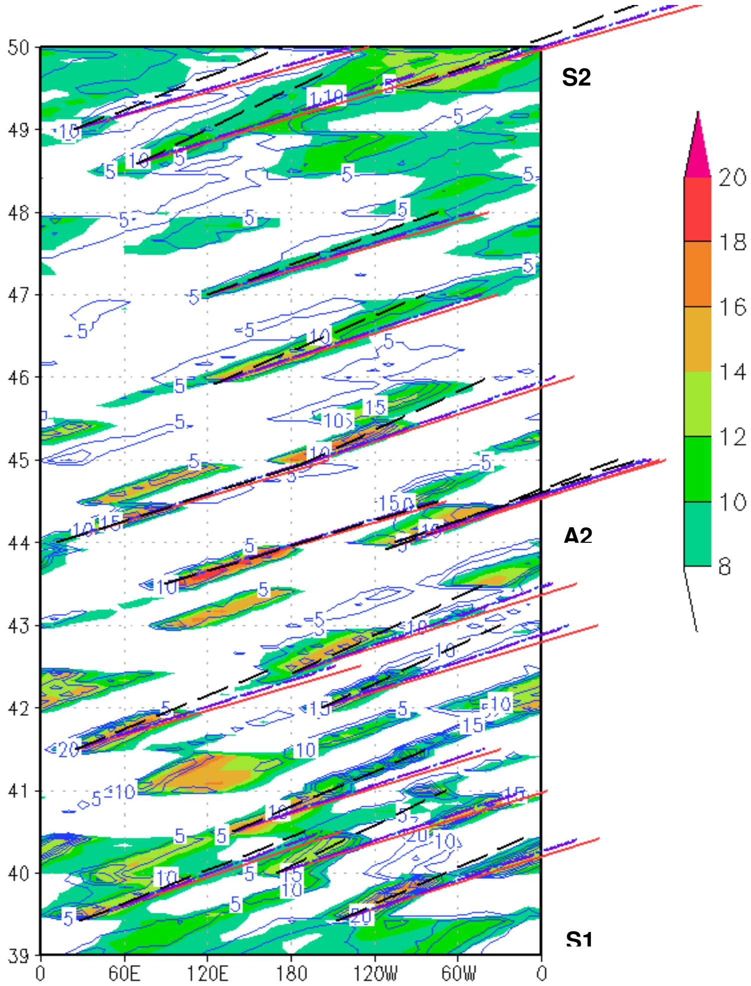

Figure 6: Hovmoller diagram of PV (shaded positive values) and vertical velocity (blue contours) at 850 hPa along the 50 km radius circle. On the horizontal axis, the direction from left to right is the cyclonic displacement. Red lines are the mean tangential flow. Black long-dashed lines indicate the azimuthal movement of the traced VHTs or PV anomalies. Purple dash-dotted lines show the phase speeds of the vortex Rossby waves calculated according to Möller and Montgomery (2000) for wavenumber 3.

During the transition from the Asymmetric phase to the Symmetric phase, we hypothesize that vortex Rossby waves may play a role in axisymmetrizing and redistributing the PV produced by VHTs in order to strengthen the mean flow near the RMW. As can be seen in the Fig. 6, the VHTs appear to behave qualitatively like vortex Rossby waves. That is, in the regions of negative radial PV gradient, vortex Rossby waves retrogress relative to the mean flow as predicted by Montgomery and Kallenbach (1997), and Möller and Montgomery (2000). In addition, it is interesting to note that the observed retrogression during the Asymmetric phase (approximately 15% slower than mean flow) is less than that which occurs near the Symmetric phase (about 30%).

Summary and Future Work

It was found from high-resolution ensemble simulations of hurricane Katrina that during rapid intensification, the simulated tropical cyclone goes through a series of structure change cycles, alternating between Symmetric and Asymmetric phases. The Symmetric phase is characterized by: a relatively symmetric eyewall consisting of stretched convective bands around the tropical cyclone center; an elevated PV ring structure; and a tendency for the maximum mean tangential wind to rapidly accelerate. In contrast, during the Asymmetric phase: the eyewall tends to be more asymmetric with 2, 3 or 4 local updraft maxima, resembling Vortical Hot Towers (Montgomery et al., 2006); these VHTs are located at inner radii much closer to the tropical cyclone center than during the Symmetric phase; the azimuthal mean PV has a monopole structure with the maximum at the center; and the mean vortex tends to intensify more slowly. In addition, the retrogression of PV anomalies and VHTs relative to the mean flow suggests that they behave as vortex Rossby waves.

We hypothesize that the transition from the Symmetric to the Asymmetric phase (i.e. the outbreak of VHTs) may be conditioned by the cooperative effects of dynamic instability (PV ring structure) as proposed by Schubert et al. (1999); and convective instability as suggested by Montgomery et al. (2006) and Nguyen et al. (2008). The VHTs and their mesoscale circulations excited by these conditions then vigorously mix the air between the eye and the eyewall resulting in a monopole PV structure by the end of the Asymmetric phase. Conversely, the transformation process from the Asymmetric to the Symmetric phase is proposed to be linked to the axisymmetrizing effects and propagation of vortex Rossby waves similar to that predicted by Montgomery and Kallenbach, (1997) and Möller and Montgomery (2000). Alternatively, the mean wind may be drawing energy from the pertubations in an upscale cascade. More work is required to clarify these processes.

Even though these findings are from simulations of one particular hurricane, the features analysed are common to most members of the ensemble. For this reason, we expect that the mechanism described may be generally present during rapid intensification of tropical cyclones. However, work needs to be done to further quantify the proposed mechanisms. Several important issues need to be addressed, including: the roles of dynamic and convective instabilities in initiating the VHTs; the roles of VHTs in strengthening the mean circulation; and environmental influences on these mechanisms from the outer part of the tropical cyclone vortex. Work is continuing and will be reported on in the near future.

Acknowledgements

The first author is grateful to Drs. Kevin Tory, Jeff Kepert, Greg Holland, and Jenni Evans for their helpful discussions while doing the analysis. This work is a part of the PhD thesis of the first author, sponsored by AusAID.

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