1C.1 TROPICAL CYCLONE FORMATION MECHANISMS IN THE BMRC TROPICAL CYCLONE LIMITED AREA PREDICTION SYSTEM (TC-LAPS)

Kevin J. Tory[1], Michael T. Montgomery[#] and Noel E. Davidson
Bureau of Meteorology Research Centre, Melbourne, Australia
[#]Colorado State University, Fort Collins CO USA

1. INTRODUCTION

Over the last decade the search for Tropical Cyclone (TC) genesis mechanisms has focussed on observations that genesis typically occurs when low-level vorticity intensifies below a mid-level vortex. A number of theories have been proposed and tested in idealized modeling studies. These theories can be loosely categorized as “top down” and “bottom up”. In the former PV/vorticity is transferred or projected from the mid-levels to the surface (e.g., Bister and Emanuel, 1997; Ritchie and Holland, 1997), and in the latter interactions between intense, small-scale, low-level vortices associated with cumulonimbus hot towers, and the mid-level vortex lead to low-level intensification on the storm-scale (e.g., Montgomery and Enagonio, 1998). Recently, Hendricks et al. (2004, hereafter HMD04) and Montgomery et al. (2004, hereafter MNCS04), have made significant advances in their investigation of the “bottom up” mechanism. Using high-resolution cloud resolving, non-hydrostatic forecast and idealized models, they have identified two processes responsible for the low-level vortex intensification responsible for TC genesis in their models. The first is the merger of small-scale but intense vortices produced by hot tower convection, leading to an “upscale vortex cascade”. The second is the large-scale convergence of absolute vorticity induced by an enhanced secondary circulation in response to the net heating within an ensemble of hot towers.

An analysis of a number of TC genesis simulations in the Australian Bureau of Meteorology’s operational TC forecast model (TC-LAPS) has shown both of these “bottom up” processes were active. Additionally we have found that the ultimate location of the intense low-level vortex that develops to at least Tropical Storm (TS) intensity is dependent on the location of the most intense and persistent convection, and the location and structure (vertical and horizontal) of the monsoon depression that the convection is embedded in.

In this paper we illustrate these mechanisms using a simulation of TC Chris, which formed off the west coast of Australia in February 2002.

2. TC CHRIS, FEBRUARY 2002

The genesis of TC Chris occurred between 1—3 February 2002 and after reaching TC strength it intensified to a Category 5 TC within 60 hours. TC Chris tracked southward until it made landfall on 7 February. Satellite observations and scatterometer winds (not shown) suggest the convection and large-scale, low-level flow during the early formation stages (first 12 hours) were both well represented by the TC-LAPS simulation. In the next 12 hours the convective and low-level flow patterns continued to be well represented, except that the simulation showed a more rapid contraction of scale and large-scale vortex intensification than that observed. Detailed verification of the genesis processes was not possible since observations of sufficient spatial and temporal resolution are not available. However, the processes introduced in the next section are consistent with available observations, and many observational studies of other storms featured in the literature.

3. GENESIS PROCESSES

Azimuthal mean tangential momentum and potential temperature budgets were performed centered on the $\sigma = 0.85$ PV centroid (here PV = Ertel’s Potential Vorticity). These budgets, summed over the first 18 hours of the simulation (not shown), identified three significant processes that contributed to the large-scale vortex intensification. 1. Eddy processes such as axisymmetrization and merger of PV/vorticity anomalies (HMD04’s upscale vortex cascade). 2. Mean low-level convergence of absolute vorticity and mean vertical advection of vorticity on the scale of intense convective bursts (introduced in the next section). 3. The large-scale vortex intensification process identified by HMD04 and MNCS04, in which the system-scale secondary circulation is enhanced by convective heating, leading to increased low-mid level convergence of absolute vorticity. Positive contributions to the mean vortex intensification from the first two processes were largely confined to a radius of about 150 km, whereas positive contributions from process 3 extended to a radius of about 300 km.

4. VORTEX CORE DEVELOPMENT

Figure 1 shows Ertel’s Potential Vorticity (PV) on the $\sigma = 0.85$ surface at 4, 6, 8 and 10 hours into the simulation. It illustrates the upscale vortex cascade process, whereby merger and axisymmetrization of PV anomalies generated by successive periods of intense convection, contribute to the growth of the low-level vortex core that forms the basis of the modeled TC (process 1).

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[1] *Corresponding author address*: Kevin J. Tory,
BMRC, GPO Box1289K, Melbourne, Australia, 3001.
Email: k.tory@bom.gov.au

A small PV anomaly associated with a cell of intense convection (labeled ‘B’ in Fig. 1a) was orbiting the main anomaly at the center of the large-scale circulation (labeled ‘A’). With time ‘B’ intensified while continuing to orbit ‘A’ (Fig. 1b—c). Eight hours into the simulation ‘B’ had become dominant and was in the process of “ingesting” PV from ‘A’ (note the reduced intensity of ‘A’ between Fig. 1b and 1c). Another two hours later ‘B’ had become the PV core, while the remnants of ‘A’ continued to be axisymmetrized by ‘B’ (Fig. 1d). Also evident in Fig. 1d is the emergence of a third anomaly ‘C’ associated with the next convective burst. As ‘C’ emerged the convection associated with ‘B’ subsided, and the cycle was repeated. Anomaly ‘C’ intensified at the expense of ‘B’ and became the new, and now more intense, PV core (not shown).

Comparisons of the horizontal wind vectors between Fig. 1a and 1d, shows enhancement of the circulation more than 100 km beyond the intensified PV core. The budgets mentioned above would suggest this is due to process 3.

The development of the vortex core has implications above the low-levels as well. A substantial westward slope with height of the monsoon depression vortex was present initially. Significant upward PV advection within the convective burst updrafts led to the development of an upright PV core (process 2), about which axisymmetrization and merger (process 1) and the large-scale convergence of absolute vorticity by the enhanced secondary circulation (process 3) contributed to a vertical alignment of the monsoon depression vortex, centered on the upright PV core. The “bottom up” development of the PV core (process 2) is evident in Fig. 2, which shows PV and horizontal winds on the σ = 0.5 surface. Figure 2a shows enhanced PV immediately above anomaly ‘B’ in Fig. 1b. Two hours later it had become the most substantial anomaly at this level (Fig. 2b). Over the next 24 hours the surrounding anticyclonic and cyclonic PV anomalies evident in Fig. 2 were gradually ejected and consumed respectively by the central PV core (process 1), which further contributed to the vortex development (not shown).

5. SUMMARY

The overall structure of the TC-LAPS monsoon depression and embedded convection verified well with satellite cloud and scatterometer wind observations during the early formation stages. Two genesis processes (vortex upscale cascade and large-scale secondary circulation enhancement) identified in contemporary genesis studies that used both idealized and realistic cloud resolving models of 5 times greater horizontal resolution (HMD04, MNCS04), were also found to be active in the TC-LAPS simulations. A third process, the building of an upright PV core, was found to be particularly important in the TC-LAPS simulations. The upright PV core may have served to focus the other two genesis processes about a common location, which led to the development of a vertically aligned vortex of TS scale and intensity.

6. REFERENCES

Bister, M., and K. A. Emanuel, 1997: The genesis of Hurricane Guillermo: TEXMEX analyses and a modeling study. *Mon. Wea. Rev.*, **125**, 2662—2682.

Hendricks, E. A., M. T. Montgomery and C. A. Davis, 2004: On the role of “vortical” hot towers in hurricane formation. *J. Atmos. Sci.,* submitted.

Montgomery, M. T., M. E. Nicholls, T. A. Cram and A. Saunders, 2004: A “vortical” hot tower route to tropical cyclogenesis. *J. Atmos. Sci.*, submitted.

Montgomery, M. T. and J. Enagonio, 1998: Tropical cyclogenesis via convectively forced vortex Rossby waves in a three-dimensional quasigeostrophic model. *J. Atmos. Sci.*, **55**, 3176—3207.

Ritchie, E. A. and G. J. Holland, 1997: Scale interactions during the formation of Typhoon Irving. *Mon. Wea. Rev.*, **125**, 1377—1396.

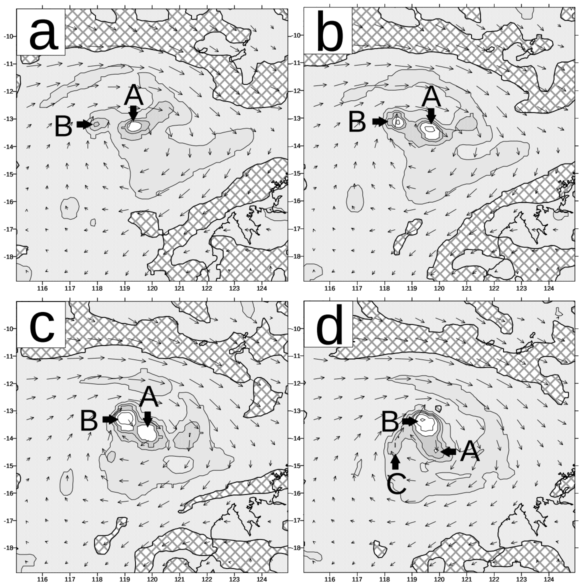

Figure 1. PV and horizontal wind on the σ = 0.85 surface at (a) 4, (b) 6, (c) 8 and (d) 10 hours into the simulation of TC Chris. Contour interval 0.5 PVU shaded, then 3, 5, 10 PVU white. Anticyclonic PV represented by cross hatching.

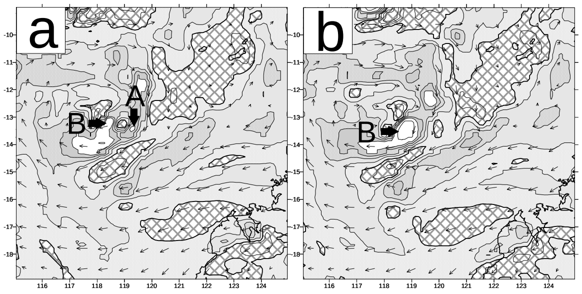

Figure 2. As in Fig. 1 except PV on the σ = 0.5 surface, (a) 6 and (b) 8 hours into the TC Chris simulation.