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TROPICAL CYCLONE GENESIS IN TC-LAPS: THE IMPORTANCE OF SUFFICIENT NET DEEP CONVECTION AND SYSTEM SCALE CYCLONIC ABSOLUTE VORTICITY

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1. Introduction

Tropical Cyclone (TC) genesis in the Australian Bureau of Meteorology's Tropical Cyclone Limited Area Prediction System (TC-LAPS), an operational Numerical Weather Prediction forecast model, has been investigated over the last five years. Despite significant differences in genesis rates and vortex evolution between events, the fundamental genesis mechanisms are the same for all simulations. The primary vortex enhancement mechanism is low- to mid-level vortex convergence in model resolved convective regions (Tory et al. 2006a). Two secondary vortex enhancement mechanisms act to focus vorticity into an upright monolithic vortex core. The first mechanism, vortex upscale cascade, is the merger and axisymmetrization of vortices to produce larger more intense vortices. The second is the System Scale Intensification (SSI) mechanism, whereby the vortex intensifies on the system–scale in response to greater net diabatic heating than adiabatic cooling in convective regions, which drives a secondary circulation in a manner akin to the classic Eliassen model of a balanced vortex driven by heat sources. This secondary circulation extends well beyond the convective region, and enhances the cyclonic environment through low- to mid-level convergence of absolute vorticity.

These mechanisms were identified by Hendricks et al. (2004) and Montgomery et al. (2005). A detailed study of the genesis dynamics in a TC-LAPS simulation of TC Chris (Tory et al., 2006b) identified both secondary mechanisms were active and responsible for genesis. The primary and two secondary mechanisms have been identified in all TC-LAPS genesis simulations we have investigated in detail so far, including three developing simulations presented in Tory et al. (2006c). In this latter work the significant differences in genesis patterns despite the common primary and secondary genesis mechanisms was illustrated. Two non-developing simulations were also presented that illustrate genesis sensitivity to shear and cyclonic environment. In this extended abstract we present two simulations, and focus on what we believe to be the fundamental ingredients for genesis in TC-LAPS and possibly the real world, sufficient net deep convection and system scale cyclonic absolute vorticity.

Here we define net deep convection as either single or multiple convective regions in which the mean horizontal divergence profile consists of low- to mid-level convergence with divergence above.

2. TC-LAPS convection

The 0.15° grid spacing used in the operational TC-LAPS results in a minimum convective scale of about 60 km. This is too large to represent individual convective elements. TC-LAPS also includes convective parameterization, which is found to be necessary for successful genesis forecasts. (See Tory et al., 2006a for a detailed description of the TC-LAPS configuration.) The following question then arises, can a model with cumulus parameterization and grid spacing too large to resolve convective elements, be producing the right answer for the right reason? We believe the answer to this is yes, while acknowledging that the

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exact path to genesis in terms of numbers of convective bursts and their interactions is not likely to be captured by the model. We argue in Tory et al. (2006c) that this level of forecast accuracy may not be necessary for qualitative success, and leads us to conclude that TC genesis is largely driven by forcing on scales resolvable by TC-LAPS.

Although the TC-LAPS resolved updrafts are poor representations of individual convective elements they appear to represent active convective *regions* quite well. The TC-LAPS updraft convergence profiles are of the same magnitude and similar structure as mean convergences observed in large-scale tropical convective regions (e.g., Mapes and Houze, 1995). We propose that at least in the middle to later stages of genesis the TC-LAPS resolved deep updrafts may adequately represent the mean convergence and net heating associated with an ensemble of convective updrafts present in a tropical convective region.

This simplified representation of convective regions appears to be sufficient for qualitative genesis forecasting success. TC-LAPS has had good success in forecasting both developing and non-developing storms (work currently underway). However, there is often a tendency for too rapid intensification in the early stages of genesis. This is likely to be due to the model updrafts forcing unrealistically large low- to mid-level convergence early in the genesis period.

The TC-LAPS resolved convective updrafts essentially represent mean Mesoscale Convective System (MCS) motions. It has been recognized for some time that MCSs are comprised of both stratiform and convective precipitation with the proportions varying considerably between systems and throughout individual MCS life cycles. Mapes and Houze (1995) identified two dominant vertical profiles of mean horizontal divergence in tropical MCSs, lower tropospheric convergence with upper tropospheric divergence (associated with deep convection), and mid-tropospheric convergence with upper and lower tropospheric divergence (associated with stratiform precipitation). It may be that TC-LAPS is not capturing the stratiform dynamics sufficiently during the early stages of genesis. If this is true then it would follow that MCSs in a genesis environment undergo some form of transition during the genesis period. Here we propose a hypothesis for such a transition.

In a convective region, a dry environment encourages convective downdrafts, which suppress further convective cells at their source. Given sufficient large-scale convective forcing in such an environment, it might be expected that multiple short-lived convective episodes would be active, the remnants of which feed a developing stratiform precipitation deck. The same forcing in a moist environment will be less affected by convective downdrafts and may favor longer-lived convection without a significant stratiform precipitation deck developing. With time it would be expected that MCS activity of any type would moisten the middle troposphere, and thus encourage a temporal transition from MCSs dominated by stratiform dynamics to those dominated by convective dynamics.

Observations do show that later in the genesis process, convective region scales typically exceed the minimum TC-LAPS updraft scales, often in excess of 100 km (e.g., Zehr, 1992). We argue in Tory et al. (2006a,b) that very cold cloud top temperatures identified in IR satellite imagery can be used to identify active convective regions. A temperature threshold of about 190 K compares well with the TRMM convective rain rate threshold of 10 mm hr^{-1} for three hourly averaged rainfall rates, suggested by Rapp et al. (2005). Assuming these very cold CTTs are a good proxy for deep convective horizontal mean divergence profiles (low- to mid-level convergence with divergence above) TC-LAPS-like genesis processes may well be active in the real atmosphere (at least during the middle to later genesis stages). Evidence in support of this includes similarity in convective region behavior between the TC-LAPS updrafts (and associated vorticity structures) and observed convective bursts. The convective contraction identified by Zehr (1992) in which the active convective regions slowly converge on a 100 km central diameter just prior to Tropical Storm (TS) intensity is present in the TC-LAPS simulations. The resolved updraft cores tend to form initially a few hundred km from the large-scale circulation center, and then spiral inwards with time, reaching TS intensity at about the time the convection becomes focused within a 100 km diameter central region.

3. Developing and non-developing storms

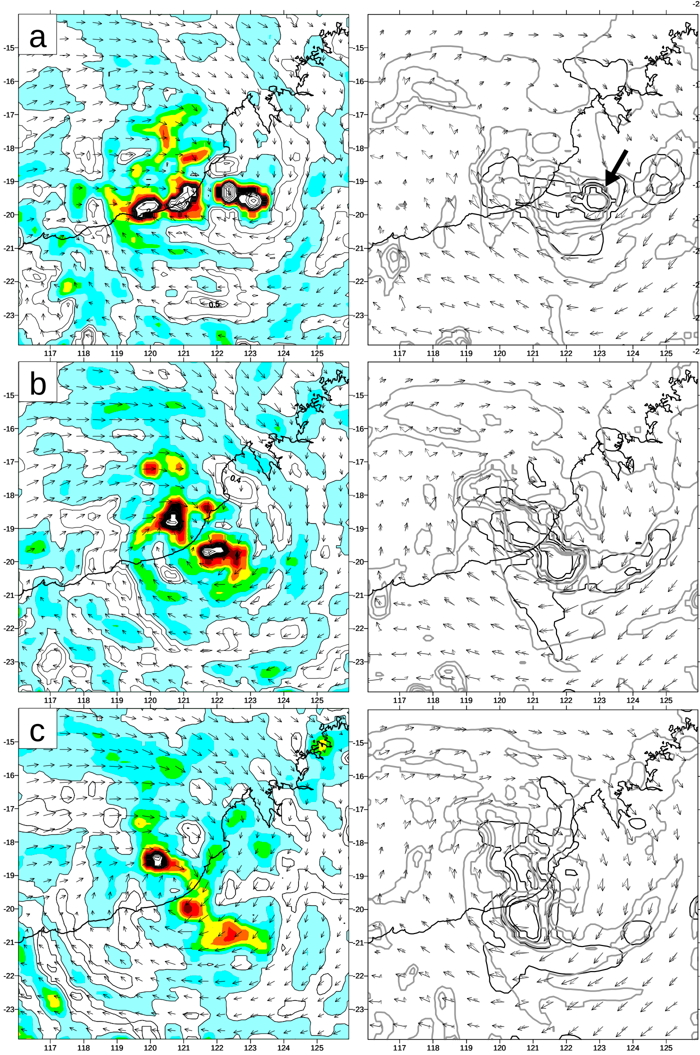
The examples presented below illustrate the genesis process in TC-LAPS and the opposition to genesis by an unfavorable environment. The events occurred one week apart and within a few hundred km of each other. Both were tropical depressions over land that passed from northern Western

Australia offshore to the Indian Ocean. The first developed into TC Monty, and the second, a decayed TC Evan, failed to re-develop.

TC Monty

Within 24 hours of the depression crossing the coastline TC Monty had been declared (Tropical Storm intensity), and had reached severe TC intensity within another 24 hours. The TC-LAPS evolution of TC Monty is illustrated in Fig. 1, which shows vertical velocity on the σ = 0.25 surface as a proxy for deep convection (left panels), and low and mid-level PV on the σ = 0.85 and σ = 0.50 surfaces respectively (right panels).

After 4 hours model time, Fig. 1a shows four active convective regions spread over a distance of about 400 km along the coast and inland. A large mid-level PV anomaly spanned the convective area and beyond. A more intense low-level anomaly was close to coincident with the furthest inland (easternmost) convective region (arrowed). This anomaly formed primarily from low- to mid-level vorticity convergence into the model resolved updraft (i.e., the primary vortex enhancement mechanism). Four hours later (Fig. 1b) convection was active in two main regions on either side of the coastline, with associated cyclonic PV maxima at both low- and mid-levels creating a PV dipole spanning the coastline. Convection was favored in the



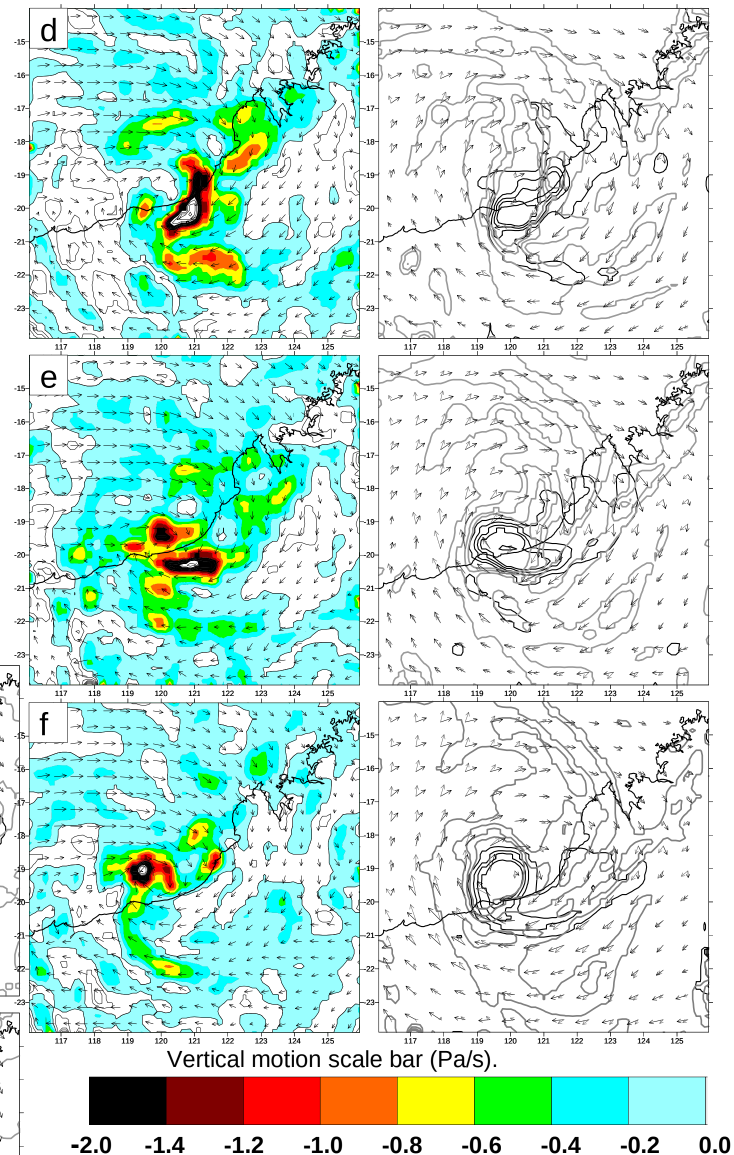
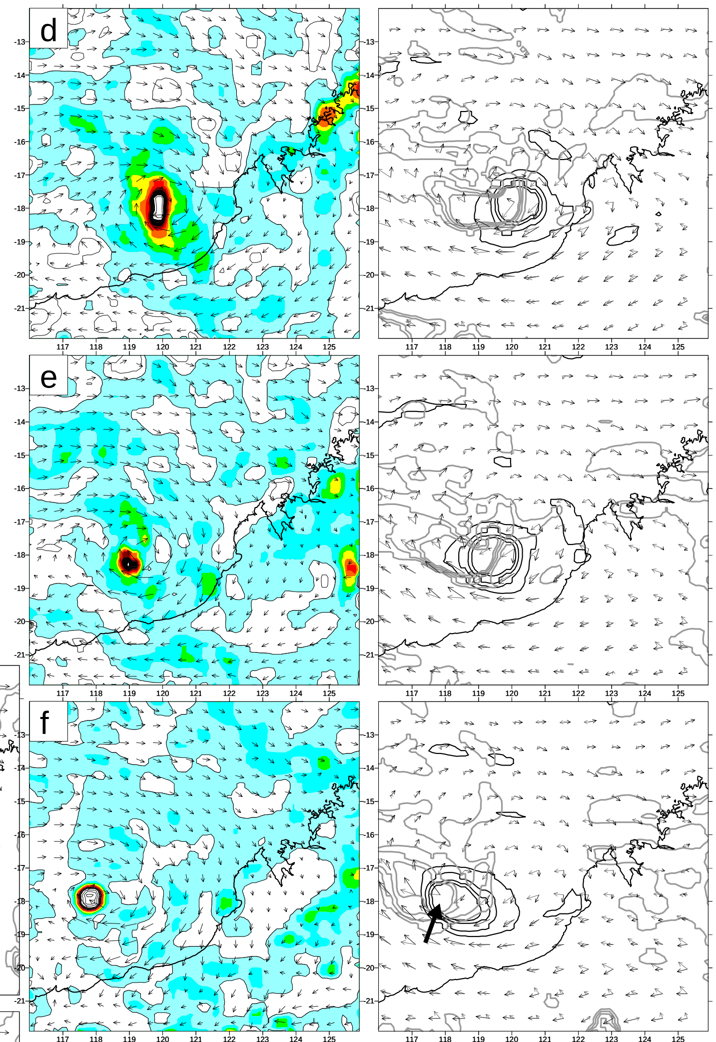


Figure 1: Vertical velocity on the σ = 0.25 surface, with horizontal wind vectors on the σ = 0.9943 surface overlaid (left panels), and low-level (σ = 0.85, black) and mid-level (σ = 0.5, gray) PV and horizontal winds (right panels), for the TC Monty simulation (initialized at 1200 UTC, 26 February 2004). The times are 4, 8, 12, 16, 20 and 24 hours model time.

vicinity of the PV maxima for at least the next 6 hours (e.g., Fig. 1c) and the PV maxima continued to intensify, while rotating cyclonically in the background flow. Figure 1c (12 hours model time) shows the inland PV maximum remained vertically aligned while the offshore maximum had begun to shear apart. Another four hours later (16 hours forecast time, Fig. 1d) intense convection was present only in the vicinity of the inland PV maximum. The offshore PV maximum was crossing the coastline at low-levels, while the mid-level PV maxima were roughly aligned north-south. An examination of the wind vectors in the lower panels of Fig. 1b—d, show the low-level cyclonic flow was roughly circular, while at mid-levels it was more elliptical with the longer axis oriented near north-south. The low-level flow was also more intense. This wind distribution explains the shearing of the offshore PV maximum. By 20 hours model time (Fig. 1e) the inland PV maximum had intensified further and was heading offshore, while



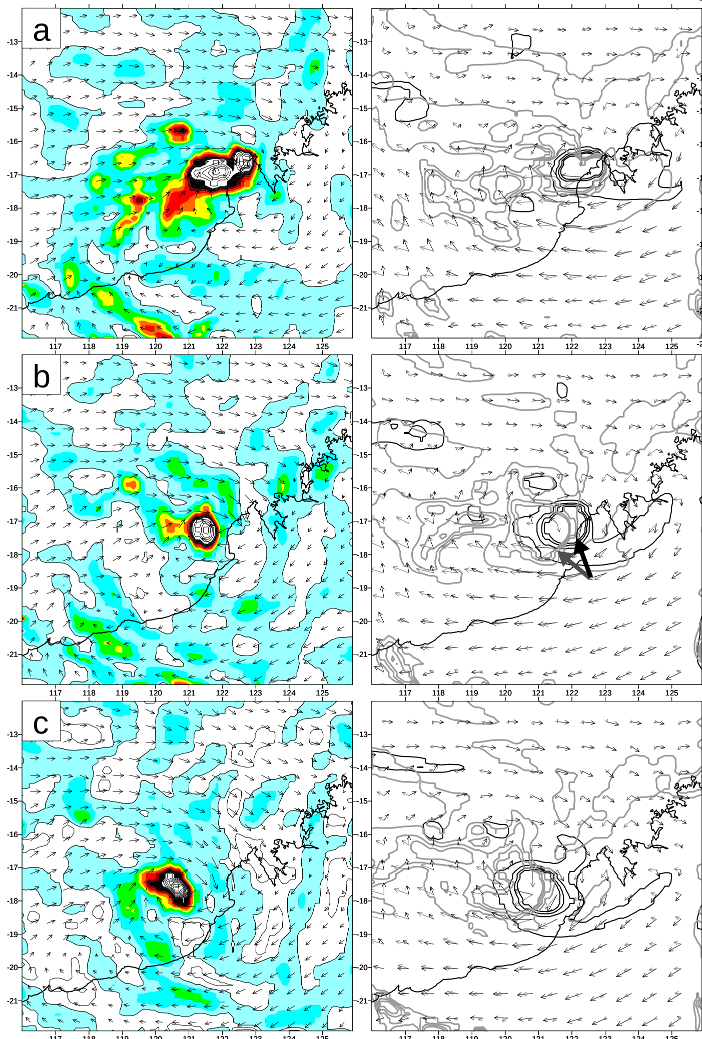


Figure 2: As in Fig. 1 but for the ex-TC Evan simulation (initialized at 1200 UTC, 4 March 2004). The times are 4, 8, 12, 16, 20 and 24 hours model time.

remnants of the offshore PV maximum were being axisymmetrized about the previously inland PV maximum, at both low- and mid-levels. This axisymmetrization is an example of the secondary vortex enhancement mechanism, vortex upscale cascade. (Although the other secondary mechanism introduced above, SSI, was active in this simulation, it is not obviously apparent in these figures.) Within another 4 hours (Fig. 1f) a PV monolith was born with an active convective region on the northwest edge. Beyond this time the PV monolith tracked westward and continued to intensify, and the most intense convection remained within the PV monolith (not shown).

Ex-TC Evan

Despite expectations that the remnants of TC Evan would redevelop once crossing the coastline it failed to do so. In the TC-LAPS simulation the storm also failed to develop. All the ingredients for strong development were present for at least the first 16 hours of the simulation. This is evident in Fig. 2a—d, which shows strong convective activity in the vicinity of substantial low- and mid-level PV anomalies. However, an upright PV monolith failed to develop due to sustained shearing and tilting of the central PV anomaly. Figure 2a shows the greatest shear between the low- and mid-levels is to the north and west of the low-level PV maximum (compare black and grey vectors). Immediately west of the low-level PV maximum the winds were southerly associated with the strong cyclonic flow around the PV anomaly, and easterly above at mid-levels. This shear pattern was responsible for the tilting of the PV core evident 4 hours later (see arrows highlighting the different positions of the low- and mid-level PV anomalies in Fig. 2b) and the downstream PV "leakage" at mid-levels evident in all Fig. 2 panels. Like numerous simulations we have investigated (e.g., Tory et al., 2006b,c) the survival of the upright PV monolith in ex-TC Evan was dependent on the balance between the destructive effects of shear and the restorative effects of convection. Another similarity between these simulations is the development of deep convection on the down-tilt side of the PV core (discussed in Tory et al. 2006b). This is evident in all panels of Fig. 2 (with the exception of the eastern updraft center in Fig. 2a).

Convection on the down-tilt side of the PV core serves to realign the tilted PV cores by converging PV into the updraft on the down-tilt side of the PV anomaly at low-levels and on the up-tilt side at mid-levels. Evidence of partial re-alignment can be seen in Fig. 2c (12 hours model time). The aligned parts of the mid- and low-level PV anomalies coincide almost exactly with the location of the convective region. Westward PV leakage from the southern side of the mid-level PV anomaly is also evident at mid-levels. This pattern is repeated four hours later in Fig. 2d, where the PV leakage is even more apparent. By 20 hours model time (Fig. 2e) it can be seen that the convective intensity had weakened and the final tearing apart of the developing PV monolith had begun. Another four hours later (Fig. 2f), a last burst of convection contributed to some form of realignment, but it was not sufficiently intense or long-lived to resurrect the monolith, and the storm began to weaken significantly as the low- and mid- level PV anomalies continued to shear apart (not shown).

Despite all the necessary ingredients for formation in TC-LAPS, strong deep convection in an environment of cyclonic PV, and the development of associated PV cores ex-Evan failed to redevelop. The shear in this case was too strong. The simulation suggests that a threshold exists between the ratio of shear and net convective activity at which shear begins to inhibit and ultimately stop TC-LAPS TC formation.

4. Critical aspects for genesis in TC-LAPS

We demonstrated in Tory et al. (2006b,c) that the pathway to genesis in four developing TC-LAPS simulations differed considerably, in terms of numbers, intensity and duration of convective bursts and how they interacted with one another and the environment. Despite these cosmetic differences the fundamental processes via the primary and secondary mechanisms was the same. The result suggests that the finer detail of the vortex interactions is not qualitatively important for genesis. The interactions occur as a consequence of the multiple, relatively short-lived convective episodes. These and numerous other simulations not yet reported on, have shown that of critical importance to genesis is that the convective episodes do occur and that they occur in a sufficiently large and intense cyclonic environment in which vertical shear is not too destructive.

Although we believe destructive shear was responsible for many non-developing systems in the TC-LAPS simulations we have investigated, by far the greatest reason for non-development is relatively weak, or insufficiently long-lived convection, or in some cases no convection at all.

This is the case for most Tropical Depression (TD) cases we have modeled. Without the development of relatively large-scale convective regions that persist on the whole for 12—24 hours (depending on the size and intensity of the cyclonic environment, and the shear intensity), the TDs at most only weakly intensified (central pressure drop of a few hPa). We have noted on numerous occasions convective bursts that developed in only weakly cyclonic (and anticyclonic) environments that, as expected, failed to spin up a vortex core on the updraft scale. In one simulation reported in Tory et al. (2006c) we comment on a non-developing storm in which repeated convective activity span up a vortex core, but the cyclonic environment in which the core developed appeared to be too small for the SSI process to be sufficiently active. Prior to the weakening and eventual decay of the vortex core an updraft appeared to implode and gravity waves radiated outwards many hundreds of km, indicative of a significant energy loss to the system.

The many simulations investigated so far have repeatedly shown that of critical importance to genesis in TC-LAPS are (i) a sufficiently intense and large low- to mid-level cyclonic environment, (ii) sufficient net deep convection and (iii) shear below some destructive limit. These three points compare well with Grays necessary conditions. Grays dynamic conditions of low-level vorticity, sufficient coriolis, and weak shear cover the first and third points, and Gray's thermodynamic conditions (sufficiently warm ocean, sufficiently moist environment) are implied in the second point because sufficient net deep convection will not develop if the thermodynamic conditions are not satisfied.

These simulations also suggest that the mix of convective activity, cyclonic environment and vertical shear intensity not only plays a role in determining whether a storm will develop or not, but also determines the rate of development. Furthermore, the fact that the genesis mechanisms appear to be qualitatively independent of the convective detail, suggests the genesis pathway via the primary and secondary mechanisms is likely to be valid for a wide range of genesis cases.

References

Hendricks, E. A., M. T. Montgomery and C. A. Davis, 2004: On the role of "vortical" hot towers in hurricane formation. *J. Atmos. Sci.,* **61**, 1209—1232.

Mapes, B. E. and R. A. Houze, 1995: Diabatic divergent profiles in Western Pacific Mesoscale Convective Systems. *J. Atmos. Sci.*, **52**, 1807—1828.

Montgomery, M. T., M. E. Nicholls, T. A. Cram and A. Saunders, 2005: A "vortical" hot tower route to tropical cyclogenesis. *J. Atmos. Sci.*, in press.

Rapp, A. D., C. Kummerow, W. Berg and B. Griffith, 2005: An evaluation of the proposed mechanism of the adaptive infrared iris hypothesis using TRMM VIRS and PR measurements. *J. Climate*, **18**, 4185—4194.

Tory, K. J., M. T. Montgomery and N. E. Davidson, 2006a: Prediction and diagnosis of Tropical Cyclone formation in an NWP system. Part I: The critical role of vortex enhancement in deep convection. *J. Atmos. Sci.*, accepted.

Tory, K. J., M. T. Montgomery, N. E. Davidson and J. D. Kepert, 2006b: Prediction and diagnosis of Tropical Cyclone formation in an NWP system. Part II: A detailed diagnosis of tropical cyclone Chris formation. *J. Atmos. Sci.*, accepted.

Tory, K. J., N. E. Davidson and M. T. Montgomery, 2006c: Prediction and diagnosis of Tropical Cyclone formation in an NWP system. Part III: Diagnosis of developing and non-developing storms. Submitted to *J. Atmos. Sci.*

Zehr, R., 1992: Tropical cyclogenesis in the western North Pacific. NOAA Tech. Rep. NESDIS 61, 181 pp.