Prediction and Diagnosis of Tropical Cyclone Formation in an NWP System. Part III: Diagnosis of Developing and Nondeveloping Storms

K. J. Tory and N. E. Davidson
Bureau of Meteorology Research Centre, Melbourne, Australia

M. T. Montgomery
Department of Meteorology, Naval Postgraduate School, Monterey, California, and Hurricane Research Division, NOAA/AOML, Miami, Florida

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ABSTRACT

This is the third of a three-part investigation into tropical cyclone (TC) genesis in the Australian Bureau of Meteorology’s Tropical Cyclone Limited Area Prediction System (TC-LAPS), an operational numerical weather prediction (NWP) forecast model. In Parts I and II, a primary and two secondary vortex enhancement mechanisms were illustrated, and shown to be responsible for TC genesis in a simulation of TC Chris. In this paper, five more TC-LAPS simulations are investigated: three developing and two nondeveloping. In each developing simulation the pathway to genesis was essentially the same as that reported in Part II. Potential vorticity (PV) cores developed through low- to middle-tropospheric vortex enhancement in model-resolved updraft cores (primary mechanism) and interacted to form larger cores through diabatic upscale vortex cascade (secondary mechanism). On the system scale, vortex intensification resulted from the large-scale mass redistribution forced by the upward mass flux, driven by diabatic heating, in the updraft cores (secondary mechanism). The nondeveloping cases illustrated that genesis can be hampered by (i) vertical wind shear, which may tilt and tear apart the PV cores as they develop, and (ii) an insufficient large-scale cyclonic environment, which may fail to sufficiently confine the warming and enhanced cyclonic winds, associated with the atmospheric adjustment to the convective updrafts.

The exact detail of the vortex interactions was found to be unimportant for qualitative genesis forecast success. Instead the critical ingredients were found to be sufficient net deep convection in a sufficiently cyclonic environment in which vertical shear was less than some destructive limit. The often-observed TC genesis pattern of convection convergence, where the active convective regions converge into a 100-km-diameter center, prior to an intense convective burst and development to tropical storm intensity is evident in the developing TC-LAPS simulations. The simulations presented in this study and numerous other simulations not yet reported on have shown good qualitative forecast success. Assuming such success continues in a more rigorous study (currently under way) it could be argued that TC genesis is largely predictable provided the large-scale environment (vorticity, vertical shear, and convective forcing) is sufficiently resolved and initialized.

1. Introduction

This paper is the third part of a three-part series on tropical cyclone (TC) genesis in the Australian Bureau of Meteorology’s TC version of the Limited Area Prediction System (TC-LAPS), an operational NWP model (Puri et al. 1998). In the previous papers (Tory et al. 2006a,b, hereafter, Parts I and II, respectively) a primary and two secondary vortex enhancement mechanisms were identified and analyzed in a simulation of TC Chris, which formed off the coast of Western Australia in early February 2002. The analysis in all three papers focuses mostly on the dynamics of genesis in TC-LAPS.

The primary vortex enhancement mechanism introduced in Part I describes the construction of vortex cores in convective updrafts through horizontal convergence and vertical advection of absolute vorticity. Drawing on work by Hendricks et al. (2004, hereafter

Corresponding author address: Dr. Kevin Tory, Bureau of Meteorology Research Centre, GPO Box 1289, Melbourne, VIC 3001, Australia.
E-mail: k.tory@bom.gov.au

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H04) and Montgomery et al. (2006, hereafter M06) two secondary vortex enhancement mechanisms were identified and demonstrated in Part II. The first, diabatic upscale vortex cascade, described the interaction of vortices generated by the primary mechanism, where vortex interaction was dominated by convergence into vortices associated with active convection. This led to the scavenging of anomalous PV and contributed to the growth of a monolithic PV core about which the TC developed. The second, system-scale intensification (SSI), described the large-scale response to the net vertical mass flux driven by diabatic heating in the convective cores. This led to the enhancement of the secondary circulation in a manner akin to the classical Eliassen model of a balanced vortex driven by heat sources. Convergence of low- to midlevel tropospheric absolute vorticity by this enhanced secondary circulation led to vortex intensification on the system scale. Thus the primary vortex intensification mechanisms provided seed vortices and vertical mass flux to drive the secondary mechanisms.

This genesis process differs from the top-down theories proposed by Simpson et al. (1997), Ritchie and Holland (1997), and Bister and Emanuel (1997), which focused on the vortex enhancement potential within the MCS stratiform precipitation region. As discussed in Part I mesoscale convective systems (MCSs) typically include both deep convective and stratiform regions, with proportions that vary from system to system, and throughout the lifetime of individual systems (e.g., Mapes and Houze 1995). Convective regions consist of low- to middle-tropospheric convergence with divergence above. This was labeled the convective divergence profile (CDP) in Part I. Similarly, a stratiform divergence profile (SDP) was introduced that represented midtropospheric convergence with divergence above and below, typical of stratiform regions. In the presence of cyclonic vorticity the convergent components of CDP and SDP lead to vortex enhancement, termed convective and stratiform vortex enhancement (CVE and SVE) respectively. The primary mechanism introduced in Part I results from CVE, whereas the top-down theories focus on SVE. Although these terms were only applied to the primary mechanism it is worth noting that the secondary vortex enhancement mechanism, SSI, is essentially CVE on the system scale.

This genesis process, like TC genesis in the real world, is dependent on sustained periods of deep convection. However, it is not clear how realistic the TC-LAPS path to genesis is. In Part I we suggested that deep convective regions with CDPs, on similar scales to the TC-LAPS updrafts, do exist in tropical oceanic environments (Zipser and Gautier 1978; Mapes and Houze 1992, 1995). Additionally observations of very cold cloud-top temperatures, interpreted as overshooting deep convective cloud, on the same spatial scales as the TC-LAPS updrafts are frequently observed during TC genesis (Zehr 1992; Gray 1998). Such observations suggest that TC-LAPS may adequately represent the mean vertical motions in real TC genesis convective regions. However, early in the genesis period the TC-LAPS convective scales may be too large, and the resulting updrafts may be more efficient at concentrating vorticity than the ensemble of convective updrafts that exist in real convective regions. This could lead to a bias toward rapid genesis during the earlier stages.

At present we are more interested in understanding the dynamical processes responsible for genesis in TC-LAPS and the real world than the quantitative forecast success. In particular, we are most interested in capturing enough realism for qualitative success (i.e., formation or nonformation). We advance the hypothesis that a model that demonstrates skill in forecasting both developing and nondeveloping storms is likely to be capturing the most important aspects of genesis in the real atmosphere. Although the purpose of this paper is primarily to investigate the universality of the genesis mechanisms identified in Parts I and II in simulations of other storms, it is also the first step toward developing a TC-LAPS genesis climatology. A more rigorous TC-LAPS genesis investigation is currently underway.

The remainder of the paper is set out as follows. In section 2 we present the results from three developing and two nondeveloping storms, highlighting the variability between the simulations, and propose reasons for the storm development or nondevelopment. In section 3 the implications of these results with respect to identifying conditions necessary for genesis are discussed. In section 4 we comment on similarities between the TC-LAPS PV anomaly behavior and observed MCS behavior in genesis environments. Section 5 contains a summary of Part III, and a summary of the main conclusions of all three papers appears in section 6.

2. TC-LAPS TC genesis simulations

In this section we present evidence of the TC formation process, introduced in Parts I and II, for an additional five TC simulations in the Australian region. In each case the primary vortex enhancement mechanism introduced in Part I is active, and the secondary mechanisms illustrated in Part II, although not specifically demonstrated in this paper, can be inferred from the
time sequence of images presented. Variations in the path to TC genesis and an examination into why genesis did not occur in two of the simulations provides further insight into the sensitivity of TC genesis in TC-LAPS to the immediate environment and intensity of convection. The LAPS domain in which all five simulations were nested is illustrated in Fig. 1. In the analysis of each simulation featured in the remaining figures we have focused on a $10^° \times 10^°$ subdomain of the full $27^° \times 27^°$ TC-LAPS domain. These subdomains are indicated in Fig. 1.

a. Basic formation mechanism

We show in this section that the primary vortex enhancement mechanism introduced in Part I is active in all simulations (developing and nondeveloping) presented in Figs. 2–6. In Part II we showed multiple convective blow-ups in the vicinity of a significant PV anomaly contributed to the development of a PV monolith, through the secondary vortex enhancement mechanisms of diabatic upscale vortex cascade and the SSI process. In each simulation presented in this paper there is also evidence of multiple convective blow-ups generally embedded in a mesoscale cyclonic circulation, and an intensification of that cyclonic circulation (at least in the developing simulations), consistent with the secondary vortex enhancement mechanisms. The alignment of low- and midlevel PV anomalies and subsequent development of PV monoliths at the center of large-scale cyclonic circulations is evident in Figs. 2–4 (developing storms). In Figs. 5 and 6 (nondeveloping storms) it appears that vertical shear, and a combination of vertical shear and an insufficient cyclonic environment, respectively, interrupted such development.

A closer examination of Figs. 2–6 shows significant variation in background environment (wind and PV distribution), and intensity and numbers of convective bursts. The paths to formation in Figs. 2–4 also show significant differences between each other and the simulation of TC Chris presented in Part II, despite the same basic formation mechanisms. An examination of these simulations provides further insight into the sensitivity and response of the TC-LAPS formation to the environment and convective intensity and duration, and gives an indication of potential formation variations in the real world.

b. Developers

1) Elcho Island storm

We call an unnamed TC that passed over Elcho Island in early January 2003 (northern Australia, 11.95°S,
Fig. 2. Elcho Island storm (initialized at 1200 UTC 2 Jan 2003), (top) vertical velocity on the \( \sigma = 0.25 \) surface, with horizontal wind vectors on the \( \sigma = 0.9943 \) surface overlaid, and (bottom) low-level (\( \sigma = 0.85 \), black) and midlevel (\( \sigma = 0.5 \), gray) PV and horizontal winds at (a) 0-, (b) 4-, (c) 8-, (d) 12-, (e) 14-, (f) 16-, (g) 20-, and (h) 24-h model time. Model updrafts greater than 2 Pa s\(^{-1}\) (\(-50 \text{ cm s}^{-1} \) at 250 hPa) are contoured (interval, 0.5 Pa s\(^{-1}\), \(-13 \text{ cm s}^{-1} \) at 250 hPa). Model downdrafts are also contoured (interval, 0.2 Pa s\(^{-1}\), at 250 hPa). Scale bar units are Pa s\(^{-1}\).
the Elcho Island storm. Uncertainty existed as to whether the storm would reach TC intensity prior to making landfall. A central pressure of 989 hPa, and wind speeds of 25 m s$^{-1}$ were recorded at Elcho Island on 5 January 2003, and in hindsight the storm was declared a TC.

The alignment and organization of PV in the TC-LAPS simulation of this event is interesting because it occurred in a low-level vertical shear environment. Vertical motion on the $\sigma = 0.25$ surface together with horizontal wind vectors on the $\sigma = 0.9943$ surface are presented for this event in the upper panels of Fig. 2. A selection of PV contours, and horizontal winds on the $\sigma = 0.5$ (gray) and $\sigma = 0.85$ (black) levels are presented in the lower panels of Fig. 2. At the initial time, Fig. 2a shows three active convective cells in a line that runs diagonally from the southwest to the northeast. An east–west line of weaker convection between 7° and 8°S and west of 130°E is located in the cyclonic shear region on the poleward edge of the low-level monsoon westerly flow. PV anomalies loosely associated with the three mature convective cells are evident. The southern two are tilted (cf. the centers on the two levels), consistent with the local vertical shear (cf. the wind vector directions on the two levels), and the northeastern anomaly has no distinct low-level signature. A PV remnant of earlier convection (during the dynamic initialization) has been torn apart by vertical shear in the northwest (see arrows in Fig. 2a). During the next four hours this anomaly continued to be sheared apart, and convection (arrowed in Fig. 2b) developed in the vicinity of the low-level remnant PV anomaly, which led to the development of a PV core tilted by the low-level vertical shear (see the Fig. 2b inset, which shows the core sloping westward with height). In the next four hours, the associated convection had intensified further (Fig. 2c, 8 h into the simulation), and there is evidence of an enhanced PV core, despite a now more pronounced westward slope with height. This shows the balance between shear destruction and convective con-
Fig. 3. As in Fig. 2 except for the TC Fiona simulation (initialized at 1200 UTC 2 Feb 2003). The times are (a) 8-, (b) 12-, (c) 16-, (d) 20-, (e) 24-, (f) 28-, (g) 32-, and (h) 36-h model time.
struction was tipped in favor of construction at this time (e.g., see comments in section 4 of Part II). During the next eight hours (8–16-h model time), both the convection remained active and the low-level vertical shear remained strong (although it weakened in the last four hours), and the tilt axis rotated cyclonically and realigned (Figs. 2d–f). The cyclonic rotation of the tilt axis of idealized vortices in a vertical shear environment has been documented by Jones (1995) and Reasor et al. (2004). Reasor et al. (2004) showed that vortex precession can lead to realignment provided the shearing rate is small compared to the precession frequency. One hour after the alignment shown in Fig. 2f, intense convection redeveloped and continued for more than 8 h (Figs. 2g,h). During this time the low and midlevel PV anomalies intensified and became more symmetric due to axisymmetrization processes. The associated flow appears to have become sufficiently strong to overcome the negative response to vertical shear, and the vortex core remained vertically aligned.

Like the TC Chris simulation presented in Part II, an intense PV monolith developed in response to a sustained period of convective bursts. As in Part II, azimuthal mean tangential momentum budgets were calculated for the Elcho Island storm (not shown). They identified significant contributions from both axisymmetrization of PV/vorticity anomalies about the PV core (the eddy terms described in Part II) and large-scale low- and midlevel mean convergence of mean absolute vorticity by the secondary circulation (the mean terms, described in Part II). Both mechanisms served to focus the surrounding PV/vorticity into a near-symmetric warm-core vortex.

2) TC FIONA

The development of TC Fiona was slow compared with TC Chris and the Elcho Island storm. Like these latter two events, the initial low- and midlevel PV distribution showed little vertical organization, and remained this way for the first 8–12 h (Figs. 3a,b). The first burst of convection labeled A developed about 12 h into the simulation (Fig. 3b), and an associated PV core developed over the next 4 h, tilted slightly by the low-level vertical wind shear (Fig. 3c). Convection also developed two degrees further south (labeled B) and an
associated PV core appeared (also tilted). However, both convective bursts were short-lived and weak vertical shear led to the loss of vertical coherence in the PV cores 20 h into the simulation (Fig. 3d, the black and gray arrows point to the lower and midlevel anomalies, respectively). During the next 10 h (20–30-h model time) the convection was suppressed (e.g., see Figs. 3e,f). Merger and axisymmetrization intensified the PV on the two levels with little apparent influence between levels (Figs. 3e,g). The merger of the two PV cores and axisymmetrization occurred more rapidly at low levels (something observed frequently in TC-LAPS simulations and noted in H04). Note, the Fujiwara (oration effect, then merger evident in the black contours between Figs. 3c–f. At midlevels the two PV cores remained distinct for another 8 h after the low-level cores merged (not shown). Soon after the merger of the midlevel PV cores convection redeveloped (Fig. 3g, 32-h model time), the low- and midlevel cores became aligned and intensified (Fig. 3h) and the PV monolith was born. It is interesting to note that the convection responsible for the vertical realignment of PV was not particularly intense compared with the TC Chris, Elcho Island, and other simulations presented in this paper, and would have contributed to the slower rate of development.

Azimuthal mean tangential momentum budgets (not shown) identified very small contributions to the large-scale vortex intensification from the mean terms while the convection was subdued. The intensification during this time, although not particularly strong, was dominated by the eddy terms, suggesting vortex interactions were the main contributors to the mean vortex growth. This pattern is consistent with the comments above of slow intensification, mostly through adiabatic upscale vortex cascade of the two PV anomalies. During the later part of the simulation when the convection redeveloped the two mean terms began to dominate reflecting large-scale amplification by the now more intense secondary circulation (SSI process), and convergence and vertical advection in the convective updrafts.

In this simulation the early convection was not sufficiently intense, nor sufficiently long-lived to support the development of a PV monolith, particularly given the initial large-scale PV/absolute vorticity environment was weaker than other developing storms we have investigated (not shown). However, like H04, the environmental PV was enhanced by the initial convective burst, and merger and axisymmetrization of the resulting PV anomalies further organized (although slowly) the environmental PV into a more symmetric distribution. The subsequent enhanced cyclonic environment was more conducive to the development of a PV mono-

3) TC Monty

TC Monty developed when a depression moved offshore across the Western Australian coastline on 27 February 2004. Within 24 h it had reached tropical storm (TS) intensity and was categorized as a severe TC within 48 h. The TC-LAPS simulation was initialized at 1200 UTC 26 February 2004. After 4-h model time, Fig. 4a shows four active convective regions spread over a distance of about 400 km along the coast and inland. A large midlevel 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). Four hours later (Fig. 4b) convection was active in two main regions on either side of the coastline, with associated cyclonic PV maxima at both low- and midlevels creating a PV couplet spanning the coastline. Convection was favored in the vicinity of the PV maxima for at least the next 6 h (e.g., Fig. 4c) and the PV maxima continued to intensify, while rotating cyclonically in the background flow. Figure 4c (12-h model time) shows the inland PV maximum remained vertically aligned while the offshore maximum had begun to shear apart. Another 4 h later (16-h forecast time; Fig. 4d) 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 midlevel PV maxima were roughly aligned north–south. An examination of the wind vectors in the lower panels of Figs. 4b–d, show the low-level cyclonic flow was roughly circular, while at midlevels 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-h model time (Fig. 4e) the inland PV maximum had intensified further and was heading offshore, while remnants of the offshore PV maximum were being axisymmetrized about the previously inland PV maximum, at both low- and midlevels. Within another 4 h (Fig. 4f), 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 (not shown).

The same basic formation process was responsible for development in this simulation, although the details differed from the previous two simulations and that of TC Chris. Like TC Fiona two convective regions dominated in the early part of the simulation leading to the development of two cyclonic PV cores that or-
Fig. 4. As in Fig. 2 but for the TC Monty simulation (initialized at 1200 UTC 26 Feb 2004). The times are (a) 4-, (b) 8-, (c) 12-, (d) 16-, (e) 20-, and (f) 24-h model time.
bited one another in the larger-scale cyclonic flow. It seems likely that the stronger vertical shear environment in which the offshore PV anomaly was embedded, served to tilt and weaken that anomaly, allowing the onshore anomaly to become dominant. This simulation shows that the early formation process in TC-LAPS can occur over land (albeit mostly within 100 km of the coast), which supports the findings in M06, that Wind-Induced Surface Heat Exchange (WISHE)-like processes (Emanuel 1986; Rotunno and Emanuel 1987) may not play a dominant role during the early formation stages.

In the latter two simulations the dominant convective bursts were located farther apart than their counterparts in the TC Chris simulation (Part II). Hence the vortex interactions more closely resembled the often observed orbiting and merger of MCS cloud systems during TC genesis (e.g., Ritchie and Holland 1997; Ritchie et al. 2003).

c. Nondeveloping events

1) Ex-TC Evan

TC Evan formed in the Gulf of Carpentaria (labeled GC in Fig. 1) on 1 March 2004 and made landfall within 24 h before decaying to a tropical depression. As the depression tracked westward across the Northern Territory it was expected to reintensify once it crossed the coastline only a few hundred kilometers farther north of where TC Monty developed one week earlier. However, after crossing the coastline it did not return to TC intensity.

In the TC-LAPS simulation of ex-TC Evan all the ingredients for strong development were present for at least the first 16 h of the simulation. This is evident in Figs. 5a–d, which shows strong convective activity in the vicinity of substantial low- and midlevel PV anomalies. However, an upright PV monolith failed to develop due to sustained shearing and tilting of the central PV anomaly. Figure 5a shows the greatest vertical shear between the low- and midlevels is to the north and west of the low-level PV maximum. 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 midlevels. This shear pattern was responsible for the tilting of the PV core evident 4 h later (Fig. 5b) and the downstream PV “ejection” at midlevels evident in all Fig. 5 panels. Like the simulations of TC Chris in Part II, the Elcho Island storm, and numerous other TC-LAPS simulations (not shown), 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 (hereafter we will refer to this as the battle between shear and convection). Another similarity between these simulations is the development of deep convection on the downdraft side of the PV core (discussed in Part II). This is evident in all panels of Fig. 5 (with the exception of the eastern updraft center in Fig. 5a).

These updrafts serve to realign the tilted PV cores by converging PV into the updraft on the downdraft side of the PV anomaly at low-levels and on the updraft side at midlevels. Evidence of partial realignment can be seen in Fig. 5c (12-h 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 ejection from the southern side of the midlevel PV anomaly is also evident at midlevels. This pattern is repeated 4 h later in Fig. 5d, where the PV ejection is even more apparent. By 20-h model time (Fig. 5e) it can be seen that the convective intensity had weakened and the final tearing apart of the developing PV monolith had begun. Another 4 h later (Fig. 5f), 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 midlevel 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 vertical 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 formation. A similar balance also appears to influence the intensity of hurricane-strength TCs in the Australian region (Paterson et al. 2005).

2) TC Erica phase II

There were two phases to the life of TC Erica. It initially developed in the Coral Sea on 5 March 2003, near 20°S, 154°E, before decaying and redeveloping on 11 March 2003, near 13°S, 158°E. The simulation presented here was initialized two days prior to the redevelopment to TC intensity, near the time of the second phase of genesis. It is an example of a failed forecast, because in reality the system had regained TC intensity by the end time of the simulation. Nevertheless, the simulation is worth studying because an investigation into the reasons for the failure provides further understanding of the formation processes. The initial environment consisted of the remnant cyclonic circulation from the original decaying TC. This is evident in the
Fig. 5. As in Fig. 2 but for the ex-TC Evan simulation (initialized at 1200 UTC 4 Mar 2004). The times are (a) 4-, (b) 8-, (c) 12-, (d) 16-, (e) 20-, and (f) 24-h model time.
Fig. 6. As in Fig. 2 but for the TC Erica phase II simulation (initialized at 1200 UTC 9 Mar 2003). The times are (a) 0-, (b) 4-, (c) 8-, (d) 12-, (e) 16-, (f) 20-, (g) 23-, (h) 24-, (i) 25-, (j) 28-, (k) 32-, and (l) 36-h model time.
Fig. 6. (Continued)
large-scale surface cyclonic wind pattern evident in Fig. 6a (upper panel, see vectors), and the large-scale near-uniform PV distribution at low- and midlevels (lower panel). Only weak convection is evident at this time. Near the surface the large-scale cyclonic circulation was oval in shape with the axis of elongation running roughly northwest to southeast. Over the next 36 h, this axis gradually rotated cyclonically (see vectors in the upper panels of Figs. 6a–l). The low-level PV structure is elongated reflecting the ovoid circulation. It also rotated cyclonically throughout the simulation. The midlevel PV anomaly is of similar size and shape to the low-level PV anomaly, and rotated cyclonically but at a slower rate. The sequence of images illustrates a gradual separation of the low- and midlevel PV over at least the first 24 h of the simulation (Figs. 6a–h), due to the varying rotation rates.

Although the convection on the $\sigma = 0.25$ surface is not particularly intense during most of the simulation, there is evidence of low-level PV intensification followed by midlevel development corresponding to convection near the southeastern edge of the initial low-level PV anomaly (marked by the arrow in Fig. 6b). Over the next 4 h, the intensity of the convection, and the associated PV anomalies increased, producing a relatively weak, elongated PV core slightly tilted in the vertical (Fig. 6c, also arrowed). Other weaker PV anomalies began to develop within the main large-scale cyclonic circulation, presumably in response to the relatively weak convection there. The same pattern of behavior continued for another 4 h, during which the southeastern PV anomaly gradually intensified and remained in near-vertical alignment (Fig. 6d, 12-h model time).

A battle between vertical shear and convection was evident in this simulation as well. The convection associated with this particular anomaly weakened considerably between 12 and 16 h, during which time the PV core tilted to the southwest consistent with the vertical shear evident in Fig. 6e [cf. the low-level (black) and midlevel (gray) vector directions]. The development of the first deep intense convection followed soon after and the vertical alignment of the PV core was reestablished (Fig. 6f, 20-h model time). Within the next 4 h the low-level PV anomaly continued to intensify slowly, whereas the midlevel anomaly weakened. At this time, the hourly sequence of images (Figs. 6g–i) show large-amplitude gravity waves radiated outward from a center near $15^\circ$S, $161^\circ$E (upper panels). In Fig. 6h, the updraft appears to have been replaced by a downdraft and the surrounding gravity wave amplitude increased, giving the impression that the updraft imploded. (All $\omega$ fields shown in Figs. 2—6 have been filtered by five passes of a 1–2–1 filter, which smooths out small-scale, small-amplitude gravity waves.) After this time the associated PV anomaly was sheared apart. Another redevelopment of convection further south led to the formation of another PV anomaly (Fig. 6j, see arrow) and another battle between shear and convection (Fig. 6k).

Shear eventually claimed victory (Fig. 6l).

It would seem that this was just another case of non-development caused by the formation process being initiated in a sheared environment. However, unlike ex-TC Evan, the convection developed in an unfavorable environment, while the perfect environment for development was located a few hundred kilometers away. The remnants TC Erica cyclonic circulation provided a large PV pool, much of it with only weak vertical shear. The persistent convective burst during the simulation was located about 100 km from this large-scale PV-rich environment, and about 300 km from the center of the main large-scale PV anomaly. (In reality, and in subsequent successful forecasts, the convection responsible for the redeveloping TC Erica appeared at the edge of the large-scale PV pool.) Of the many simulations we have investigated in detail this is the only example exhibiting such dramatic gravity wave behavior. These large-amplitude gravity waves propagated more than 500 km within a few hours. They adjust the temperature and winds to bring the atmosphere to a new state of balance. The larger the Rossby radius of deformation, the greater the area of adjustment, but the weaker the adjustment magnitude. If the convection had developed closer to the midlevel PV anomaly center, where the Rossby radius of deformation is smaller, the wind and temperature adjustment would have been more concentrated near the convection, resulting in more enhanced cyclonic flow and warming. This simulation highlights the importance of reliable specification of both the rotational and divergent flows in the initial condition.

In summary, this simulation shows further evidence of TC formation being dependent on the balance between the vortex enhancement mechanism of deep convection in a sufficiently cyclonic environment (locally), and the destructive shear mechanism. It also provides evidence to suggest that TC formation may only succeed when the primary vortex enhancement mechanism develops within a larger-scale cyclonic environment. In such an environment the SSI mechanism will also be more effective.

3. TC-LAPS formation mechanism: Identification of critical aspects

The simulations presented in the previous section and in Part II show that the pathway to genesis in the
four developing cases differed considerably (in terms of numbers, intensity, and duration of convective bursts and how they interacted with other convective bursts and the environment), although the fundamental process, via the primary and secondary mechanisms, was the same. The simulations suggest that the finer detail of the vortex interactions is not qualitatively important for genesis. Indeed sensitivity tests of various simulations (not shown) could often yield different numbers of convective bursts and as a consequence quite different patterns of interaction, however the final TC intensity, and location varied little. The interactions occur as a consequence of the multiple, relatively short-lived convective episodes. The above simulations and numerous others not yet reported on have shown that of critical importance to genesis is that these convective episodes do occur and that they occur in a sufficiently large and intense cyclonic environment in which vertical shear is not too destructive.

An interesting question that arises from the above discussion is: How important are the two secondary vortex enhancement processes in TC-LAPS and indeed the real world? While these simulations do not provide an answer to this question, they do offer some insight. The failure to spin-up a PV monolith in the TC Erica simulation (Fig. 6), and the apparent updraft implosion accompanied by relatively large-amplitude gravity waves in Figs. 6g–i may have occurred because the system-scale cyclonic environment was too weak (in the vicinity of the persistent convection). In which case, it could be argued that the SSI process is critical for TC genesis in TC-LAPS and possibly the real world. In the case of the diabatic upscale vortex cascade, it would be hard to imagine genesis without this process. Even in the unlikely scenario of continuous convection or repeatedly developing convection in the same PV anomaly, the vortex interactions would very likely have a role to play in ejecting anticyclonic PV anomalies from the developing cyclonic PV monolith region (e.g., Part II; H04).

During much of the simulation of TC Fiona convection was weak and no convective bursts were active. At this time the only vortex enhancement appeared to be associated with the adiabatic interaction of existing PV anomalies. This is a pattern we have seen in many simulations of tropical depressions (TD) that did not develop (including TD2 and TD7 of the 2003 Atlantic season, not shown). In each case there was no sustained deep intense convective activity, and no development beyond TD intensity. In TC Fiona sufficient convective activity did eventually develop and TC intensity was reached, which illustrates the critical importance of the primary mechanism for TC formation in TC-LAPS. The simulation of ex-TC Evan showed that a sufficient cyclonic environment and sustained deep convective activity do not guarantee TC formation. Vertical shear can inhibit formation by tearing apart the individual PV cores on the scale of the model updrafts or on the scale of the developing monolithic PV cores that form the basis of the developing TC. In the simulation of TC Chris (Part II), the Elcho Island storm, TC Erica phase II, and ex-TC Evan the battle between shear and convection was present for all or part of the simulations. In the latter example the balance was tipped in favor of the shear for a sufficiently long period for the developing monolithic PV core to be destroyed. Reasor et al. (2004) showed that the resiliency of a vortex in a vertically sheared environment was dependent on the strength and size of the vortex, and the intensity of shear. Thus, for an accurate forecast the vertical shear intensity is important to capture, but perhaps more importantly the duration, intensity and frequency of the convection. Convection, too active early in the storm development, could rapidly build a vortex core of sufficient size and strength to withstand the vertical shear, in a storm that otherwise would not have developed. This idea was tested by unrealistically increasing the heating rate while the convection was being forced during the assimilation and initialization period of a simulation of ex-TC Evan (not shown). The additional heating forced more intense convection during the initialization and as a consequence greater vortex enhancement. This resulted in a broader and more intense initial cycloonic PV anomaly and, either as a consequence or independently, more intense initial convective activity (a more favorable combination for development). The simulation rapidly generated a PV monolith and subsequent TC that withstood the early destructive effects of vertical shear.

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. This is most evident when comparing the size and intensity of convection between the simulations of the Elcho Island storm and TC Fiona (Figs. 2 and 3, respectively) and the subsequent rates 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 may be valid for a wide range of genesis cases.

4. Similarities with observed genesis patterns

In this section a few similarities between the TC-LAPS PV anomaly behavior and observed MCS behav-
ior are explored. While recognizing that the use of cloud features as a proxy for PV anomalies gives little indication of the anomaly size and intensity, and runs the risk of missing remnant anomalies from old convective regions, such a comparison can highlight similarities in TC genesis patterns between the model and observations.

a. Convection concentration and the construction of the PV monolith

Zehr (1992) noted that early in the genesis process convection is more active outside a radius of 1° than inside, and during the genesis process the convection contracted inwards toward the circulation center. He noted that this concentration of convection coincided with the transition to tropical storm. The concentration of convection and associated PV anomalies is a pattern we have observed in all developing simulations investigated (e.g., Figs. 2–4; Figs. 4 and 5 of Part II). It is also evident in the relatively coarse resolution (0.625° grid spacing) simulation of Kurihara and Tuleya (1981, see their Figs. 9 and 22). In the TC-LAPS simulations convection contraction involved the orbiting of convective bursts and associated PV anomalies about the circulation center, followed by an inward spiral as the anomaly or anomalies intensified and eventually became the circulation center.

The spiral path to convection concentration can only be identified in observations with sufficient temporal resolution. In most of the observational papers of TC genesis we have investigated, insufficient resolution has been provided to clearly observe such behavior. A possible exception is the study of Typhoon Robyn by Harr et al. (1996). In their Figs. 15 and 16, a convective element (labeled C) appears to spiral into the circulation center. Ritchie and Holland (1997) include satellite imagery of pre–Typhoon Irving (their Figs. 8a–d), which illustrates the concentration of convection leading to the development to TS. [The official TS declaration was 6 h later, however, the structure shown in their Fig. 8d was consistent with Zehr’s (1992) TS definition.] The satellite images clearly show orbiting convective systems, but it is not clear if an inward spiral of one or more preceded the large burst of convective activity at the circulation center. In the analysis of Hurricane Floyd by Ritchie et al. (2003), the inward spiral of cloud masses is evident throughout the development process (see their Fig. 5). Their Fig. 5k suggests a cloud mass had spiraled into the circulation center at the time of the first big convective burst responsible for rapid deepening of Hurricane Floyd. In Simpson et al. (1997) the inward spiral of a convective region toward the circulation center can be inferred in the satellite images provided, and is supported by a map of vortex tracks. This is summarized well in Fig. 1 of Ritchie et al. (2003), with the addition of an extra few satellite images. In this figure, vortex B is seen to follow a circular path into what eventually becomes the circulation center. (From our own analysis of the satellite data we believe vortex A has been incorrectly identified. We suggest the early vortex A is a separate system from the later vortex A. The later stages of the vortex A circular path represents a large convective burst that soon begins to orbit the considerably more intense vortex B.) The inward spiral to the circulation center is also evident in the satellite imagery of TC Chris presented in Part II (see the convective burst labeled 4 in Fig. 4).

In the TC-LAPS simulations the inward spiral of the PV anomalies focuses PV toward the circulation center, which is consistent with Zehr’s (1992) observations of “convection concentration.” As observed by Zehr, an intense convective burst in the vicinity of the circulation center soon follows, after which the system reaches TS intensity. In the TC-LAPS simulations a similar re-establishment of convection serves to rapidly organize the PV distribution horizontally and vertically into the monolithic PV core. At this stage the TC-LAPS PV monoliths have also reached TS intensity (e.g., TC Chris; Part II).

b. Evidence of the system-scale intensification process in observations

As mentioned in section 3 the TC-LAPS simulations suggest that the detail of the secondary vortex enhancement process, diabatic merger, may not be of importance to the genesis process, whereas it was postulated that the SSI process is likely to be essential for TC genesis. If this is the case it would be reasonable to expect the SSI process to play an important, if not critical role in TC genesis in the real world. Evidence of the SSI process in observations is not very conclusive. Satellite imagery showing clouds initially advected by a cyclonic background flow, followed by an inward spiral, and more remote cloud features showing signs of axisymmetrization (e.g., Harr et al. 1996; Ritchie and Holland 1997; Ritchie et al. 2003), are all consistent with the notion that the background cyclonic circulation is intensifying on scales larger than the convective regions. But the satellite images alone cannot show that the SSI process is responsible for this behavior. H04 and M06 illustrated the SSI process in a realistic forecast model and an idealized model, respectively, and showed that the system-scale toroidal (overturning) circulation was enhanced by the net effect of diabatic heating in the multiple vortical hot towers. When constructing their vertical profiles of horizontal mean
divergence in the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) MCSs, Mapes and Houze (1995) were essentially sampling the net effect of diabatic heating. They investigated the effect of such divergence profiles on the large-scale environment using a simple two-dimensional, motionless, hydrostatic, nonrotating model. They noted that two dominant gravity wave modes were present: a fast-moving mode that responded to the deep convective region divergence profile and a slower-moving mode that responded to the stratiform region divergence profile. Houze (1997), commenting on the same experiment, noted that the gravity waves propagated as bores at 52 and 23 m s\(^{-1}\) (convective and stratiform modes, respectively). The faster convective mode displaced environmental mass downward to mass balance the convergent inflow to the convective region at low levels and the divergent outflow aloft. The associated adiabatic response was a rapid wave of warming throughout the troposphere.

This experiment would suggest the atmosphere is likely to respond quickly to a burst of convective activity with tropospheric warming potentially to a radius in excess of 1000 km within 6 h. However, for a horizontally localized heat source in an environment with ambient rotation, the heating magnitude will decrease with distance from the updraft. This heating gradient will enhance the inward-pointing pressure gradient force, and partly balance the enhanced tangential winds accelerated by the inflow that feeds the updraft. Mapes and Houze (1995) noted that deep mesoscale temperature perturbations of \(>1^\circ\)C did exist in the vicinity of the TOGA COARE MCSs.

This process describes the communication between the convective burst and the system-scale environment: in particular, the warming and enhancement of the tangential wind outside individual convective updrafts and convective regions as a whole. It would be reasonable to assume that wherever deep convective convergence profiles are observed in a cyclonic rotating environment the SSI mechanism will be active.

5. Summary

The five simulations presented in section 2 show the paths to genesis follow the primary and secondary vortex enhancement mechanisms described in Parts I and II, whereby the primary mechanism generates PV cores on the scale of the resolved updrafts, and provides net heating and vertical mass flux to the system. The secondary mechanisms 1) organize the PV cores into a monolithic PV core and 2) enhance the system-scale vortex. Vertical shear can inhibit the development of the PV cores or tear them apart. In many cases there was a fine balance between the destructive effects of shear and the constructive effects of vorticity convergence and vertical advection in the updraft cores. In the simulation of TC Erica phase II, there was evidence to suggest that the active convective region was not embedded in a sufficiently large and intense cyclonic environment for genesis to occur.

Despite each developing case following the same general path to genesis, the finer details (e.g., large-scale structure, convective intensity, frequency and location, vortex interactions) differed considerably. These details are interesting because they appear to mirror patterns observed in the real atmosphere, but they may be relatively unimportant in the overall genesis picture, at least in a qualitative sense. The critical aspects appear to be sufficient net deep convection, in a sufficiently cyclonic environment in which the vertical shear is less than some critical level. The interesting details of vortex interactions are simply a consequence of the convective intensity, frequency and location. The SSI process is dependent on the net convective activity and the strength of the system-scale cyclonic environment, and is thus more or less independent of individual convective bursts. The upscale vortex cascade process is also in a sense independent of the individual convective bursts, in that given sufficient time it will organize any arrangement of vortex structures (within a reasonable separation radius) into a central near-symmetric anomaly. This result suggests TC formation rates are likely to be largely dependent on the net convective activity and the size and intensity of the cyclonic circulation the convection is embedded in. Furthermore, because the overall genesis process described here is largely independent of the convective detail (at least on a qualitative level) the process is valid for a wide range of genesis scenarios. It is certainly the fundamental TC-LAPS genesis process, and we propose that it may also be important in the real world.

Like all proposed genesis theories, insufficient observational evidence currently exists to prove the TC-LAPS mechanisms are active in the real atmosphere. We can only comment on evidence that supports the theory. Satellite imagery shows similarities between the TC-LAPS convective patterns and those in the real genesis environment. Zehr’s (1992) concentration of convection, prior to the system reaching TS intensity, is evident in all TC-LAPS developing simulations. The simulations show the convective regions first orbit the large-scale vortex center, and then begin to spiral inward and become the large-scale vortex center as the associated vortex cores intensify. This final stage corresponds with the construction of the TC-LAPS PV monolith, which happens to be of TS scale and inten-
sity. These similarities support the notion that TC-LAPS may capture the later stages of genesis identified by Zehr (1992).

Unlike the upscale vortex cascade process, which is visible in time sequences of satellite imagery, evidence in support of the SSI process is more difficult to identify. Mapes and Houze (1995) found in an idealized model the atmospheric response to large convective mode convergence profiles was the outward propagation of gravity waves in excess of 50 m s^{-1} that resulted in warming throughout the depth of the troposphere. We suggest that in a rotating environment the warming acts to partly balance the enhanced tangential winds accelerated by the inflow that feeds the updraft. Thus, deep convection contributes to an enhanced circulation and warming beyond the convection and the convective region as a whole.

6. Closing remarks

In Part I we argue that the TC-LAPS updrafts represent mean vertical motions in real TC genesis convective regions, and that the associated vortex enhancement is likely to be sufficiently realistic, for qualitative genesis forecast success. We comment on the similarity between observed and TC-LAPS vertical profiles of horizontal mean divergence, in which both stratiform and convective divergence profiles (SDP and CDP, respectively) were present. In Part II we note that early in the simulation of TC Chris the TC-LAPS genesis rate appears to be more rapid than that estimated from satellite observations. It is possible that the TC-LAPS updrafts, dominated by a CDP, may have been too large or intense or long-lived at that time, particularly if the real MCSs were dominated by an SDP.

We note in Part I that it is possible MCS dynamics evolve throughout the genesis process, with very early MCSs dominated by the SDP, and later MCSs dominated by the CDP, with associated vortex enhancement in the respective convergent regions. If this is the case, then TC-LAPS may not perform well during the very early stages. Furthermore if this early period of development is essential for genesis, TC-LAPS (an operational model initialized every 12 h) may have to rely on the initialization scheme to capture such development after it has occurred. This could have forecasting implications in the Atlantic basin where enhanced evaporation in the dry Saharan air layer may favor stratiform dynamics in MCSs. Despite these perceived misgivings, preliminary results have shown TC-LAPS has had qualitative success in the Indian Ocean, northwest, southwest, and eastern Pacific Ocean and the Atlantic Ocean (not shown). A more rigorous climatology is currently underway.

We propose that this apparent success can be attributed to the ability of TC-LAPS to capture what appears to be the most important aspects of genesis: the large-scale environment (vorticity, vertical shear, and convective forcing); and convective regions dominated by the CDP (at least after the earliest stages of genesis). When this large-scale environment is sufficiently well represented by the model, the mix of convective forcing, cyclonic environment, and vertical wind shear will determine where and when the primary vortex enhancement mechanism will be effective in generating vortex cores on the updraft scale, and it will determine how the upward mass flux and locally enhanced vorticity in these cores, will fuel the construction of the vortex monolith through the secondary mechanisms of diabatic upscale vortex cascade, and the SSI process. Thus, the critical aspects of TC genesis in TC-LAPS appear to be sufficient net deep convection in a sufficiently cyclonic environment in which the vertical shear is less than some critical level. For qualitative success, that is, whether or not the vortex monolith develops, the finer details of the convection are not likely to be important. However, such detail is likely to be important for determining when and where the TC center develops.

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