The TT Problem

Forecasting the Tropical Transition of Cyclones

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According to the Tropical Cyclone Reports issued by NOAA's Tropical Prediction Center, the development of nearly half of the Atlantic tropical cyclones from 2000 to 2003 depended on an extratropical precursor (26 out of 57). Many of these disturbances had a baroclinic origin and were initially considered cold-core systems. A fundamental dynamic and thermodynamic transformation of such disturbances was required to create a warm-core tropical cyclone. We refer to this process as tropical transition (TT), to be contrasted with extratropical transition (ET), which results in an extratropical disturbance given a tropical cyclone.

Tropical cyclogenesis associated with extratropical precursors often takes place in environments that are initially highly sheared, contrary to conditions believed to allow tropical cyclone formation. The adverse effect of vertical wind shear[1] exceeding 10–15 m s^{-1} on the formation of low-latitude storms (equatorward of 20°N) is well documented (DeMaria et al. 2001). However, a beneficial role of vertical shear, hypothesized to organize convection, was indicated by the statistical analysis of Bracken and Bosart (2000) for 24 developing cases in the northern Caribbean Sea.

This article, focusing on the Atlantic basin, reviews briefly what is known about TT and how it can be anticipated. While TT storms typically do not exceed Category 2 intensity, their tendency to form close to North America can create significant forecast and evacuation problems. In addition, many TT cases become ET cases and can affect land areas from eastern North America to western Europe.

[1] Throughout this article, vertical shear is expressed as a velocity difference through the depth of the troposphere.

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TT CLASSIFICATION. It is convenient to represent TT cases with two paradigms, based on the amplitude and structure of the precursor disturbance: strong extratropical cyclone (SEC) and weak extratropical cyclone (WEC). The distinguishing factor between these archetypes is that in SEC cases, extratropical cyclogenesis produces a surface cyclone capable of wind-induced surface heat exchange (WISHE; Emanuel 1987), whereas in WEC cases, the baroclinic cyclone is an organizing agent for convection. The convection must then undergo self-organization to produce a disturbance capable of self-amplification. Because these archetypes represent end points on a spectrum of precursors, we do not anticipate the existence of a clear threshold separating one type from another. Once a sufficiently strong surface vortex is formed, there is no obvious distinction of the ensuing tropical cyclone intensification in either SEC or WEC cases.

In reality, TT cases reside within what is an even broader continuum of marine cyclogenesis, ranging from cool-season baroclinic cyclones to hurricanes initiated from weak extratropical systems. While the intensity of many marine cyclones is enhanced through storm-induced fluxes, the TT subspectrum of marine cyclones is dominated by such fluxes. However, the detailed pathway to TT appears principally determined by baroclinity (given a sufficiently warm underlying ocean).

As we will show, SEC cases have a more consistent and repeatable evolution than WEC cases. WEC cases can arise through a variety of extratropical precursors. Because the precursor is merely an organizing agent, its detailed structure is perhaps less important than in SEC cases. Furthermore, being of smaller ampli-

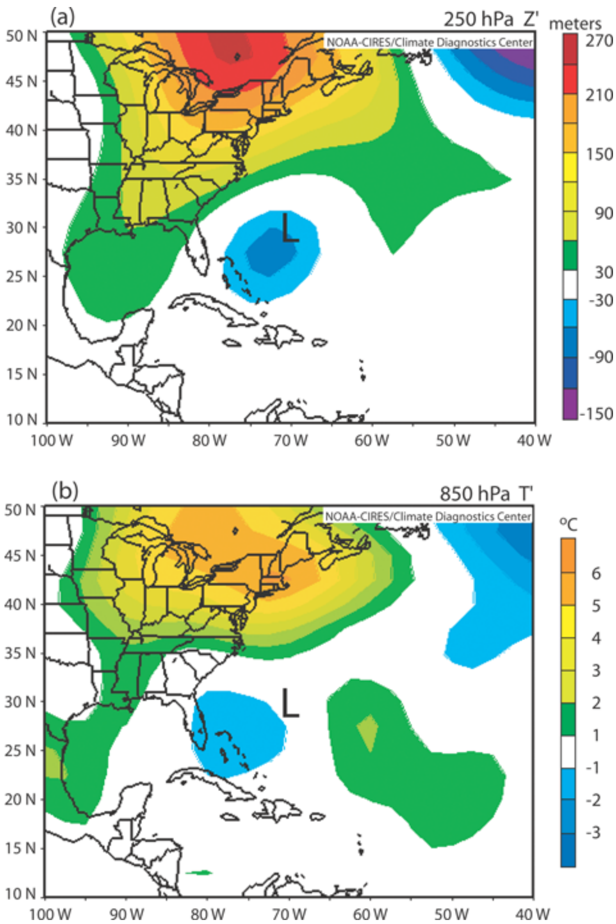

Fig. 1. (a) 250-hPa height anomaly and (b) 850-hPa temperature anomaly for four-case composite prior to tropical cyclogeneis. The position of the composite surface low center is indicated with an "L." Dates of composite are 10 Sep 2000, 15 Oct 2000, 11 Oct 2001, and 9 Sep 2002. For each date, the four available analyses (0000, 0600, 1200, and 1800 UTC) are averaged. Images were provided by the NOAA–CIRES Climate Diagnostics Center, Boulder, CO, from their Web site at www.cdc.noaa.gov (also see Kalnay et al. 1996).

tude, precursors in WEC cases are more difficult to identify in conventional data, and it is more difficult to definitively state the essential steps toward tropical cyclogenesis. Recent examples of SEC storms include Florence (2000), Michael (2000), Erin (2001)[2], Karen (2001), Noel (2001), Olga (2001), and Gustav (2002). Examples of recent storms in the WEC category are Leslie (2000), Nadine (2000), Allison (2001), Gabrielle (2001), and Humberto (2001).

[2] Note that Erin was a tropical storm in the eastern Atlantic, but it almost completely decayed in the central Atlantic. Its regeneration took place in the presence of extratropical perturbations.

TT FORECASTING: SEC CASES. *Synoptic-scale.* The composite structure for four SEC cases (Florence, Michael, Karen, and Gustav) shows a pronounced, localized anomalous trough in the upper troposphere to the west of the surface low just prior to TT (Fig. 1a). The lower-tropospheric temperature pattern exhibits warm and cold anomalies consistent with horizontal transport due to the precursor cyclone and anomalous warmth across the northeastern United States and eastern Canada (Fig. 1b). This mini-composite strongly resembles the 24-case composite shown by Bracken and Bosart (2000). It also resembles the anticyclonic wave-breaking scenario (LC1) presented in Thorncroft et al. (1993).

In SEC cases, a low-latitude frontal cyclone develops to an intensity sufficient to trigger WISHE. The vertical shear is eliminated by diabatic processes, as shown in Davis and Bosart (2003, hereafter DB03). The reduction in shear is caused by both the upper-tropospheric outflow from convection and from the diabatic redistribution of potential vorticity (PV), both of which tend to homogenize the horizontal gradients of PV directly above the storm center. The process leaves an equilibrated cyclone resembling an occluded system and creates a subsynoptic "cocoon" of weak shear, within which TT occurs and the resulting tropical cyclone grows. Observations of occluded and secluded cool-season marine cyclones (e.g., Shapiro 1990) have also revealed a deep column of weak shear over the cyclone center. However, the occlusion prior to TT departs from the classical model in which the surface cyclone migrates poleward (that is, toward colder air) beneath the upper-tropospheric jet. In TT cases, the jet itself is rearranged by diabatic processes and leads to an apparent migration of the surface cyclone toward warmer mean tropospheric air (on the synoptic scale).

Mesoscale. The rainfall and cloud signatures of the four SEC cases discussed above are shown in Fig. 2 just prior to TT. In each case, there is a pronounced asymmetry associated with the rainfall, with a tendency for a "bent back" frontal structure and heavy rainfall on the west and even southwest side of the still extratropical (or perhaps subtropical) surface low. This structure is present prior to some of the stronger hurricanes resulting from TT.

It is possible that the bent-back structure merely indicates a stronger precursor disturbance from which it is easier to create a stronger tropical cyclone. However, it is also possible that such a bent-back structure, with enhanced rainfall upshear from the surface low (the

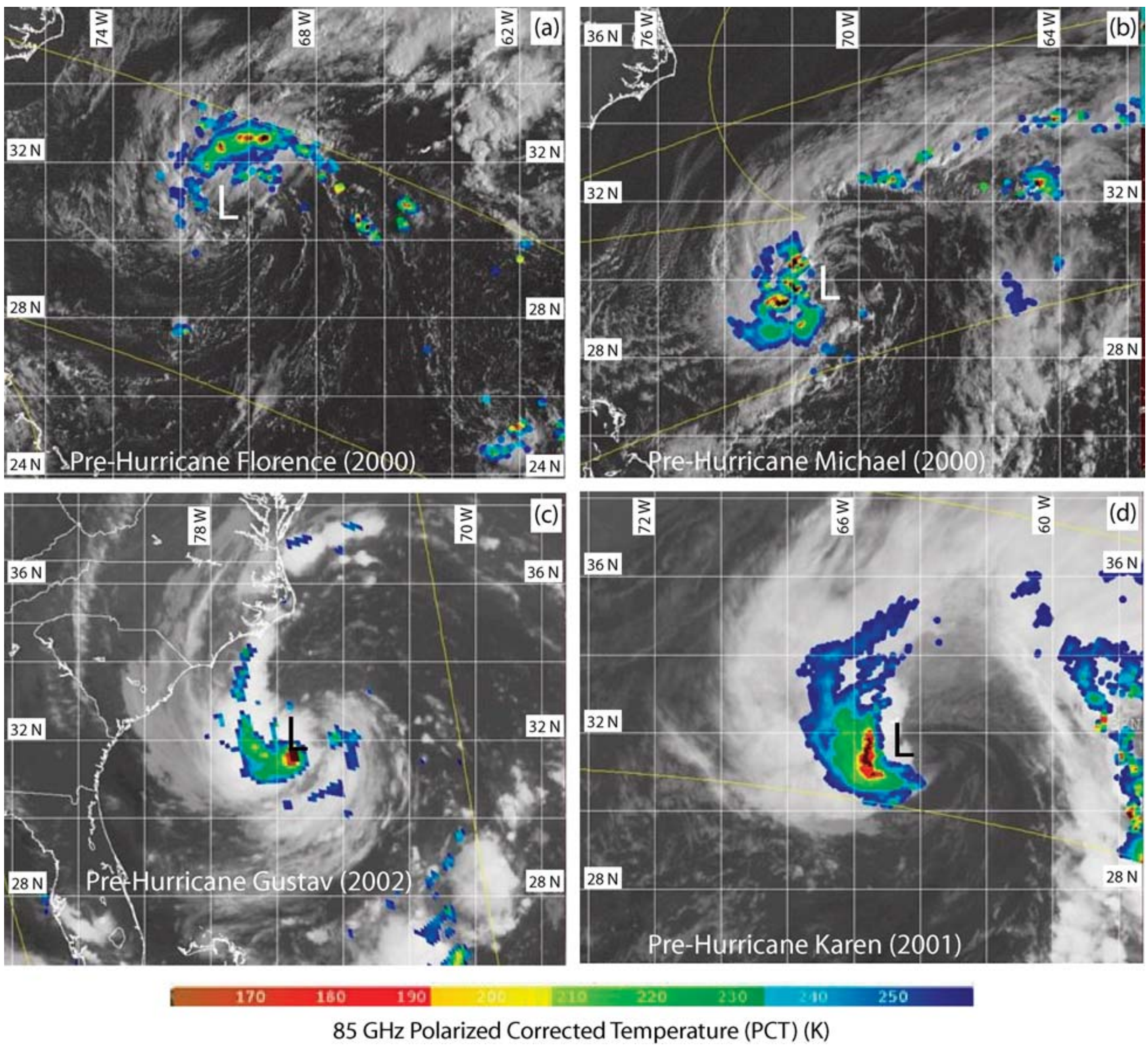

Fig. 2. (a) Visible satellite and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) 85-GHz polarized corrected temperature (PCT) imagery at 1145 and 1209 UTC 10 Sep 2000, respectively; (b) (upper right), as in (a) but for visible and TMI 85-GHz PCT at 1245 and 1335 UTC 15 Oct 2000; (c) IR and Special Sensor Microwave/Imager 85-GHz PCT at 0015 and 0219 UTC 10 Sep 2002; and (d) IR and TMI 85-GHz PCT at 2045 and 2132 UTC 11 Oct 2001. In all panels, the "L" indicates the position of the surface low. Images were obtained courtesy of the Naval Research Laboratory at www.nrlmry.navy.mil/tc_pages/tc_home.html.

upshear direction based on a synoptic-scale average), is particularly efficient for eliminating the vertical shear over the cyclone center as shown by the conceptual model in Fig. 3. These schema are based on simulations of Michael (DB03) and of nontransitioning cases (Davis and Bosart 2002) and are intentionally simplified to illustrate the salient differences. The pathway to an occluded cyclone corresponding to Fig. 3a is distinct from classical occlusion because it is driven by diabatic heating and advection arising from its secondary circulation, rather than from quasi-horizontal advection by the swirling flow around the cyclone.

Forecast rules. The conditions favoring development outlined by DeMaria et al. (2001) still apply to SEC cases, but only after the environment is modified by the precursor extratropical disturbance. Because such modification usually occurs on time scales less than 1 day, the key forecast challenge is to anticipate a favorable environmental modification.

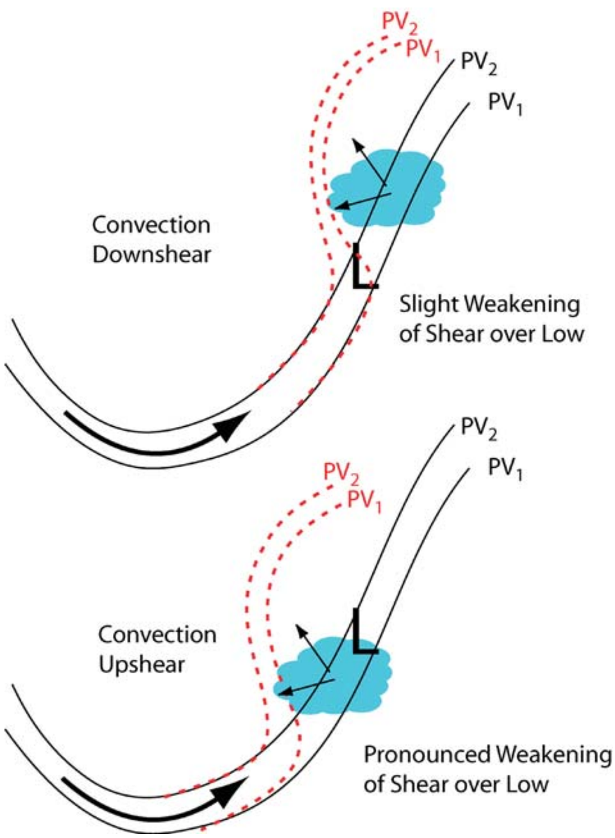

FIG. 3. Schema showing the effect of convection (blue area) (top) downshear and (bottom) upshear, relative to a surface low ("L"). Small arrows indicate divergent motion near the tropopause. Large arrow indicates flow within upper-level jet. Solid lines are two initial PV contours ($PV_2 > PV_1$), and red dashed lines indicate positions of the same contours after deep convection has developed.

The primary empirical forecast rule for predicting the tropical transition of cases with strong extratropical precursors may be stated, "The precursor cyclone must occlude and remain over warm water (>~26°C) for at least a day following occlusion." The failure of TT occurs for one of two reasons. First, transition fails if the occluding cyclone is embedded within a mean current that translates it over cool water before TT can occur (hence, the empirical "1-day rule" above). It should be noted that transition can occur, though rarely, over sea surface temperatures lower than the empirical 26°C. Tropical Storm Ana (2003), occurring in April, was possibly one example. Another was the South Atlantic "hurricane" of March 2004.[3]

Second, transition fails if the primary cyclone is prevented from occluding. This happens when additional upper-tropospheric short wavelength disturbances approach the surface cyclone and increase the vertical wind shear over its center before occlusion can occur or delay the occlusion until the storm is over cool water. The western Atlantic cyclones occurring on 1–2 October 2000 and 14–15 November 2001 illustrate this mode of TT failure (DB03). Because the occlusion process often requires more than a day to complete, this qualitatively represents a minimum allowable period of upper-tropospheric waves. Furthermore, if the upstream disturbance is of comparable or greater amplitude than the disturbance causing cyclogenesis, occlusion will probably not occur or will occur in response to development associated with the upstream wave.

WEC CASES. *Synoptic-scale.* Two types of WEC precursors considered herein are midtropospheric mesoscale vortices and baroclinic systems with a structure similar to SEC cases (i.e., an upshear tilt with height) but with smaller amplitude. The weak baroclinic systems in this category simply have insufficient amplitude to create a surface cyclone capable of amplifying by WISHE without invoking an intermediate process to enhance mesoscale vorticity. Hurricane Diana (1984) (Bosart and Bartlo 1991) and Hurricane Humberto (2001) are examples of storms that began by such a process. Their structure strongly resembles the composite of developing depressions shown by Bracken and Bosart (2000).

Mesoscale. Midtropospheric vortices, themselves often formed by antecedent convection, have been observed to initiate tropical cyclogenesis in Danny (1997) (Molinari et al. 2004) and Gabrielle (2001) (K. Musgrave 2003, unpublished manuscript). Midtropospheric convectively generated vortices have also been observed to initiate tropical cyclogenesis in lower latitudes (e.g., Simpson et al. 1997). It is through understanding the initiation of tropical cyclogenesis by mesoscale vortices at higher latitudes that the link with tropical cyclone formation in the deep Tropics can be made.

Just as there is a continuum between the weak and strong baroclinic precursors, there is a range of realizations between mesoscale vortices and weak baroclinic systems.

Numerical simulations of Diana (1984) (Powers and Davis 2002) showed that the path to tropical cyclogenesis required a lower-middle-tropospheric vor-

[3] It is possible that the range of similar disturbances should be extended to "hurricane-like" vortices that are occasionally observed in the Mediterranean Sea and in polar regions.

tex that formed within convection initiated by an extratropical precursor. The distinguishing character between cases such as Gabrielle (Fig. 4a) and Humberto (Fig. 4b) or Diana (1984) is that with Gabrielle, the midtropospheric vortex existed for more than two days before tropical cyclogenesis began. In such cases, the vortex must organize new convection through its interaction with vertical shear. When a weak extratropical cyclone is maintained, such as with Diana or Humberto, the organization of convection occurs through a superposition of vortex and cyclone-induced ascent. In Diana, there were multiple vortices formed within a mesoscale ascent region, and the coalescence and growth of these vortices formed the nascent tropical storm (Hendricks et al. 2004).

Forecast rules. Considerable research remains to understand how convection organizes in systems with weak precursors. Therefore, it is difficult to derive a set of forecast rules. However, it is apparent that PV "debris" extruded from the midlatitude jet is common over the warm oceans of the subtropical Atlantic, even as far south as 15°N on occasion. In September 2001 alone, we counted 34 upper-level vorticity maxima (averaged over a 3° × 3° latitude–longitude box) greater than 10^{-5} s^{-1} persisting for at least 12 h while over ocean temperatures greater than 25°C. Most of these upper-tropospheric disturbances had little effect on clouds and precipitation. Only disturbances that encountered (or persisted over) lower-tropospheric baroclinic zones helped initiate significant convection. The baroclinic zones exhibited typical contrasts ranging from 0.2° to 0.5°C (100 km)$^{-1}$. This was insufficient for baroclinic development on time scales of 1–2 days, but ample for focusing mesoscale ascent. The authors believe that the lower-middle tropospheric ascent is most important because it more effectively destabilizes the atmosphere. Overall, then, favorable conditions for WEC cases of TT involve mid-upper-tropospheric cyclone PV anomalies encountering lower-tropospheric baroclinity (and, hence, vertical shear). In the cases that develop into tropical cyclones, the shear either remains roughly 10 m s^{-1} or less, or it is reduced to such values following convection organization (Powers and Davis 2002). We note that at lower latitudes, convection has also been observed to organize when upper-tropospheric disturbances approach easterly waves, wherein systematic baroclinity is hard to identify.

There are almost certainly other factors involved in WEC cases of TT, but research has yet to fully clarify

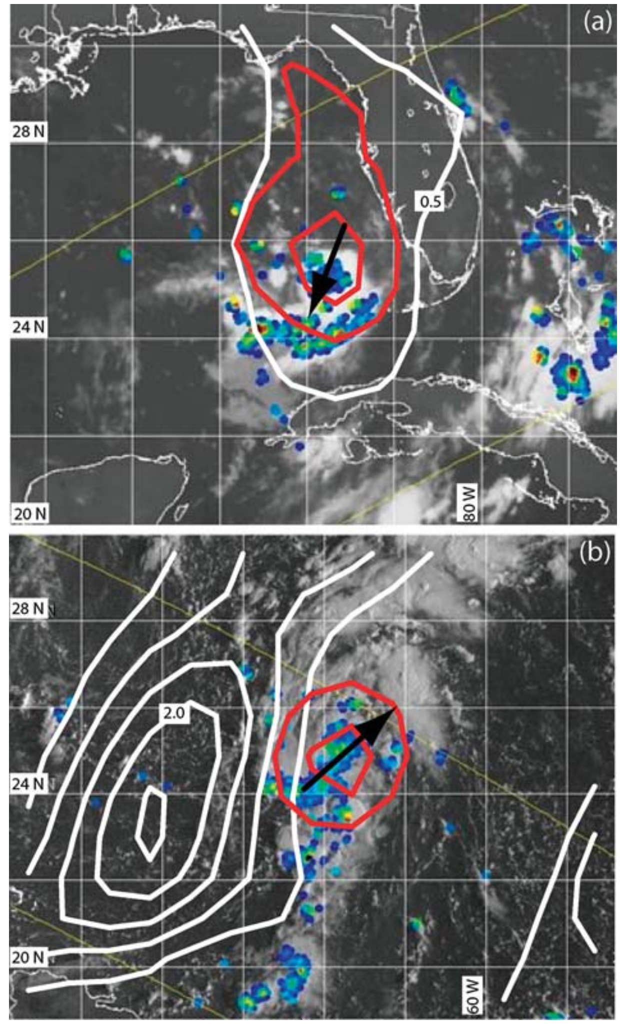

Fig. 4. (a) PV on the 310 K isentropic surface (white, contour interval 0.5 PVU) and 900-hPa relative vorticity (red, 0.5 and 1.0 × 10^{-4} s^{-1}, contoured) for 1200 UTC 11 Sep 2001; (b) as in (a) but for 340 K PV and at 1200 UTC 21 Sep 2001. Black arrow indicates shear vector orientation over low-level vorticity center. Fields are superposed on SSM/I 85-GHz PCT as in Fig. 2 for nearest corresponding time.

them. Numerical simulations (K. Musgrave 2003, unpublished manuscript) of Gabrielle (2001) suggest that following the growth of convection downshear of the precursor disturbance (Fig. 4a), there is a period during which the shear drops off dramatically to a value less than 5 m s^{-1}. Although this period is relatively short (about 6 h), the depression undergoes a full warm-core transformation. It is believed that the ongoing convection is somehow responsible for this decrease in shear. Unlike the schematic in Fig. 3, the ambient shear in cases like Gabrielle is weak enough that the diabatic secondary circulation can partially cancel it on the upshear side of the convection where the incipient low resides.

FOR FURTHER READING

Bosart, L. F., and J. Bartlo, 1991: Tropical cyclone formation in a baroclinic environment. *Mon. Wea. Rev.*, **119**, 1979–2013.

Bracken, E., and L. F. Bosart, 2000: The role of synoptic-scale flow during tropical cyclogenesis over the North Atlantic Ocean. *Mon. Wea. Rev.*, **128**, 353–376.

Davis, C. A., and L. F. Bosart, 2002: Baroclinic tropical cyclogenesis: Developing and non-developing cases. Preprints, *25th AMS Conf. on Hurricanes and Tropical Meteorology,* San Diego, CA, 395–396.

——, and ——, 2003: Baroclinically induced tropical cyclogenesis. *Mon. Wea. Rev.,* **131**, 2730–2747.

DeMaria, M., J. A. Knaff, and B. H. Conell, 2001: A tropical cyclone genesis parameter for the tropical Atlantic. *Wea. Forecasting*, **16**, 219–233.

Emanuel, K. A., 1987: An air–sea interaction model of intraseasonal oscillations in the Tropics. *J. Atmos. Sci.*, **44**, 2324–2340.

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.

Kalnay, E. and Coauthors, 1996: The NCEP/NCAR Reanalysis 40-Year Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Molinari, J., D. Vollaro, and K. Corbosiero, 2004: Tropical storm formation in a sheared environment. *J. Atmos. Sci.,* **61**, 2493–2509.

Powers, J. G., and C. A. Davis, 2002: A cloud-resolving, regional simulation of tropical cyclone formation. *Atmos. Sci. Lett.*, **3**, 15–24.

Shapiro, M. E., 1990: Fronts, jet streams and the tropopause. *Extratropical Cyclones*. C. Newton and E. O. Holopainen, Eds., Amer. Meteor. Soc., 167–189.

Simpson, J., E. Ritchie, G. J. Holland, J. Halverson, and S. Stewart, 1997: Mesoscale interactions in tropical cyclone genesis. *Mon. Wea. Rev.,* **125**, 2643–2661.

Thorncroft, C. D., B. J. Hoskins, and M. E. McIntyre, 1993: Two paradigms of baroclinic-wave life-cycle behaviour. *Quart. J. Roy. Meteor. Soc*., **119**, 17–56.