16.7

TOP-DOWN VS BOTTOM-UP GENESIS OF TORNADOES AND TROPICAL CYCLONES

W. R. Cotton*
Colorado State University, Fort Collins, Colorado

1. INTRODUCTION

While preparing updates and revisions to the 2nd Edition of "Storm and Cloud Dynamics", I reviewed the theories for tornado genesis in supercells and non-supercell convection, and tropical cyclone (TC) genesis from mesoscale convective vortices (MCVs). In so doing I found a number of common features between the two theories. In this paper I will first provide an overview of top-down vs bottom-up theories of tornado genesis including the environmental properties that favor the bottom-up genesis. I will then review the theories for top-down vs bottom-up genesis of TCs from MCVs, including the environmental properties that favor TC genesis from MCVs. This will include the role of vertical hot towers and book-end vortices.

2. EVOLUTION OF TORNADO-GENESIS THINKING

Early views of tornado genesis in supercell storms were based on a "top-down" concept in which the mesocyclone builds downward by a pressure-deficit tube (Smith and Leslie, 1978). While this may occur in idealized axisymmetric models, it is not very likely that vorticity in the mesocyclone will become sufficiently localized and intense that a pressure-deficit tube can form. Grasso and Cotton (1995) simulated the formation of a pressure deficit tube in an idealized three-dimensional supercell simulation. However, the simulated vortex did not build down from the center of the vortex. Instead, the vortex was initiated at the periphery of the updraft in the region of strong horizontal gradient of updraft velocity. Furthermore, the pressure-deficit tube vortex did not directly build downward to the surface to form a surface-based tornado vortex. Instead the descending vortex coalescenced with a preexisting surface-based vortex, possibly associated with the downdraft. The resultant enriched vorticity allowed the pressure field tube to descend to the surface forming a tornado.

Klemp and Rotunno (1983) showed that the development of the midlevel rotation was fundamentally different than that at low levels in the simulated storm. At midlevels the primary source of rotation is the vertical shear of the horizontal wind, which is tilted into the vertical. Klemp and Rotunno (1983) found that a major contribution to the production of horizontal vorticity at low levels was the baroclinicity along the gust front As a vortex line travels along the gust front, it mixes with low-valued Theta-E downdraft air, where baroclinic production of vorticity is also occurring.

A weakness in Klemp and Rotunno's argument is that little tilting of the baroclinically-produced horizontal vorticity cannot occur near the ground where vertical motion is nearly zero. If a tornado derives its vorticity from near-surface tilting of baroclinically produced vorticity, how then can a tornado's vortex lines remain essentially vertical down close to the ground, turning horizontal in the friction layer? In order for Klemp and Rotunno's concept to work, the baroclinically produced low-level vortex must build downward by a pressure-deficit tube.

The origin of "bottom-up" thinking of tornado genesis can be found in the observational studies of non-supercell tornado (NST) genesis (Wakimoto and Wilson, 1989; Brady and Szoke, 1989; Wilczak et al.,1992). In Wakimoto and Wilson's conceptual model (Figure 1), mesocyclones or small vortices originate at low levels by shearing instability along a convergence boundary such as a cold outflow from early storms. Relatively small cumuli form above the convergence boundary. By chance, one of the low-level vortices along the boundary collocates with a cumulus above. Then convergence and stretching by the towering cumulus generates a tornado of modest intensity.

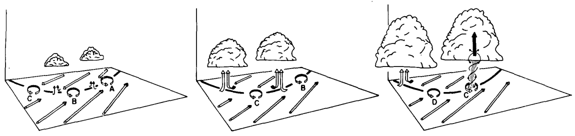

Fig. 1: Schematic model of the lifecycle of the non-supecell tornado. The black line is the radar detectable convergence boundary. Low-level vortices are labeled with letters. [From Wakimoto and Wilson (1989)]

Lee and Wilhelmson (1997) performed idealized three-dimensional simulations of a NST with 60 m grid spacing. Their simulations produced a quite realistic looking line of vortices some of which evolved into tornadic vortices. Figure 2 portrays a conceptual model of NST evolution they derived from their simulations.

At the interface between an outflow boundary and an air mass with a low-level wind field relatively parallel to the leading edge of the boundary, strong horizontal shear (i.e., a vertical vortex sheet) is found along the boundaries. Horizontal shearing instabilities develop along the boundary leading to the formation of mesoscale eddies, which subsequently merge and coalesce to form strong vortices that feed on the vorticity of neighboring eddies. They conclude that the collocation of the deep convective cells and the larger surface mesocyclones is not by chance but that the mesocyclones induce low-level convergence that

---

* *Corresponding author address:* W. R. Cotton, Colorado State Univ., Dept. of Atmospheric Science, Fort Collins, CO 80523-1371; e-mail: cotton@atmos.colostate.edu

favors the formation of the deep convective cells. Once the deep convective cells become coupled to the low-level vortices, low-level stretching associated with friction-induced low-level inflow intensifies the mesocyclone to tornadic intensity. This is a clear example of "bottom-up" tornado genesis.

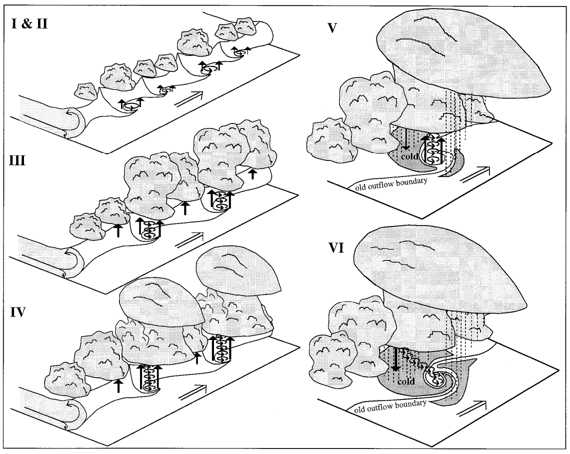

Fig. 2: Schematic presentation of the lifecycle stages of NST evolution. State I, vortex sheet development; stage II, vortex sheet rollup; stage III, mesocyclone interaction and merger; stage IV, early mature NST, stage V, late morning NST, and stage VI, dissipation. The diagrams in stages V and VI focus on just one member of the NST family. The viewing perspective is from an elevated position looking northwest. [From Lee and Wilhelmson (1997)]

Examples of "bottom-up" tornado genesis in supercell thunderstorms include simulations by Gaudet and Cotton (2006), Grasso (1996), Snook and Xue (2008), and Lerach et al. (2008). The latter two simulations revealed that the strength of the cool pool in rear flank downdrafts (RFDs) is an important factor in tornado genesis. If the cold pool is weaker (warmer and more buoyant) either as a result of suppressed evaporation of precipitation by reduced rainfall rates or by fewer and larger raindrops and hailstones, the gust fronts move slower in a storm-relative sense, increasing the likelihood that an intensified and deepened surface-based vortex ahead of the gust front will become coupled to a low-level mesocyclone and the parent mesocyclone aloft much like NSTs.

Once a surface-based vortex becomes coupled to the mesocyclone aloft, stretching and convergence of the surface-based vortex by the strong mesocyclone updrafts favors the intensification of the vortex into a tornado. Perhaps as suggested by Greg Tripoli (personal communication), the main role of the low-level mesocyclone is not convergence and stretching of a surface-based vortex, but convergence of surface-based vortices that favors their merger and coalescence to form an intense tornadic vortex. From this perspective of the tornado genesis process is quite *stochastic* with many processes contributing to the formation of surface-based vortices. The strong dynamics of the supercell, including its downdrafts and gust fronts, develops strong low-level shears that favors generation of surface vortices by shearing instabilities and vortex breakdown. But it is the overall intensity of the supercell mesocyclone and its associated updrafts, and the strength of the underlying cold pool that determines the probably that surface-based vortices (initiated by a variety of mechanisms) will be intensified to tornadic strength.

These ideas are consistent with observational evidence that the air within RFDs of tornadic supercell storms is more buoyant and potentially buoyant (higher CAPE) than in non-tornadic supercell storms (Fujita et al., 1977; Brown and Knupp, 1980; Bluestein, 1983; Rasmussen and Straka, 1996; Markowski et al., 2002; Grzych et al., 2007). Markowski et al. (2002) also found that there was a high correlation between the coldness of the downdraft and the ambient (inflow) relative humidity. More buoyant low-level downdrafts were found in moist level environments than dry.

3. EVOLUTION OF TC-GENESIS THINKING

Like tornado genesis, much discussion has occurred in recent years regarding whether TC genesis is a top-down vs a bottom-up process. Emanuel (1993) and Bister and Emanuel (1997) argue that a TC can form from the descent of a single MCV to the surface. They argue that sustained stratiform precipitation from the stratiform-anvil of an MCS or MCV will gradually saturate the lower troposphere. At the same time the slantwise descending flow in the MCS will advect cyclonic vorticity associated with the MCV to the surface. It is argued that the moistening and cooling by the stratiform precipitation destabilizes the boundary layer to support deep convection and also weakens convective downdrafts. They argue that convergence of lower tropospheric mean vorticity in a region of convection where downdrafts are weak favors the spin-up of the low-level vortex. I argue that in analog-to-tornado genesis, the weakened cold pools as a result of moistening of the lower troposphere may aid the genesis of a TC by favoring the sustained vertical coupling between the MCV aloft and an evolving low-level vortex.

Another example of a top-down theory of TC genesis was proposed by Ritchie and Holland (1997) and Simpson et al. (1997). Using modeling studies and supporting observations, they argue that the merger of middle level MCVs on scales of 100-200 km will result in larger, more intense MCVs whose circulations have greater penetration depths thus favoring the spin-up of a low-level vortex.

Nolan (2007) describes the results of a series of idealized simulations, which are interpreted as top-down genesis of a TC. As in the above studies, the TC-genesis process is intimately associated with an MCV and associated stratiform precipitation. He notes that after several days of amplification of the MCV, when it contracts to a radius of maximum winds of 60 km and a maximum wind speed of 12 m s^{-1}, a single strong updraft or cluster of updrafts form near the center of the MCV aloft. In response to the strong updrafts a single, dominant low-level vortex forms that became the central core of the developing TC. He notes that this single, dominant low-level vortex does not form until low-levels become nearly saturated (by evaporation of stratiform precipitation and convective showers) and the MCV becomes inertially stable (well balanced).

The bottom-up theories proposed by Montgomery and Enagonio (1998), Enagonio andMontgomery (2001), Hendricks et al. (2004) focus more on the MCS convective region where low-level convergence enhances vorticity rather than the descent of the MCV itself. Hendricks et al.introduced the concept of vertical hot towers (VHTs) wherein strong convective updrafts generate strong cyclonic and anticyclonic eddies, principally by tilting of horizontally oriented vortex tubes as in the theories for formation of mesocyclones in supercells. Idealized modeling studies (Montgomery et al., 2006) suggest that the VHTs merge to form stronger and larger low-level vortices, which then can serve as the embryos for genesis of the low-level TC vortex. Important to the bottom-up theory is initially off-center low-level vortices become vertically aligned with the MCV aloft to produce a deep tropospheric vortex. As in bottom-up theories of tornado-genesis, moistening of the lower troposphere by evaporating precipitation would result in relatively less cold, cold pools, which would favor a reduction in storm-relative motion of the low-level vortex relative to the MCV thus favoring coupling through the depth of the troposphere. As noted by Davis and Galarneau (2009), optimum low-level vertical wind shear, can also favor the movement of a low-level vortex in a storm-relative sense rearward beneath the middle tropospheric MCV.

4. SUMMARY AND CONCLUSIONS

A common theme between tornado genesis and TC genesis is the need for coupling between low-level vortices and middle to lower tropospheric mesoscale cyclones or MCVs. This is important regardless of whether the surface-based vortices form by a top-down or a bottom-up process. Weaker cold pools are important to genesis of both tornadoes and TCs as weaker cold pools favor a vertical coupling between surface-based vortices and higher level mesoscale circulations. Thus both TCs and tornadoes are found to form in very deep moist environments, where evaporation of precipitation is less.

5. ACKNOWLEDGEMENTS

This research was funded by NSF under grant ATM-0638910 and DHS/NOAA under contract NA17RJ1228.

6. REFERENCES

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

Bluestein, H. B., 1983: Surface meteorological observations in severe thunderstorms. Part II: Field experiments with TOTO, *J. Appl. Meteor.,* **22**, 919–930.

Brady, R. H. and E. J. Szoke, 1989: A case study of nonmesocyclone tornado development in northeast Colorado: Similarities to waterspout formation, *Mon. Wea. Rev.,* **117**, 843-856.

Brown, J. M. and K. R. Knupp, 1980: The Iowa cyclonic-anticyclonic tornado pair and its parent thunderstorm, *Mon. Wea. Rev.*, **108**, 1626-1646.

Davis, C. A. and T. J. Galarneau, Jr., 2009: The vertical structure of mesoscale convective vortices. *J. Atmos. Sci.*, **66**, 686-704.

Emmanuel, K. A., 1993: The physics of tropical cyclogenesis over the eastern Pacific. *Tropical cyclone disasters. Proceedings of ICSU/WMO International Symposium on Tropical Cyclone Disasters*. Eds. J. Lighthill, Z. Zhemin, G. Holland, and K. Emanuel. Peking University Press, 136-142.

Enagonio, J. and M. T. Montgomery, 2001: Tropical cyclogenesis via convectively forced vortex Rossby waves in a shallow water primitive equation model. *J. Atmos. Sci.*, **58**, 685-706.

Fujita, T. T., M. R. Hjelmfelt, and S. A. Changnon, 1977: Mesoanalysis of record Chicago rainstorm using radar, satellite, and raingauge data, Preprints *10th Conf. on Severe Local Storms*, Omaha, NE, Amer. Met. Soc., 65-72.

Gaudet, B. J. and W. R. Cotton, 2006: Low-level mesoscale concentration by non-axisymmetric process. Part I: Supercell and mesocyclone evolution, *J. Atmos. Sci.*, **63**, 1113-1133.

Grasso, L. D., 1996: Numerical simulation of the May 15 and April 26, 1991 thunderstorms. Ph.D. dissertation, Colorado State University, Dept. of Atmospheric Science, Fort Collins, CO 80523, ATS paper 596, 151 pp.

Grasso, L. D. and W. R. Cotton, 1995: Numerical simulation of a tornado vortex, *J. Atmos. Sci.*, **52**, 1192-1203.

Grzych, M. L., B. D. Lee, and C. A. Finley, 2007: Thermodynamic analysis of supercell rear-flank downdrafts from Project ANSWERS, *Mon. Wea. Rev.*, **135**, 240-246.

Hendricks, E. A., M. T. Montgomery, and C., A. Davis, 2004: The role of “vertical” hot towers in the formation of tropical Cyclone Diana (1984). *J. Atmos. Sci.*, **61**, 1209-1232.

Klemp, J. B. and R. Rotunno, 1983: A study of the tornadic region within a supercell thunderstorm, *J. Atmos. Sci.*, **40**, 359-377.

Lee, D. B. and R. B. Wilhelson, 1997: The numerical simulation of nonsupecell tornadogenesis. Part I: Evolution of a family of tornadoes along a weak outflow boundary, *J. Atmos. Sci.*, **54**, 2387-2415.

Lerach, D. G., B. J. Gaudet, and W. R. Cotton, 2008: Idealized simulations of aerosols on tornado genesis, *Geophys. Res. Letters*, **35**, L23806-L23806.

Markowski, P. M., J. M. Straka, and E. N. Rasmussen, 2002: Direct surface thermodynamic observations within the rear-flank downdrafts of nontornadic and tornadic supercells, *Mon. Wea. Rev.,* **130**, 1692-1721.

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

Montgomery, M. T., M. E. Nicholls, T. A. Cram, and A. Saunders, 2006: A vertical hot tower to tropical cyclogenesis, *J. Atmos. Sci.*, **63**, 355-386.

Nolan, D., 2007: What is the trigger for tropical cyclogenesis? *Aust. Met. Mag.*, **56**, 241-266.

Rasmussen, E. N. and J. M. Straka, 1996: Mobile mesonet observations of tornadoes during VORTEX-95. Preprints *18th Conf. on Severe Local Storms*, San Francisco, CA, Amer. Met. Soc., 1-5.

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

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

Smith, R. K. and L. M. Leslie, 1978: Tornadogenesis, *Quart. J. Roy. Meteor. Soc.,* **104**, 189-199.

Snook, N. and M. Xue, 2008: Effects of microphysical drop size distribution on tornadogenesis in supercell thunderstorms, *Geophys. Res. Letters*, **35**, L24803, doi:10.1029/2008GL035866.

Wakimoto, R. M., and J. W. Wilson, 1989: Non-supercell tornadoes, *Mon. Wea. Rev.,* **117**, 1113–1140

Wilczak, J. M., T. W. Christian, D. E. Wolfe, R. J. Zamora, and B. B. Stankov, 1992: Observations of a Colorado tornado. Part I. Mesocale environment and tornadogenesis, *Mon. Wea. Rev.,* **120**, 497-520.