15.4 MID-LEVEL DRY INTRUSIONS AS A FACTOR IN TORNADO OUTBREAKS ASSOCIATED WITH LANDFALLING TROPICAL CYCLONES FROM THE ATLANTIC AND GULF OF MEXICO

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1. INTRODUCTION

The potential for landfalling tropical cyclones to produce tornadoes has been documented by various researchers. Some storms produce outbreaks of tornadoes while others produce few or none. Vescio et al. (1996) noted that dry intrusions at mid-levels have the potential to substantially alter the thermodynamic structure of the tropical cyclone environment (with substantial enhancement of CAPE and surface-based instability, as well as enhanced evaporative cooling within the RFD), and suggested it would be beneficial to document future tornado outbreaks to better understand the role of dry intrusions in the outbreaks. Examination of *historical* outbreak cases yields important information and has the advantage of providing improved understanding of the role of mid-level dry intrusions without waiting for future storm landfalls.

Thirteen "outbreak" cases (storms producing twenty or more tornadoes) for tropical cyclones making landfall from the Atlantic and Gulf of Mexico since 1960 have been examined for evidence of mid-level dry intrusions. Ten of those cases were found to offer clear evidence of a dry intrusion at mid-levels in or close to the area where the outbreak occurred.

2. PRIOR RESEARCH

The author has previously reported on tropical cyclones that made landfall along the coast of the central and western Gulf of Mexico and produced outbreaks of twenty or more tornadoes. (Curtis 2000; Curtis 2001) The storms previously considered were: *Alicia* (1983), *Allen* (1980), Andrew (1992), *Beulah* (1967), *Carla* (1961), *Danny* (1985), *Gilbert* (1988), *Georges* (1998), and *Opal* (1995).

2.1 Factors in Tornado Formation and Location

Two areas of tropical cyclones produce most of the reported tornadoes: near the core of the storm and in the outer rainbands. (Gentry 1983; Weiss 1987) Although Gentry said that most tornadoes occur in areas close to the coastline and Novlan and Gray (1974) asserted that nearly all hurricane-induced tornadoes occur within 200 km of the coast, it is now clear that the threat can extend inland and be well removed from areas affected by the storm center.

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Novlan and Gray (1974) found that the centroid of tornadogenesis is 240 km northeast (50 degrees east of true north) from the storm center. Gentry (1983) noted that the tipping term of the vorticity equation is twice as large in the northeast quadrant of a landfalling storm. McCaul (1991) examined 1,296 proximity soundings from tropical cyclones producing tornadoes and found that ambient helicity is maximized in the right-front quadrant. Bogner et al. (2000) examined dropwindsonde data from six Atlantic storms while over open water and found that the right-front quadrant (relative to storm motion) contained the greatest speed and directional shear.

2.2 Factors Leading to Tornadogenesis

Various factors have been proposed to explain tornadogenesis in landfalling tropical cyclones. Novlan and Gray (1974) noted that speed shear is pronounced in areas within 200 km of the coast as a storm makes landfall. They estimated a 20 m s^{-1} increase in wind velocity from the surface to 850 hPa. Gentry (1983) noted that wind speeds over land areas were reduced by surface friction while the flow at slightly higher levels remained strong and was not affected by friction.

Studies since the deployment of the WSR-88D radars indicate that many of the tornadoes are related to intense, persistent cells within the outer rainbands (Spratt et al. 1997). These cells develop mesocyclones, although identifying the mechanism by which this occurs has proven elusive. McCaul and Weisman (1996) simulated shallow supercell storms in landfalling hurricane environments and found that, while the wind shear profiles often favor the development of storms with rotating updrafts, surface mesocyclogenesis may be hampered by a relative lack of strong storm-induced baroclinicity.

2.3 Significance of Mid-Level Dry Intrusions

The traditional tropical cyclone paradigm is a system dominated by barotropic influences. The barotropic structure of the typical tropical cyclone limits CAPE to levels well below those normally associated with deep convective storms on the Great Plains. (McCaul 1991) Somewhat in contrast to McCaul's findings, Bogner et al. (2000) examined dropwindsonde data from six Atlantic hurricanes over open ocean, and found CAPE of around 1500–1700 J kg^{-1} at 300 km or more from the storm center. They found that CAPE varied little by storm quadrant.

The origin of baroclinicity in an otherwise barotropic system has been the subject of investigation, informed speculation, and some consternation for at least the past four decades. Discussing convective instability as a "concomitant ingredient" for tornado formation in hurricanes, Hill et al. (1966) noted that the notion of relatively dry air at intermediate levels aloft is difficult to reconcile with the generally held view that the tropical cyclone consists of a roughly uniform air mass that is at or near saturation both vertically and horizontally. Thus, the notion that mid-level dry intrusions may occur in tropical cyclones is not of recent origin. Novlan and Gray (1974) specified "significant dry air intrusions in the right rear quadrant … at 850-700mb" as an indicator for potential tornado "family" outbreaks. McCaul (1987) noted that dry air advected into a landfalling storm's mid-levels may influence the structure of the storm, and that mid-level dry air intrusions are fed by a large-scale reservoir of dry air outside the hurricane that may eventually penetrate quite close to the center of a storm, causing local increases in the lapse rate, thereby contributing to an increase in convective instability.

Edwards (1999) studied tornadoes associated with exiting tropical cyclones (storms headed back toward the Atlantic) and found baroclinic influences in every tornadic event related to those storms.

3. OUTBREAK CASES

Outbreak cases are defined as those occurring subsequent to 1960 and producing 20 or more tornadoes with landfall on the Atlantic or Gulf coast (including the northern Mexican coast because of its proximity to Texas). The location of each tornado was ascertained utilizing SVRPLOT2 and the Storm Prediction Center database of severe events and Storm Data. The storms considered herein are: *Agnes* (1972), *Alicia* (1983), *Allen* (1980), Andrew (1992), *Beryl* (1994), *Beulah* (1967), *Carla* (1961), *David* (1979), *Danny* (1985), *Gilbert* (1988), *Georges* (1998), *Josephine* (1996), and *Opal* (1995). [Hurricane Agnes is included based on recent work by Hagemeyer and Spratt (2202).] *Beryl* and *Josephine* were tropical storms; all others were hurricanes.

All thirteen storms were examined in the same manner: rawinsonde data at three levels: 500hPa, 700hPa and 850hPa for the period commencing 36 hours prior to landfall through 36 hours following landfall was examined. Analysis involved a smoothed plot of layer relative humidity at those levels for evidence of a mid-level dry intrusion. This was accomplished using Digital Atmosphere © software applying a standard Barnes analysis scheme utilizing a 2-pass filter.

A more thorough examination of each case can be found at: http://www.vvm.com/~curtis/AMSTCTor.html. Of the thirteen cases, three were determined not to have involved clear evidence of mid-level dry air intrusions: *Alicia*, *Carla, and Josephine.* Although not discussed herein, they are covered in the material at the above website. The ten positive cases account for at least 300 tornadoes, and appear below in alphabetical order.

Hurricane Agnes (1972)

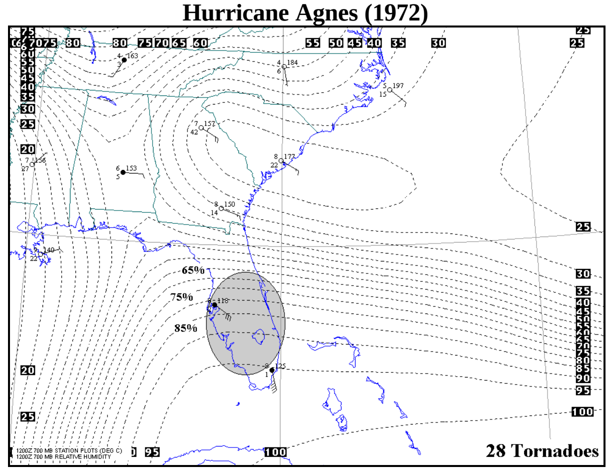

Figure 1. 700hPa relative humidity on June 18, 1972 at 7am EST (1200UTC) with the outbreak area indicated by shading.

Hurricane Allen (1980)

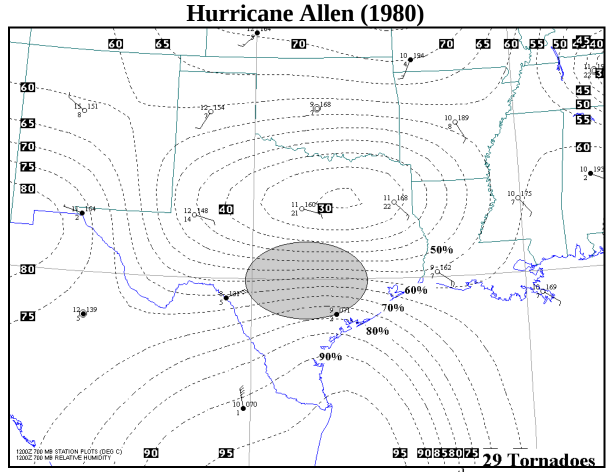

Figure 2. 700hPa relative humidity on Aug. 10th, 1980 at 6am CST (10/1200UTC) with outbreak area indicated by shading.

Hurricane Andrew (1992)

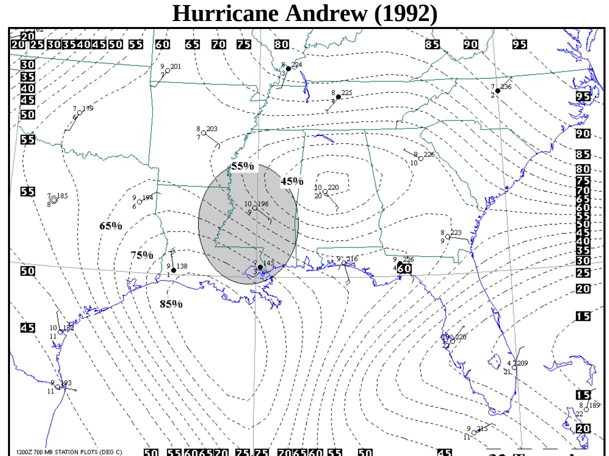

Figure 3. 700hPa relative humidity on Aug. 26th, 1992 at 6am CST (26/1200UTC) with outbreak area indicated by shading.

Tropical Storm Beryl (1994)

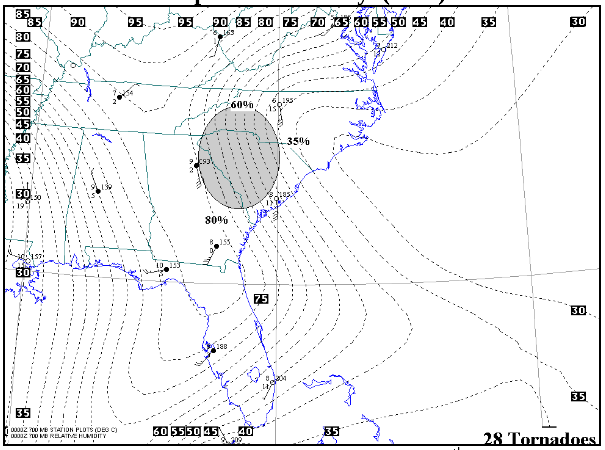

Figure 4. 700hPa relative humidity on Aug. 16th, 1994 at 7pm EST (17/0000UTC) with outbreak area indicated by shading.

Hurricane Beulah (1967)

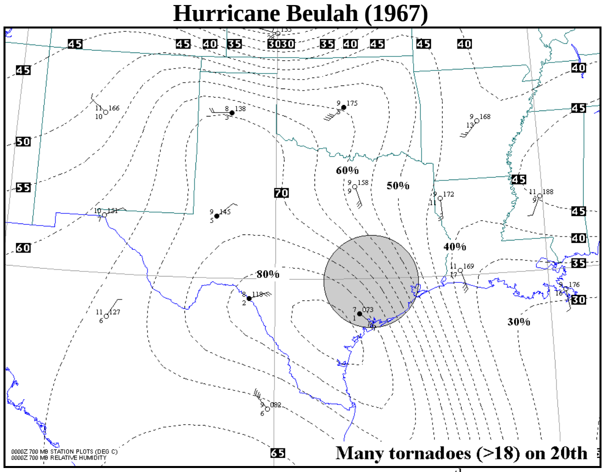

Figure 5. 700hPa relative humidity on Sept. 20th, 1967 at 6pm CST (21/0000UTC) with outbreak area indicated by shading.

Hurricane Beulah (1967)

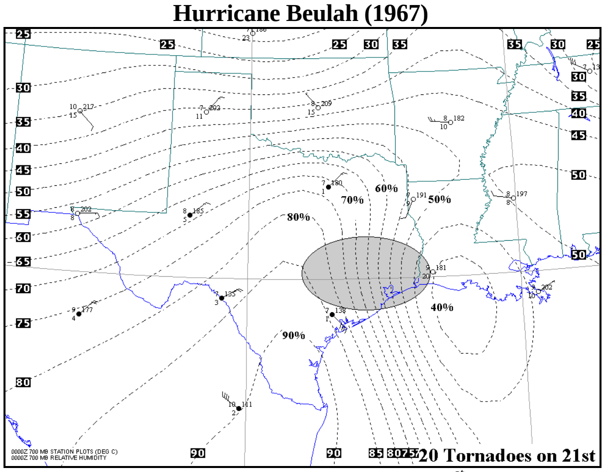

Figure 6. 700hPa relative humidity on Sept. 21st, 1967 at 6pm CST (22/0000UTC) with outbreak area indicated by shading.

Hurricane Beulah (1967)

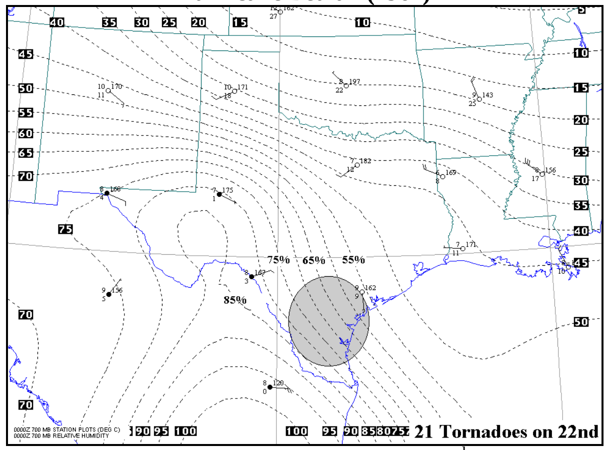

Figure 7. 700hPa relative humidity on Sept.22nd, 1967 at 6pm CST (23/0000UTC) with outbreak area indicated by shading.

Hurricane Danny (1985)

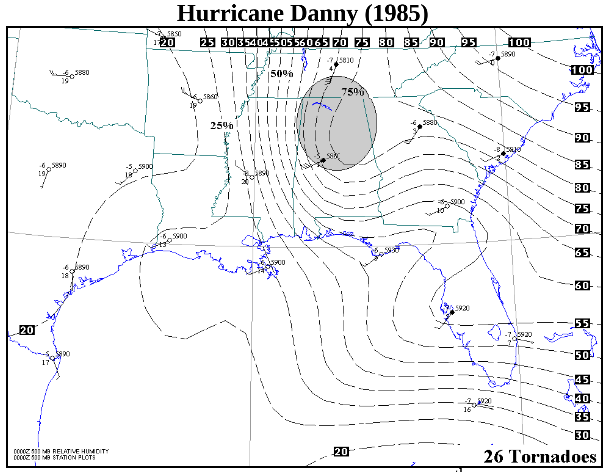

Figure 8. 500hPa relative humidity on Aug. 17th, 1985 at 6pm CST (17/0000UTC) with outbreak area indicated by shading.

Hurricane David (1979)

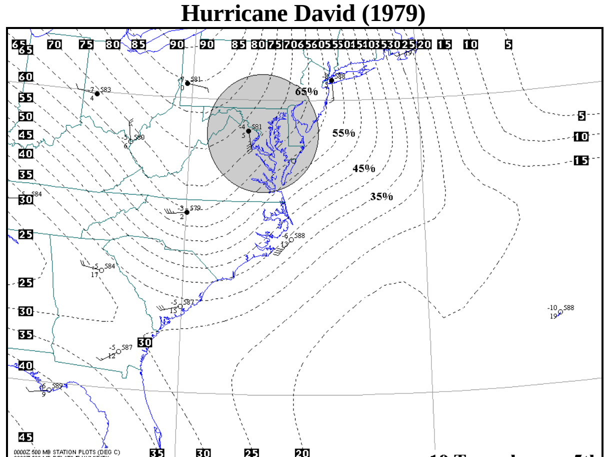

Figure 9. 500hPa relative humidity on Sept. 5th, 1979 at 7pm EST (06/0000UTC) with outbreak area indicated by shading.

Hurricane Gilbert (1988)

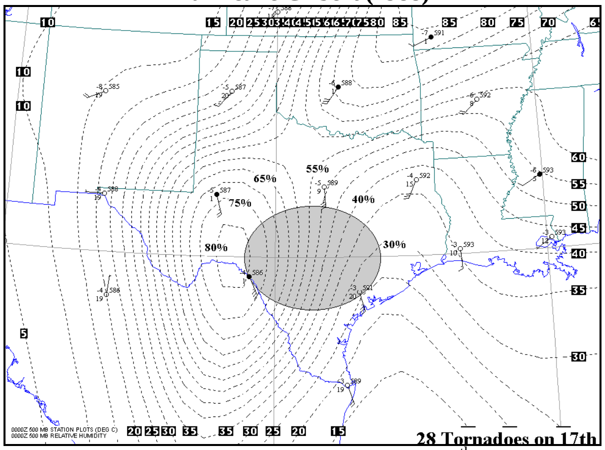

Figure 10. 500hPa relative humidity on Sept.17th, 1988 at 6pm CST (18/0000UTC); outbreak area indicated by shading.

Hurricane Georges (1998)

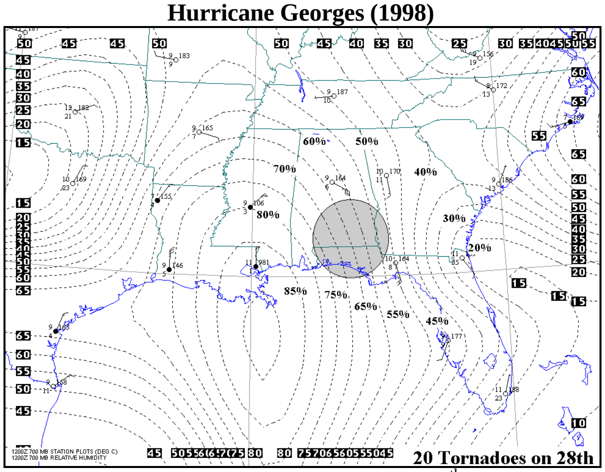

Figure 11. 700hPa rel. humidity on Sept. 28th, 1998 at 6am CST (28/1200UTC) with outbreak area indicated by shading.

Hurricane Georges (1998)

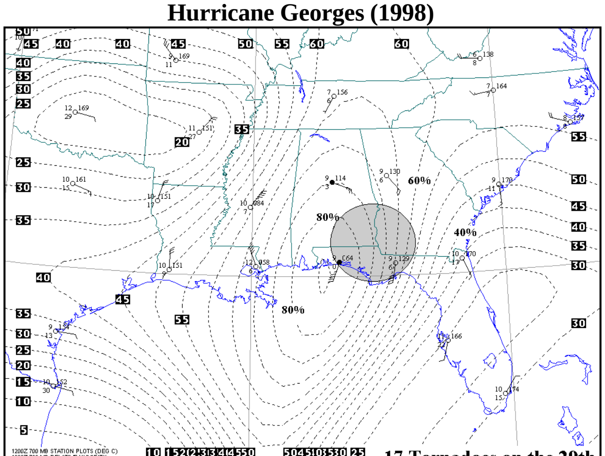

Figure 12. 700hPa rel. humidity on Sept. 29th, 1998 at 6am CST (29/1200UTC) with outbreak area indicated by shading.

Hurricane Opal (1995)

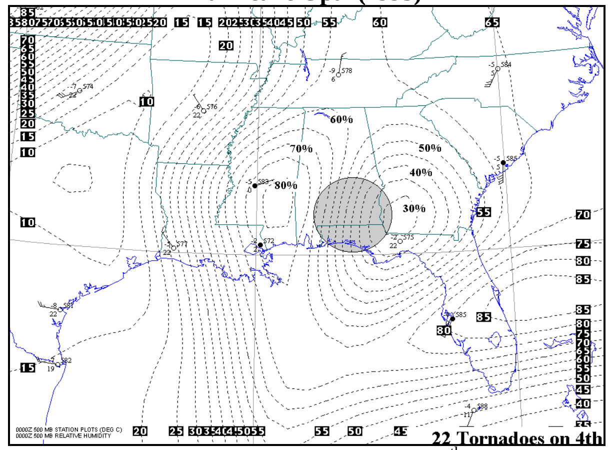

Figure 13. 500hPa relative humidity on Oct. 4th, 1995 at 6pm CST (05/0000UTC) with outbreak area indicated by shading.

5. DISCUSSION AND CONCLUSIONS

A total of thirteen tornado outbreak cases occurring since 1960 along the coast of the Atlantic and of the Gulf of Mexico have been analyzed for evidence of mid-level dry intrusions as a factor in the outbreaks. Ten of the thirteen cases offer clear evidence of a dry intrusion at mid-levels in or close to the outbreak area. The favored area for tornadogenesis appears to be in the gradient between maxima and minima of relative humidity, and is generally best reflected at the 700hPa and/or 500hPa levels. However, the sparse resolution of the sounding data is a continuing limitation on defining the true lateral and vertical extent of the intrusions.

Modern remote sensing platforms are invaluable aids in ascertaining the existence and extent of mid-level dry intrusions, but in situ observations (rawinsonde and dropwindsonde) are also critical. While not all tornado outbreaks associated with tropical cyclone landfalls result from dry intrusions, it is clear that the recurrence of the distinctive pattern seen in these cases should heighten forecaster vigilance when seen operationally as a storm approaches landfall.

REFERENCES

Please see this website for a complete list of references: http://www.vvm.com/~curtis/AMSTCTor.html.