

TORNADOES ASSOCIATED WITH TROPICAL STORM BERYL

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Abstract

Tropical Storm Beryl significantly affected the eastern United States over the three-day period, 15–17 August 1994. Although no tornadoes occurred around the climatologically preferred time of landfall on the 15th, an outbreak of 31 tornadoes occurred in the southeast U.S. on the 16th. Nine of the tornadoes were F-Scale 2 or 3, considerably stronger than most tornadoes associated with tropical cyclones. This was the largest tornado outbreak on record for a tropical cyclone with peak intensity below hurricane strength. Tornado production diminished considerably on the 17th as the system continued north-northeast, with only 5 weak tornadoes reported in the mid-Atlantic States region. An effort is made in this study to ascertain what parameters contributed to the distinct tornado maximum on 16 August 1994. Results show that a pronounced dry intrusion into the northeast quadrant of the tropical circulation on the 16th destabilized the air mass by creating steeper lapse rates and enhancing surface heating. Increased instability and stronger storm-relative (SR) helicity on the 16th provided a much more favorable environment for supercell storms compared to the 15th when the system made landfall. It is also hypothesized that dry air in the storm environment increased the potential for tornadoes by enhancing baroclinic generation of vorticity through evaporative cooling in the rear flank downdraft (RFD). The dry intrusion moved offshore on the 17th limiting instability and decreasing the potential for baroclinic generation of low-level vorticity along the RFD.

1. Introduction

Tropical Storm Beryl made landfall near Panama City, Florida around 0000 UTC 16 August 1994 with maximum sustained winds of 26 m s^{-1} (50 kt) and a minimum central pressure of 999 mb. Beryl weakened to a tropical depression around 1200 UTC 16 August over southwest Georgia. Throughout the remainder of the 16th and 17th, Beryl gradually decayed as it moved north-northeast to the lee of the Appalachians, reaching western Virginia by 0000 UTC 18 August. The remnants of the tropical system then turned northeast, moving into southern New England before being absorbed in a frontal trough. The track of Beryl is shown in Fig. 1.

Although no tornadoes were reported near the time of Beryl's landfall on 15 August, a total of 37 tornadoes occurred after the system moved inland. An outbreak of 31 tornadoes occurred from late morning on the 16th through the early morning hours on the 17th, extending from northeast Georgia across the Carolinas into southern Virginia¹. Twenty-three tornadoes struck

western and central South Carolina, including three of F3 and five of F2 magnitude. Three additional F2 tornadoes were reported: one in northeast Georgia, another in western North Carolina, and a third in extreme southern Virginia. The spatial distribution of tornadoes during the outbreak is displayed in Fig. 2. The tornadoes resulted in more than 50 injuries and caused property damage in excess of 10 million dollars. This was the most prolific tornado outbreak on record from a tropical cyclone whose maximum intensity remained below hurricane strength. As a tornado producer, Beryl ranks fifth when all tropical cyclones are considered (Table 1). The number of tornadoes diminished considerably during 17 August with only five reports of weak (F0-F1) tornadoes.

The purpose of this study is to examine the meteorological characteristics of the 15–17 August period to determine factors that contributed to the tornado outbreak on the 16th. Because Beryl was a relatively weak tropical cyclone, a severe tornado

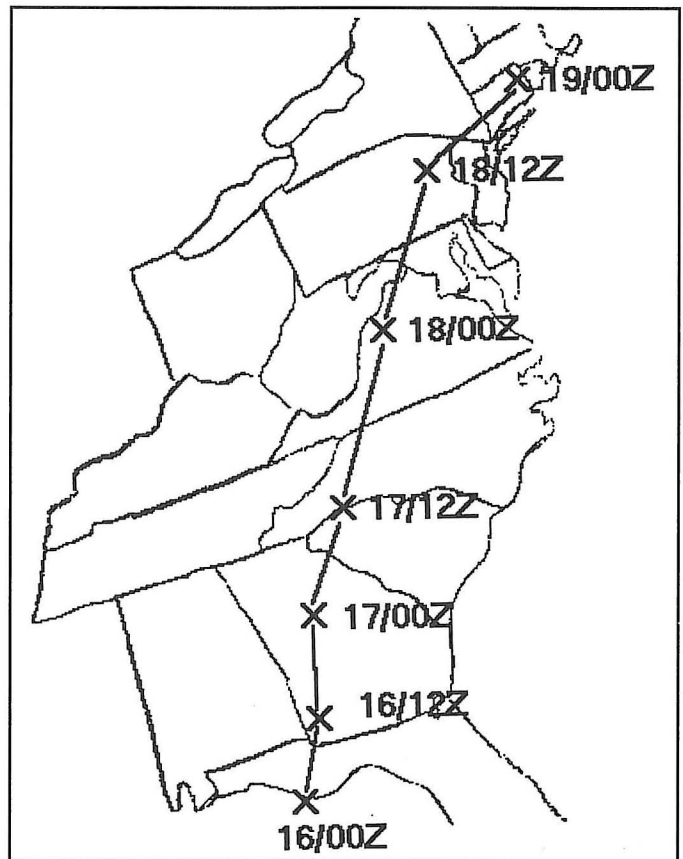


Fig. 1. Observed track of Tropical Storm Beryl during the period 16 to 18 August 1994.

¹ One additional tornado, rated F0, occurred in the Florida panhandle, well removed from the main outbreak region.

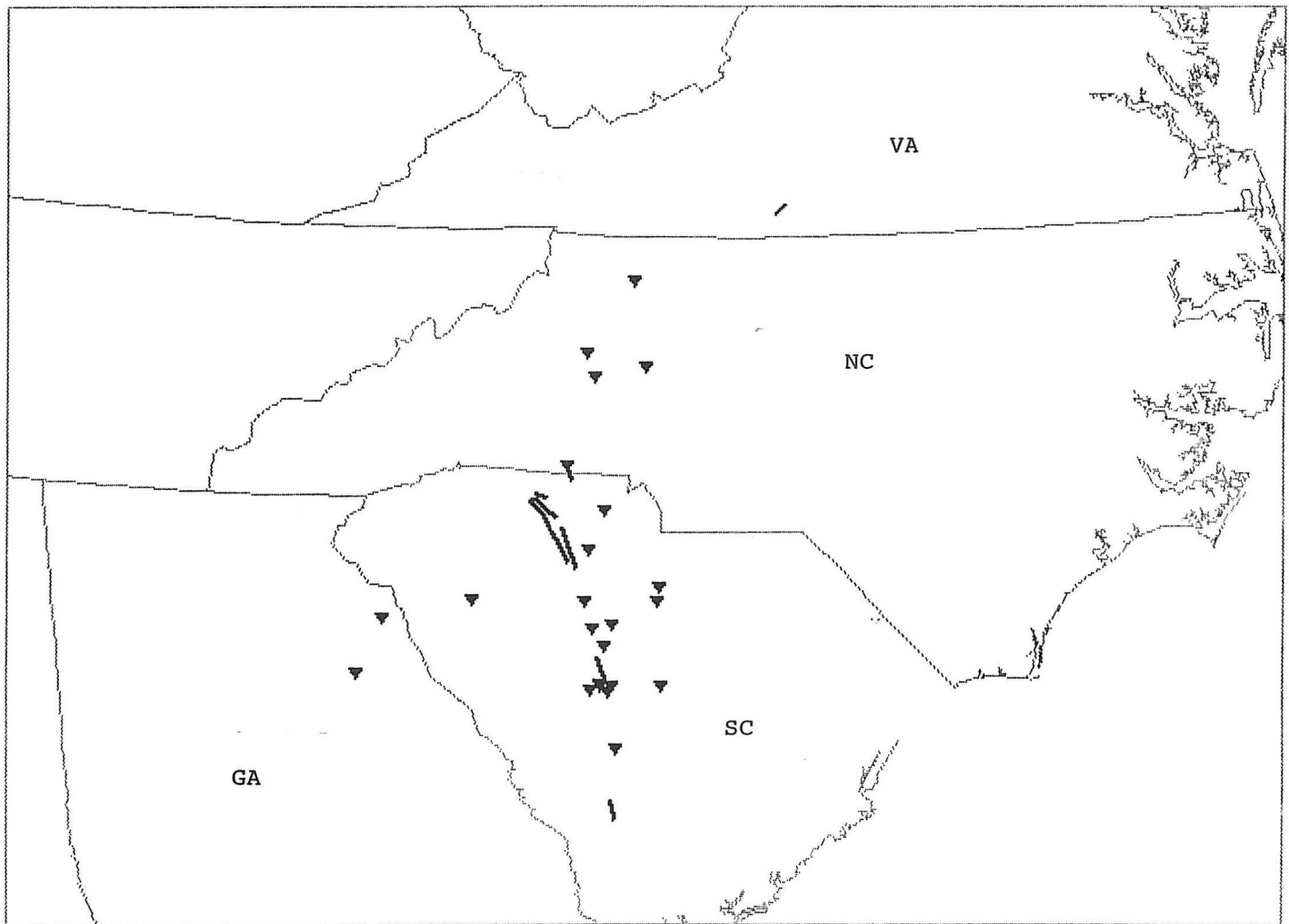


Fig. 2. Plot of tornadoes during the 16 August outbreak. Inverted triangles indicate brief touchdowns. Line segments indicate longer damage tracks.

Table 1. The five most prolific tornado producing tropical cyclones on record affecting the United States.

Tropical Cyclone	Year	Number of Tornadoes
Beulah	1967	113
Andrew	1992	48
Gilbert	1989	47
Danny	1985	39
Beryl	1994	37

outbreak might not be expected. Output from the National Weather Service (NWS) National Centers for Environmental Prediction (NCEP) operational early Eta numerical weather prediction model² is examined to help determine if this event could have been anticipated. We also briefly examine the distri-

²The operational early Eta model is widely used throughout the National Weather Service. The version of the Eta used in this study has an 80 km horizontal grid spacing with forecasts available in 6 h increments through 48 h.

bution of tornadoes relative to the center of the tropical cyclone, and compare this distribution with those found in other climatological and case studies.

2. Location of Tornadoes Relative to Beryl

Two methods of portraying tornado location relative to the center of tropical cyclones have been used in previous studies. For example, Pearson and Sadowski (1965) and McCaul (1991) used a reference frame relative to the storm motion, whereas Novlan and Gray (1974) and Weiss (1987) referenced tornado location relative to true north. Orton (1970) and Gentry (1983) used both methods and found that a tighter spatial distribution was obtained when using the true north frame of reference, with a strong preference for tornadoes to occur in the northeast quadrant of the tropical circulation. Ostby and Weiss (1993) found similar results for tornadoes accompanying Hurricane Andrew. Thus, for this study we have chosen to depict tornado location relative to true north, and results for Beryl are displayed in Fig. 3. Nearly all of the tornadoes (35 of 37) occurred in the northeast quadrant relative to the center of Beryl, primarily within the azimuthal range of 020 and 060 degrees. The tornadoes tended to develop 220–445 km (120–240 nm) from the

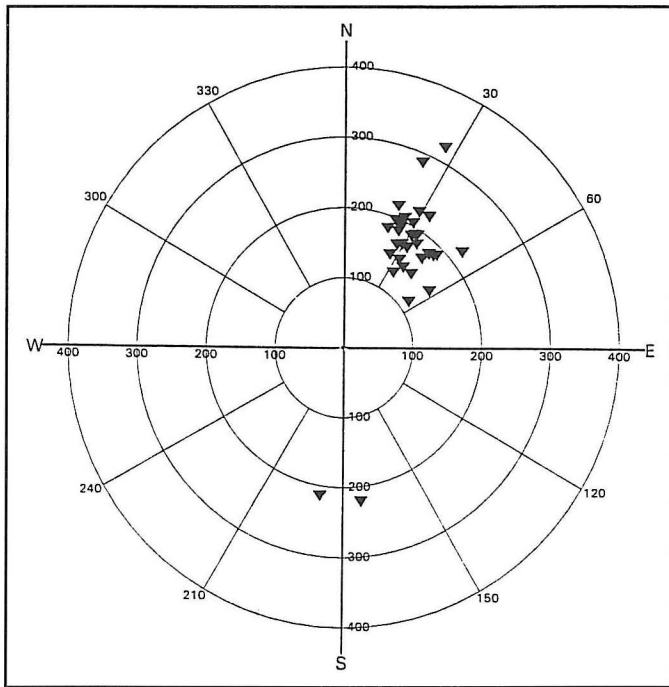


Fig. 3. Distribution of tornadoes relative to the center of Beryl using a reference frame of true north. Concentric range circles are shown at 100 nm intervals.

circulation center, consistent with the findings of McCaul (1991).

3. Environmental Buoyancy and Shear for the Period 15–17 August 1994

As mentioned previously, no tornadoes occurred around the time of Beryl's landfall, defined here as the period from 2100 UTC 15 August to 1200 UTC 16 August (3 hours prior to through 12 hours after landfall, following the procedure used by Weiss 1987). Weiss (1985) determined, from a climatological perspective, that multiple tornadoes are not likely near the time of landfall with tropical cyclones below hurricane intensity, except for those reaching land along the Texas and Louisiana coast. Figure 4 is the 0000 UTC 16 August sounding and hodograph from Tallahassee, Florida (TLH). At this time, TLH was in the northeast quadrant of the circulation, a climatologically favorable region for tornadoes. The observed lapse rate was nearly moist adiabatic throughout the depth of the troposphere. As a result, only 38 J kg^{-1} of Convective Available Potential Energy (CAPE) was obtainable by lifting a surface parcel. McCaul (1991) found that tornado proximity soundings in tropical cyclone environments are usually characterized by deep moisture and limited instability, qualitatively similar to the TLH sounding. However, the mean CAPE for the tornado proximity soundings in McCaul's data set was 768 J kg^{-1} , much higher than that at TLH. Figure 5 displays the objectively analyzed, surface-based Lifted Index (LI)³ field at 0000 UTC 16 August.

³The Lifted Index is the difference between the ambient 500 mb temperature and the temperature an air parcel would have if lifted from a layer near the surface. Negative values indicate air mass instability. Values less than -6 are considered very unstable.

LI values were around 0 across north Florida and south Georgia, reaffirming that instability was minimal around the time of Beryl's landfall.

The vertical wind profile at TLH exhibited very strong low-level speed shear with slight veering of the winds with height below 850 mb (Fig. 4). It is interesting to note that despite the strong low-level shear, the 0–3 km storm relative (SR) helicity was only $71 \text{ m}^2 \text{ s}^{-2}$ (assuming a storm motion of 30 degrees to the right of and 75% of the 0–6 km density-weighted mean wind, hereafter referred to as 30R75)⁴. Numerical simulations by Droegemeier et al. (1993) show that SR helicity predicts storm rotation potential better than mean low-level shear. Davies-Jones et al. (1990) suggested that the minimal threshold of SR helicity for mesocyclone formation is around $150 \text{ m}^2 \text{ s}^{-2}$, more than twice the value observed at TLH. A closer inspection of the wind profile shows that the strongest shear was actually in the 0–1 km layer, which is consistent with previous studies of wind profiles in tropical cyclone environments (e.g., Novlan and Gray 1974, and McCaul 1991). The 0–1 km SR helicity at TLH was $125 \text{ m}^2 \text{ s}^{-2}$, much higher than the 0–3 km integration, but still less than the suggested minimal threshold for rotating storms. Thus, it appears that during the time of landfall, very marginal instability and limited SR helicity inhibited the development of supercell storms.

The character of the air mass changed considerably on the 16th as Beryl began to entrain dry air from off the Atlantic into the northeast quadrant of the circulation. Figure 6 is the 1200 UTC 16 August sounding and hodograph at Charleston, South Carolina (CHS). A significant amount of dry air is evident throughout much of the troposphere with maximum dew point depressions in a layer from about 650 to 550 mb. The unsaturated air mass was associated with steeper lapse rates above 900 mb resulting in a significant increase in surface-based CAPE (1096 J kg^{-1}) compared to the value at TLH the previous evening.

Limited cloudiness also allowed for enhanced surface heating during the day. Visible satellite imagery at 1500 UTC 16 August (not shown), about 30 minutes prior to the onset of the tornado outbreak in South Carolina, clearly showed thin spots in the high overcast across the eastern portion of the Carolinas extending westward into a region of developing tornadic convection over central South Carolina. Surface-based CAPE values reached $2000\text{--}3000 \text{ J kg}^{-1}$ over much of eastern South Carolina by early afternoon, with LI values of -4 to -8 over the eastern two-thirds of the state (Fig. 7), representing a substantial increase in instability compared to the previous day when the system made landfall.

In addition to destabilizing the air mass, the availability of dry air in the storm environment may have increased the potential for tornadoes. Recent modeling studies conducted by Davies-Jones and Brooks (1993) indicate that baroclinic generation of vorticity through evaporative cooling in the rear flank downdraft (RFD) is important for the development of low-level mesocyclones (and subsequent tornadoes). Thus, in this case, the dry intrusion allowed for steeper lapse rates, promoted boundary layer destabilization through surface heating, and may have enhanced baroclinically generated vorticity in the RFD. Vescio et al. (1993) documented another case where a dry

⁴Forecasters must assume a storm motion before thunderstorms develop. A 30R75 storm motion represents a "worst case" scenario for convection that is deviating significantly to the right of the mean wind.

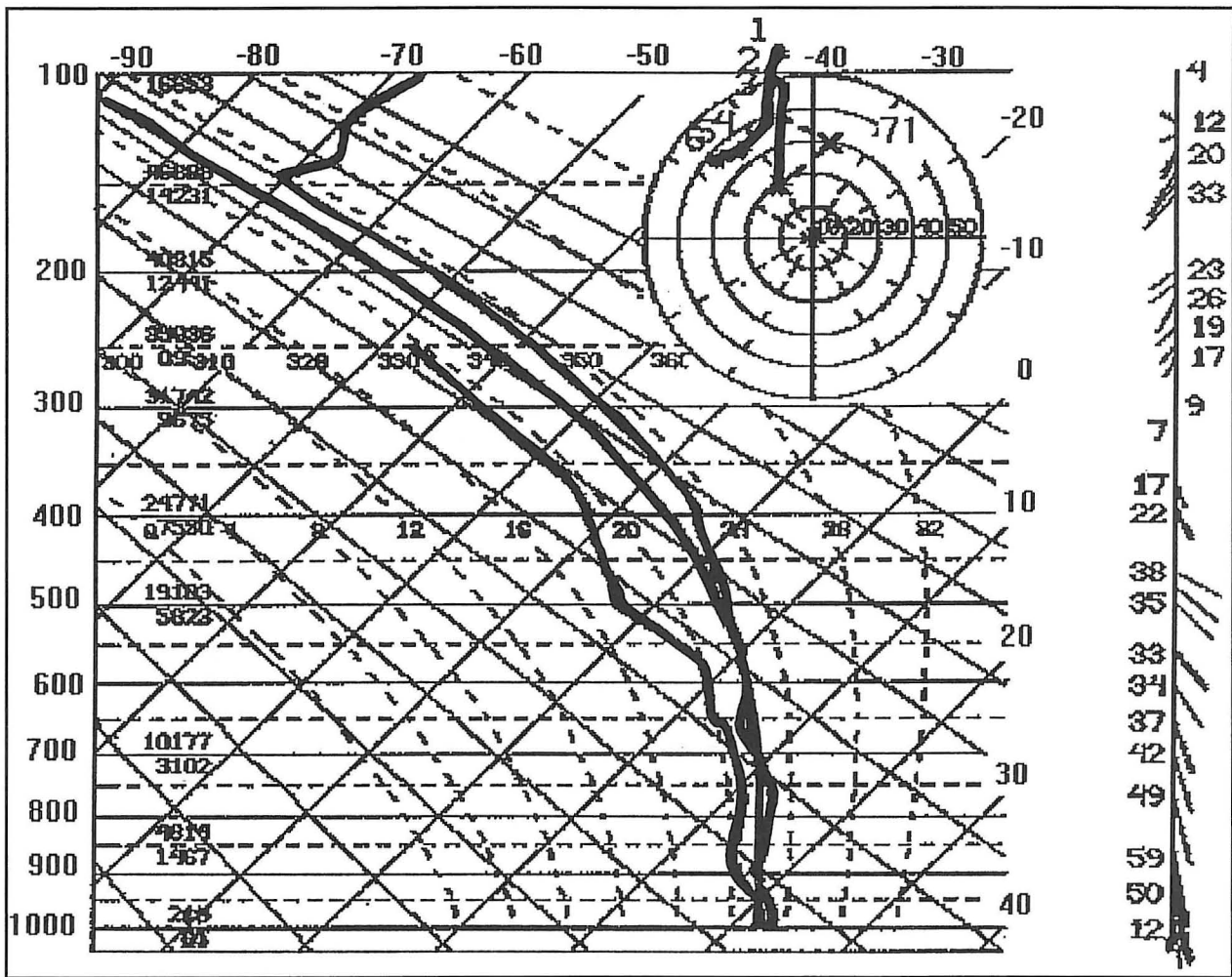


Fig. 4. 0000 UTC 16 August Skew-T (including lifted parcel) and hodograph at Tallahassee, Florida (TLH).

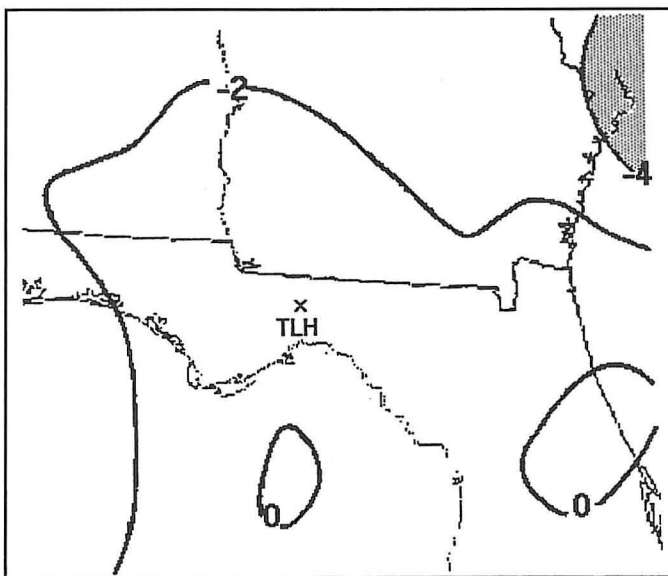


Fig. 5. Objectively analyzed, surface-based LI field for 0000 UTC 16 August for portions of Florida, southeast Alabama, and southern Georgia. Values < -4 are shaded. Tallahassee, FL is located at the "x".

intrusion from the Atlantic played a significant role in a severe weather outbreak in eastern North Carolina.

It is interesting to note that the drying was predicted well by the Eta model. Figure 8 shows the 0 h Eta model forecast of mean relative humidity in the 850-400 mb layer valid at 0000 UTC 16 August. Dry air, with mean relative humidities of less than 40%, is evident off the southeast U.S. coast. The drying was in association with an upper-level anticyclone. The Eta model forecasts maintained the dry pocket despite trajectories over water, and by 1200 UTC 16 August (Fig. 9) dry air was forecast to begin impinging on the South Carolina coast, which is consistent with the observed 1200 UTC sounding at CHS.

In addition to increased instability, the low-level helicity at CHS was noticeably stronger than that observed at TLH the previous evening, with 0-3 km SR values of $207 \text{ m}^2 \text{ s}^{-2}$ for a 30R75 storm motion (refer to Fig. 6). Moderate to high instability, adequate SR helicity, and the availability of dry air created an environment much more favorable for tornadic supercells on the 16th.

Figure 10 is a velocity azimuth display (VAD) wind profile (VWP) from the Columbia, South Carolina (CAE) WSR-88D radar near the time that an F3 tornado passed just west of the radar site. The vertical wind profile is characterized by low-level speed shear and some veering with height. Figure 11 is a hodograph using the CAE VWP at 1739 UTC using the

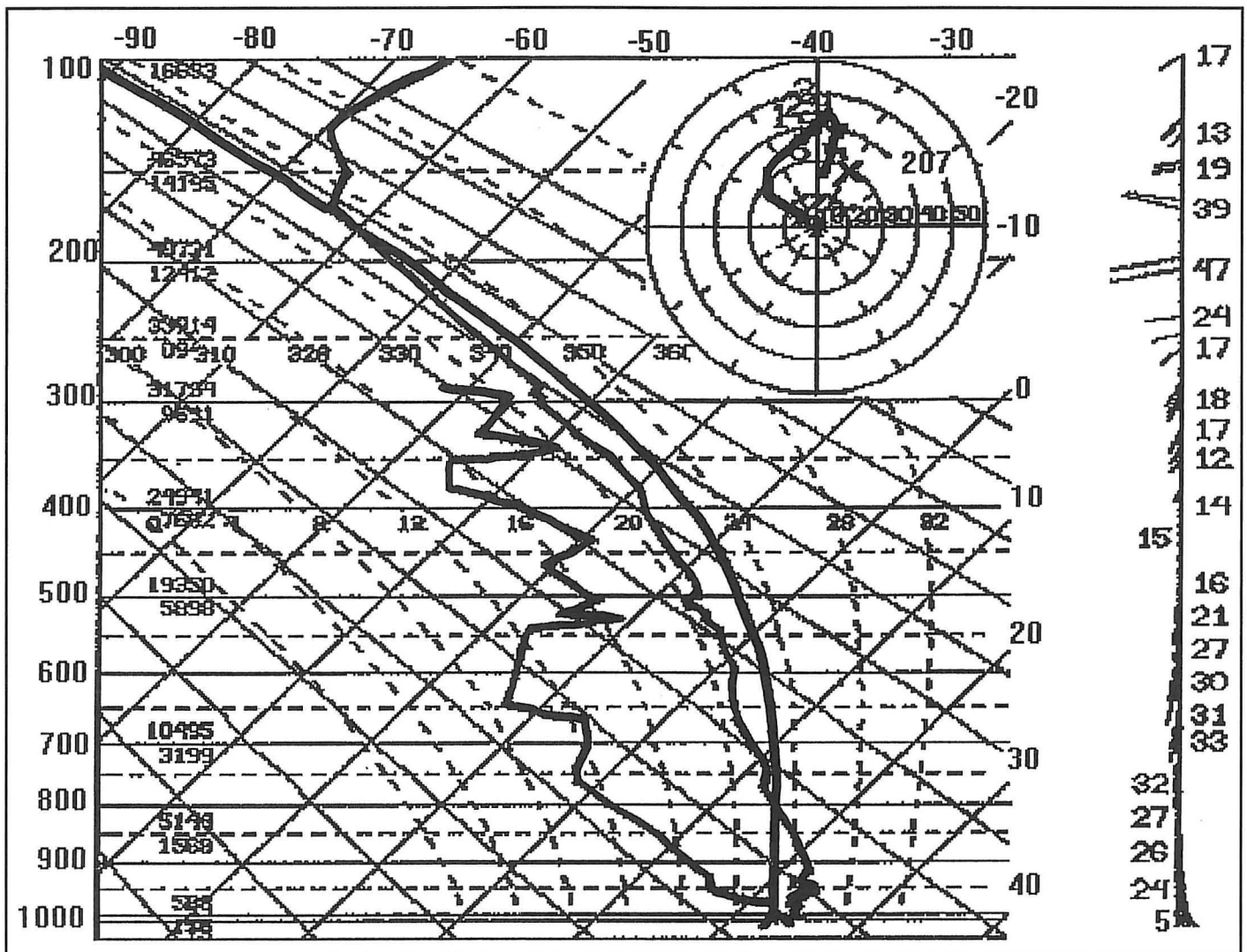


Fig. 6. 1200 UTC 16 August Skew-T (including lifted parcel) and hodograph at Charleston, South Carolina (CHS).

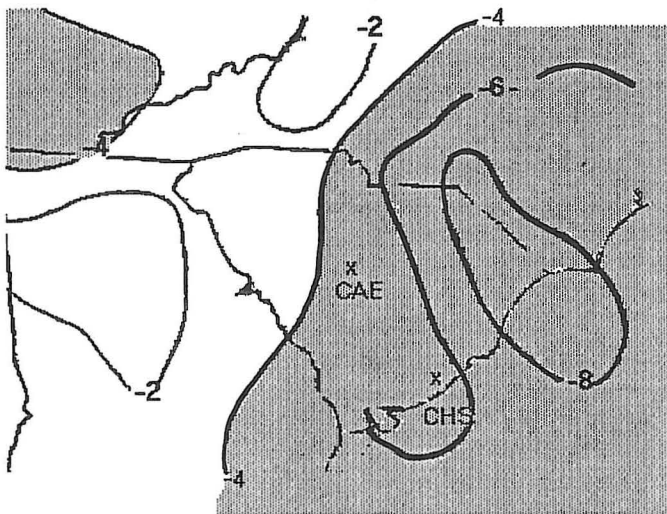


Fig. 7. Objectively analyzed, surface-based LI field for 1800 UTC 16 August. Values < -4 are shaded. The 500 mb temperature field used is the 6 h forecast from the 1200 UTC Eta model. Locations of Charleston, SC (CHS) and Columbia, SC (CAE) are labeled "x"s.

observed motion of the tornadic supercell. Notice that the 0–3 km helicity was only $128 \text{ m}^2 \text{ s}^{-2}$, considerably less than the 30R75 value at CHS. In this case, the supercell (and others during the event) deviated little from the mean wind. Thus, it is possible that meso- β and storm-scale interactions played a role in strengthening the available SR helicity. This example also provides clear evidence of the sensitivity of SR helicity to the storm motion vector. If a 30R75 storm motion was used for the KCAE hodograph, the helicity would have been $216 \text{ m}^2 \text{ s}^{-2}$. Once thunderstorms develop, forecasters must consider the true storm motion when assessing the environmental helicity rather than relying on default values of storm motion.

By early afternoon on 17 August, the region of dry air had moved offshore as the remnants of Beryl reached the central Appalachians. Tornado production diminished considerably with only five weak tornadoes reported in the mid-Atlantic States region. Figure 12 is the 1200 UTC 17 August sounding and hodograph at Washington-Dulles (IAD). The 0–3 km SR helicity was $221 \text{ m}^2 \text{ s}^{-2}$, comparable to that observed at CHS the previous day. However, the thermal and moisture structure was significantly different. The sounding was nearly saturated in the 900–700 mb layer. The moist adiabatic lapse rate allowed for only 258 J kg^{-1} of CAPE, about one-third the mean value

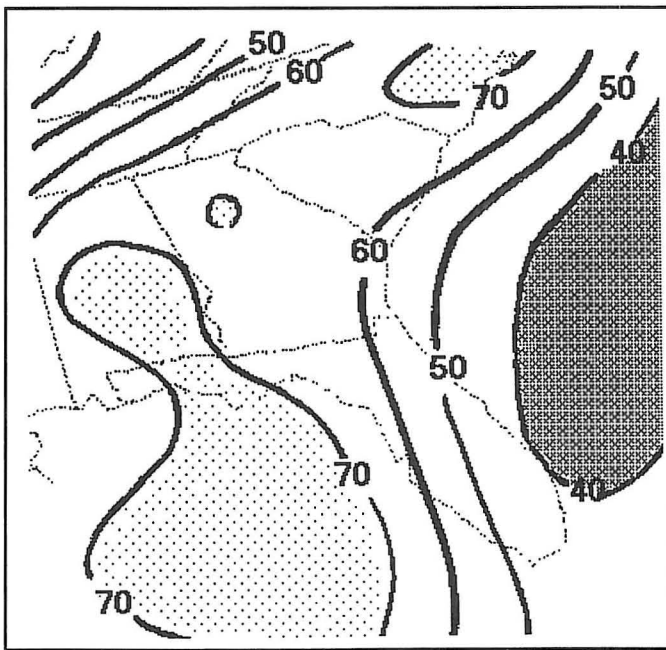


Fig. 8. The 0 h Eta model forecast of mean relative humidity (%) in the 850-400 mb layer across the southeast United States. Valid time is 0000 UTC 16 August. Values $> 70\%$ stippled; values $< 40\%$ shaded.

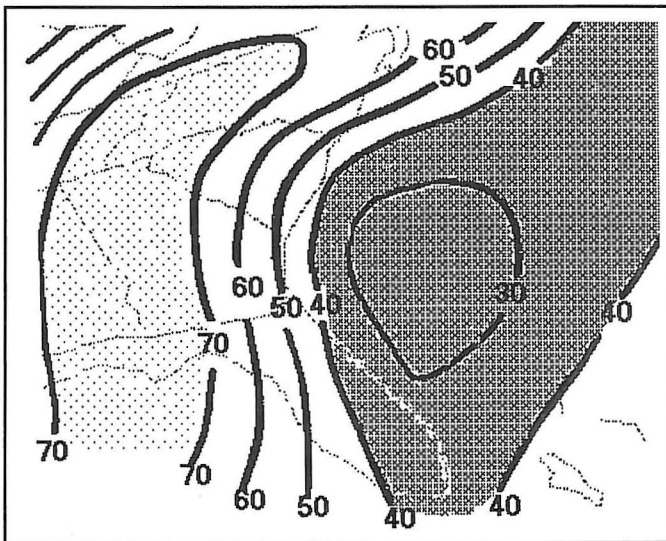


Fig. 9. Same as Fig. 8 except for the 12 h Eta model forecast valid at 1200 UTC 16 August.

of tornado proximity soundings in McCaul's (1991) data set.⁵ In addition, cloud cover throughout the day diminished surface heating, reducing boundary layer destabilization. Afternoon LI values were generally in the -2 to -4 range (Fig. 13). Thus it appears that the movement of the dry air offshore contributed

⁵The IAD sounding exhibits a superadiabatic lapse rate just above 700 mb that appears erroneous. Therefore, the actual CAPE was probably less than the calculated value.

to the significant decrease in the number of tornadoes on the 17th by: 1) reducing convective instability, and 2) diminishing the potential for baroclinic generation of low-level vorticity.

The Eta model correctly forecast the offshore movement of the dry air. Figure 14 is the 18 h forecast of the 850-400 mb mean relative humidity from the 0000 UTC 17 August model run. Notice that minimum humidity values are over the western Atlantic Ocean.

4. Summary and Conclusions

Tropical Storm Beryl produced a total of 37 tornadoes as it moved up the east slopes of the Appalachians from 15 to 17 August 1994. The temporal distribution of tornadoes included 0 on the 15th, 32 on the 16th into the early morning hours on the 17th (specifically 1500–0700 UTC), and 5 during the 17th. Nearly all of the tornadoes occurred in the climatologically preferred northeast quadrant of the storm. Soundings within the northeast quadrant of the tropical cyclone were examined to help define the thermodynamic and kinematic properties of the air mass on each of the three days. It appears that supercell development around the time of landfall on the 15th was inhibited by minimal instability due to a nearly saturated air mass and weak SR helicity.

By the 16th, however, low-level helicity had strengthened with 0–3 km SR values exceeding $200 \text{ m}^2 \text{ s}^{-2}$ (for 30R75 storm motion). In addition, dry air in a deep layer above the surface was entrained into the northeast quadrant of the tropical system over portions of the Carolinas. Steeper lapse rates were associated with the dry air resulting in greater instability compared to the previous day. The lack of extensive cloudiness contributed to destabilization of the boundary layer as well. By early afternoon LI values of -4 to -8 extended across much of South Carolina, the focal point for an outbreak of 31 tornadoes extending across northeast Georgia, the Carolinas, and southern Virginia. Clearly the very unstable, moderately sheared air mass provided a favorable environment for supercells and tornadoes. In addition to increasing convective instability on the meso-scale, the availability of dry air may have been important for storm-scale dynamics as well. Dry air in the storm environment likely enhanced evaporative cooling in the RFD. Recent modeling studies conducted by Davies-Jones and Brooks (1993) indicate that baroclinic generation of vorticity from evaporative cooling within the RFD is important for the development of low-level mesocyclones. Thus, it is apparent that the dry intrusion was a critical element for the tornado outbreak associated with Beryl. This hypothesis agrees with Hill et al. (1966), who first suggested that hurricane-tornado outbreaks are more likely to occur when dry air is entrained into the tropical circulation. This conclusion was also reached by McCaul (1987).

Although the low-level helicity remained moderately strong on the 17th (similar to values on the 16th), the dry air intrusion had moved offshore. This resulted in decreased mid-level instability. Cloudiness was more extensive on the 17th as well, and this limited boundary layer destabilization. With weaker instability and the absence of dry air, the environment became less favorable for the development of tornadic supercells, and this probably accounts for the marked decrease in the number of tornadoes on the 17th.

It is encouraging to note that the operational early Eta model forecast the position and evolution of the dry intrusion quite well. The Eta model also accurately simulated the helicity field for the three-day period studied here. Consecutive model runs showed only weak SR helicity in the 0–3 km layer for a 30R75 motion over the eastern semi-circle of the circulation near the

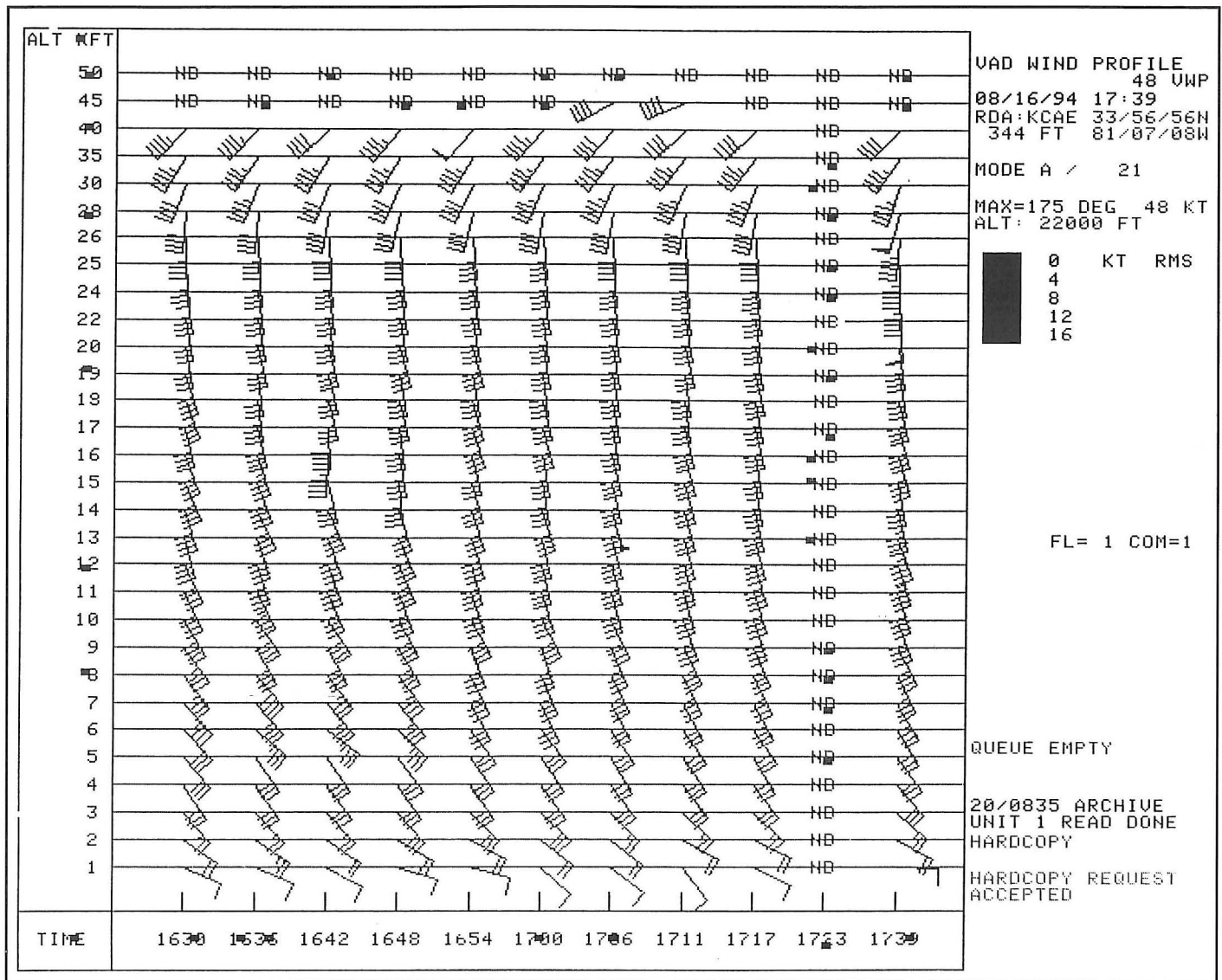


Fig. 10. Vertical time-section of VAD Wind Profile (VWP) from the Columbia, South Carolina WSR-88D from 1630 to 1739 UTC 16 August.

time of landfall on the 15th. Helicity values increased significantly 12 hours after the model low center made landfall, then remained nearly steady in a corridor from the southeast U.S. through the mid-Atlantic States region. Forecast helicity values were comparable to those actually observed at upper-air sites along and to the east of Beryl's track. Other information regarding the Eta model performance for this event can be found in Vescio and Weiss (1996).

Previous studies (e.g., Weiss 1987) indicate a positive correlation between the strength of tropical cyclones and tornado production near the time of landfall. However, this study illustrates that even weak systems of tropical origin can produce tornadoes after making landfall. Forecasters must focus on the air mass structure and wind fields associated with the system. If the environment is favorable for supercell storms, then the possibility of tornadoes must be considered. It would be beneficial to document future tornado outbreaks with tropical cyclones to further understand the importance of dry intrusions with these systems.

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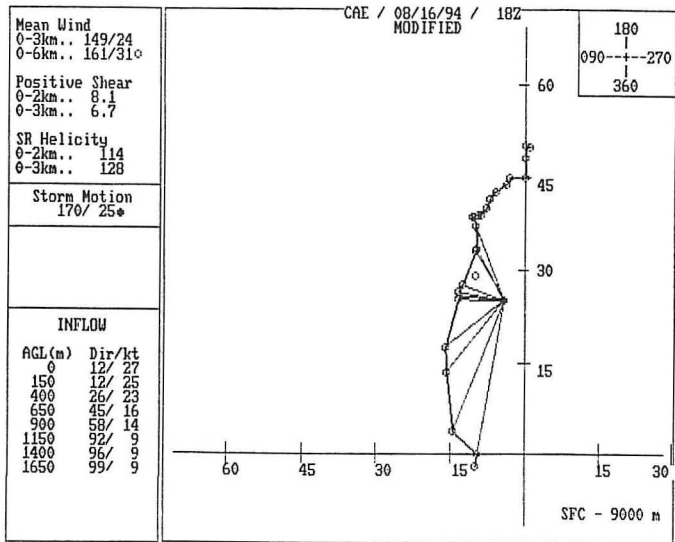


Fig. 11. The 1739 UTC 16 August hodograph constructed from Columbia, South Carolina WSR-88D VWP.

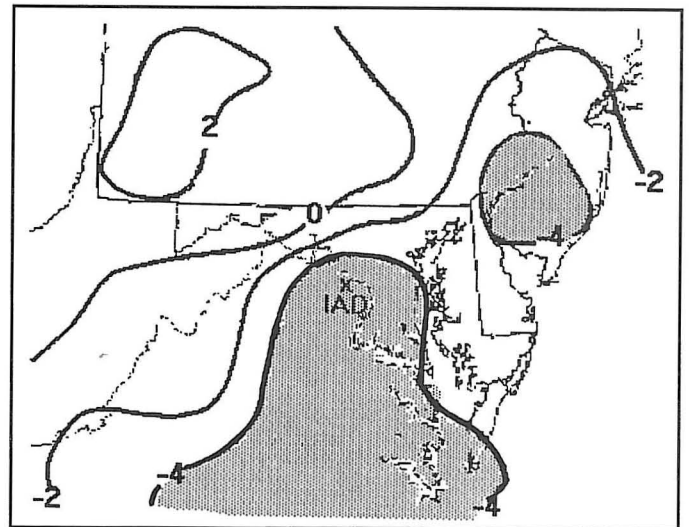


Fig. 13. Objectively analyzed, surface-based LI for 1800 UTC 17 August across the mid-Atlantic States region. The 500 mb temperature field used is the 6 h forecast from the 1200 UTC Eta model. LIAD is located at the "x".

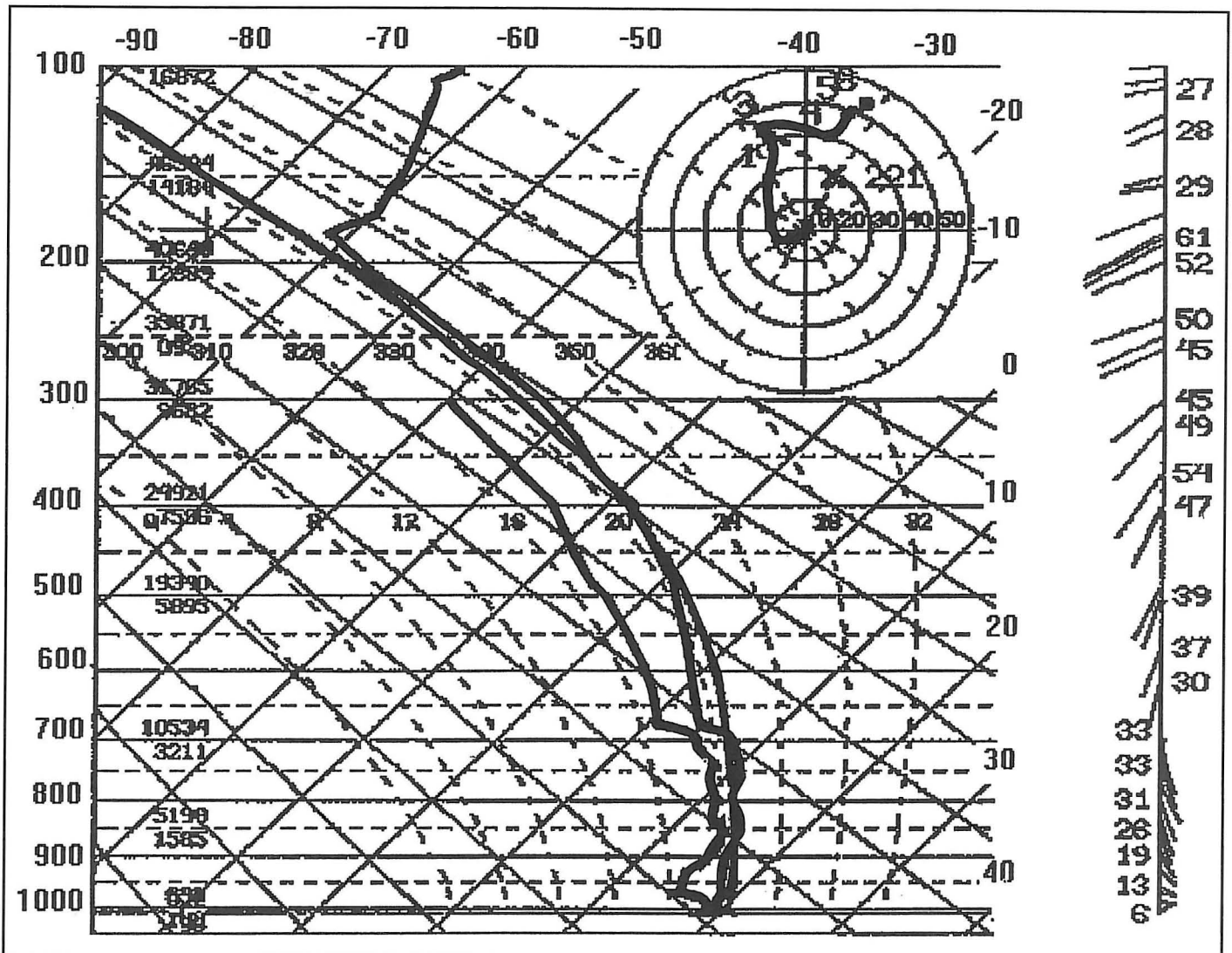


Fig. 12. The 1200 UTC 17 August Skew-T (including lifted parcel) and hodograph at Washington-Dulles (IAD).

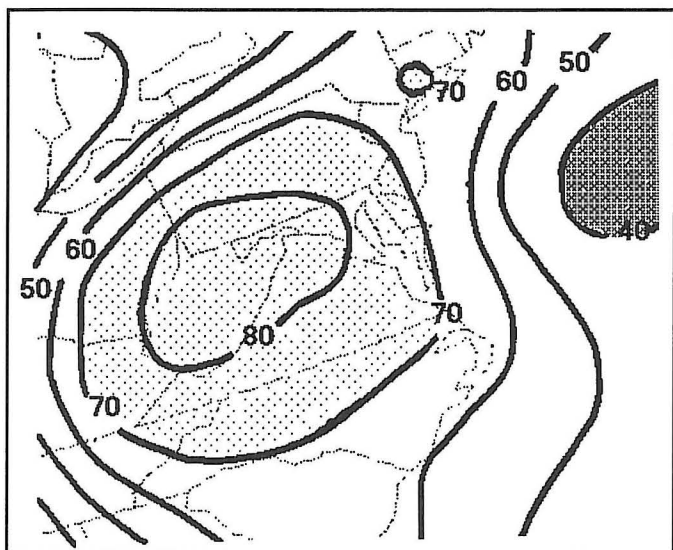


Fig. 14. Same as Fig. 8 except for the 18 h Eta model forecast valid at 1800 UTC 17 August.

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