‘‘Bookend Vortex’’ Induced Tornadoes along the Natchez Trace

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ABSTRACT

This study focuses on the evolution of the northern end of a bow echo that moved across parts of southwest Mississippi on 8 May 1995. A well-defined, cyclonically rotating ‘‘comma head echo’’ developed north of Natchez, Mississippi, and moved northeast for about 120 km (75 mi) before dissipating. The circulation associated with this comma head echo passed through several diameter changes during which the diameter varied between that of a classic mesocyclone and that more typical of a ‘‘bookend vortex.’’ The circulation and a strong rear inflow jet helped spawn small tornadoes (F0–F2) in Claiborne County, Mississippi, and wind damage in western Hinds County, Mississippi. The observed damage path from the tornadoes was more than 8 km (5 mi) long. For much of the track, the tornadoes paralleled the Natchez Trace, a scenic federal highway that extends from Natchez to Nashville, Tennessee.

1. Introduction

For many years it has been known that bow echoes can produce a wide spectrum of severe weather including downbursts, large hail, and occasionally tornadoes. Fujita (1978) offered the first conceptual model of the bow echo with his well-known schematic (Fig. 1). Subsequent investigations of synoptic meteorological patterns (e.g., Johns and Hirt 1987; Johns et al. 1990; Johns 1993) and numerical simulations (e.g., Weisman et al. 1988; Smull and Weisman 1993) have strengthened the conceptual model. Observations of bow echoes using radar data by Smith (1990), Przybylinski and Schmocker (1993), and Przybylinski (1995) have refined and verified the conceptual model in the central United States.

The oppositely rotating vortices at either end of the bow echo, which act to focus the developing cold pool and rear inflow structure and give the system the characteristic bow shape, are called ‘‘bookend vortices.’’ This term originated from numerical studies by Weisman (1990). Severe weather warnings are readily issued by field meteorologists based on damaging straight-line winds that accompany the bow, but the possibility of tornadoes with the vortex can be overlooked. The environment associated with the northern, cyclonically rotating vortex is particularly favorable for tornadoes, and this fact should be used by field forecasters when issuing severe weather warnings.

This study will focus on the evolution of the northern cyclonically rotating ‘‘comma head echo’’ (hereafter CHE) that moved across parts of southwest Mississippi on 8 May 1995. The CHE developed north of Natchez, Mississippi, and moved northeast for about 120 km (75 mi) before dissipating. This CHE contained a persistent strong circulation that varied between smaller diameters (5–6 km) more typical of a mesocyclone and larger diameters (10–13 km) characteristic of a bookend vortex. These are not uncommon severe weather structures in the south, and

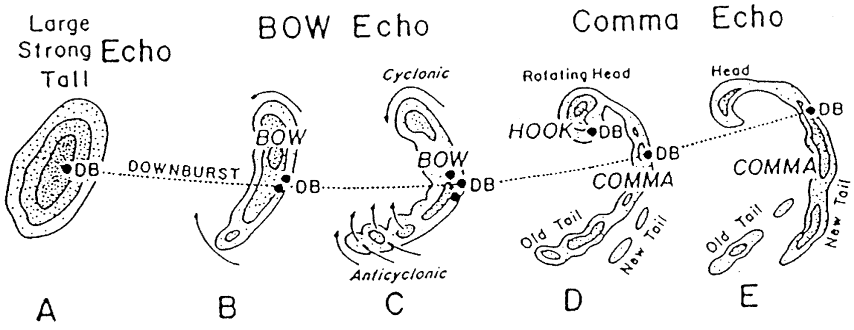

FIG. 1. Fujita’s (1978) conceptual model of a bow echo with a rotating comma head.

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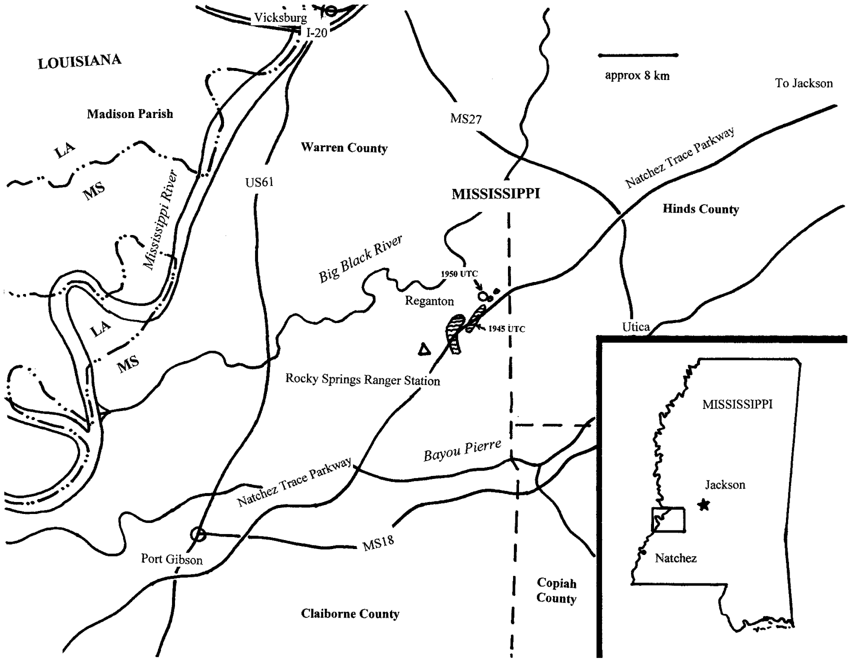


FIG. 2. Inset state map and area locator map showing track of tornadoes (hatched area) through rural Claiborne County, MS.

early pattern recognition and diagnosis can help speed accurate warnings. The circulation associated with the CHE and a strong rear inflow jet helped spawn small tornadoes in Claiborne County, Mississippi, and wind damage in western Hinds County, Mississippi. The observed damage path from the tornadoes was more than 8 km (5 mi) long but was fortunately through sparsely populated forested areas so that no one was hurt. For much of the track, the tornadoes paralleled the Natchez Trace, a scenic federal highway that extends from Natchez to Nashville, Tennessee.

2. Description of the event

The tornado track was photographed from aircraft and later mapped from the pictures. The damage track (Fig. 2) began about 2.4 km (1.5 mi) east-southeast of the Rocky Springs Ranger Station and Campground, extended about

FIG. 3. Aerial view of tree damage between the Natchez Trace and a county road.

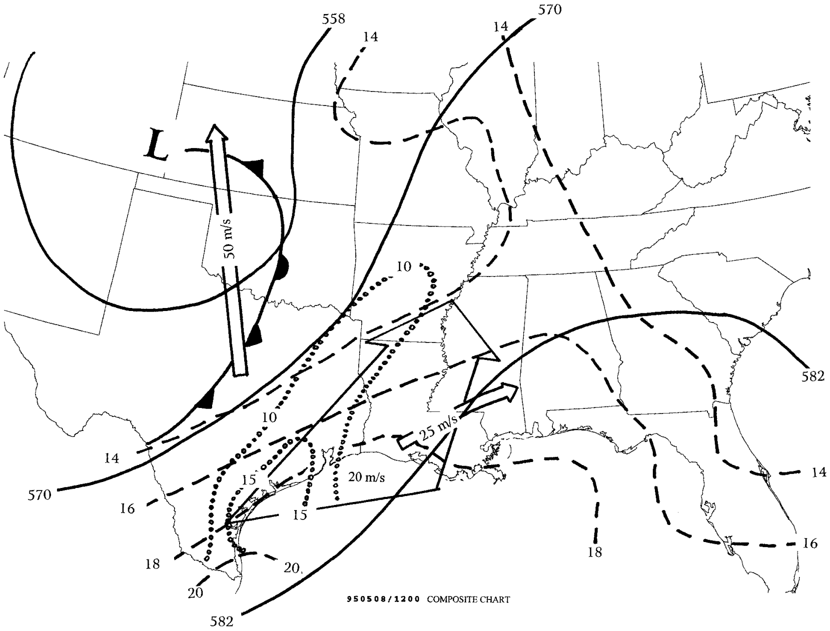
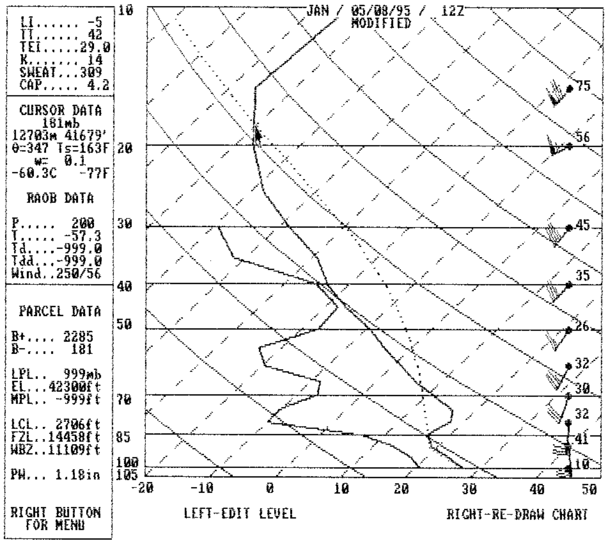


FIG. 4. Composite chart for 1200 UTC 8 May 1995. Identified are 500-mb heights in decameters (solid lines), surface front (conventional symbol), position of the 500-mb and surface lows (both in same location depicted by block L), 300-mb jets (narrow arrows labeled in m s^{-1}), 850-mb jet (wide arrow labeled in m s^{-1}), 850-mb temperature in degrees Celsius (dashed lines), and 850-mb dewpoint temperature in degrees Celsius (lines of small circles).

1.6 km (1 mi) northwest to the Natchez Trace highway, then deviated toward the north-northeast just north of the Trace, where the damage briefly became more widespread. The tornado then tracked north for about 0.8 km (0.5 mi) before dissipating. A second, more narrow damage path began just east of where the first track ended, on the opposite side of the Trace, and extended north for about 0.4 km (0.25 mi), crossing the Trace and Big Sand Creek before disappearing. This second damage path (Fig. 3) was not as wide or extensive as the first. The third segment of the damage path was not continuous but scattered, and extended from the end of the second path northeast toward the town of Reganton and beyond. In addition, wind damage from straight-line winds was reported in western Hinds County along Mississippi Highway 27 near Utica and near the Big Black River.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LI...... -5
TT...... 42
TEI.....29.0
K....... 14
SWEAT...309
CAP..... 4.2

CURSOR DATA
181mb
12703m 41679'
θ=347 Ts=163F
w= 0.1
-60.3C  -77F

RAOB DATA

P.....  200
T..... -57.3
Td....-999.0
Tdd...-999.0
Wind..250/56

PARCEL DATA

B+.... 2285
B-....  181

LPL..  999mb
EL...42300ft
MPL.. -999ft

LCL.. 2706ft
FZL..14458ft
WBZ..11109ft

PW... 1.18in

RIGHT BUTTON
FOR MENU
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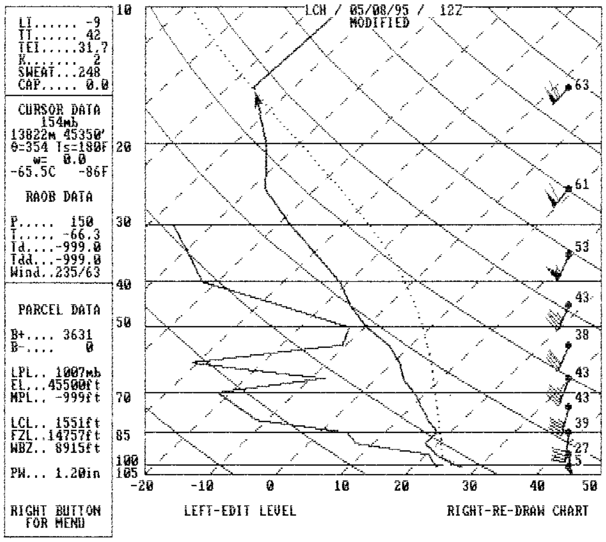
FIG. 5. Sounding for Jackson, MS, 1200 UTC 8 May 1995.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LI...... -9
TT...... 42
TEI.....31.7
K.......  2
SWEAT...248
CAP..... 0.0

CURSOR DATA
154mb
13822m 45350'
θ=354 Ts=180F
w= 0.0
-65.5C  -86F

RAOB DATA

P.....  150
T..... -66.3
Td....-999.0
Tdd...-999.0
Wind..235/63

PARCEL DATA

B+.... 3631
B-....    0

LPL.. 1007mb
EL...45500ft
MPL.. -999ft

LCL.. 1551ft
FZL..14757ft
WBZ.. 8915ft

PW... 1.20in

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FIG. 6. Sounding for Lake Charles, LA, 1200 UTC 8 May 1995.

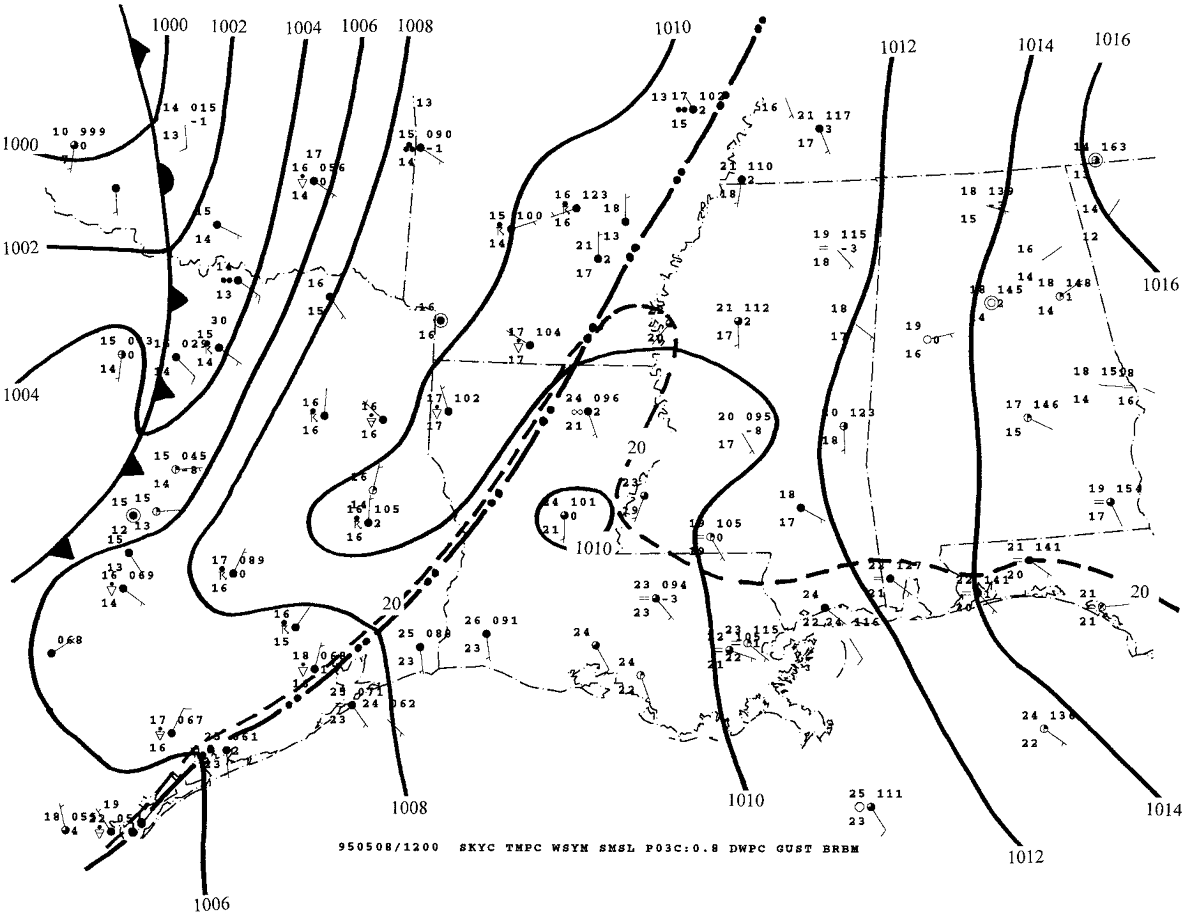


FIG. 7. Surface analysis for 1200 UTC 8 May 1995. Pressure analysis is in millibars, and winds are in m s^{-1} with the 20°C dewpoint isodrosotherm dashed. Surface front and squall line positions designated by conventional symbols from the 1200 UTC NCEP analysis in *Daily Weather Maps.*

3. Synoptic environment

The synoptic-scale environment for this event is summarized by the composite chart valid for 1200 UTC 8 May 1995 (Fig. 4). A strong, southerly, low-level jet of 20 m s^{-1} at 850 kPa was located over the lower Mississippi valley. This low-level jet was advecting 850 kPa dewpoints of 10°–15°C north into the region well ahead of a surface cold front over the southern plains. At upper levels, a wind maximum of 25 m s^{-1} at 300 kPa was located near the gulf coast. However, the main upper-level jet of 50 m s^{-1} at 300 kPa was located over the southern plains. Upper-level difluence was occurring over much of the lower Mississippi valley between the main upper jet and the weaker upper wind maximum noted along the gulf coast. The winds in the main upper-level jet were southerly and nearly parallel in orientation to the low-level jet. The nearly parallel orientation of the main upper- and low-level jets, combined with a strong surface low pressure system passing northwest of the area and the approach of a strong upper-level shortwave trough, reveals a synoptic pattern similar to the dynamic bow echo pattern discussed by Johns (1993).

The 1200 UTC 8 May 1995 upper-air sounding from Jackson, Mississippi (JAN), even when modified using the 1800 UTC surface temperature (Fig. 5), revealed a very capped environment, with a cap strength of nearly 5°C. However, the Lake Charles, Louisiana (LCH), sounding (Fig. 6) revealed significant instability with a surface-based lifted index of -9°C, convective available potential energy (CAPE) of approximately 3500 J kg^{-1}, and no cap. The surface chart valid for 1200 UTC 8 May 1995 (Fig. 7) showed that more unstable air as shown by the LCH sounding would be advected northward by southerly winds ahead of a prefrontal surface boundary extending from eastern Arkansas to southeast Texas [shown in the National Centers for Environmental Prediction (NCEP) surface analysis as a squall line]. This surface boundary provided low-level convergence to help focus and organize the convection as it moved across the region. The boundary reached central Louisiana and western Mississippi by 1800 UTC (Fig. 8), with the organized convection maintaining itself in spite of the cap shown on the JAN sounding.

In addition to the instability, the 1200 UTC LCH sounding indicated strong drying above 850 kPa. This feature,

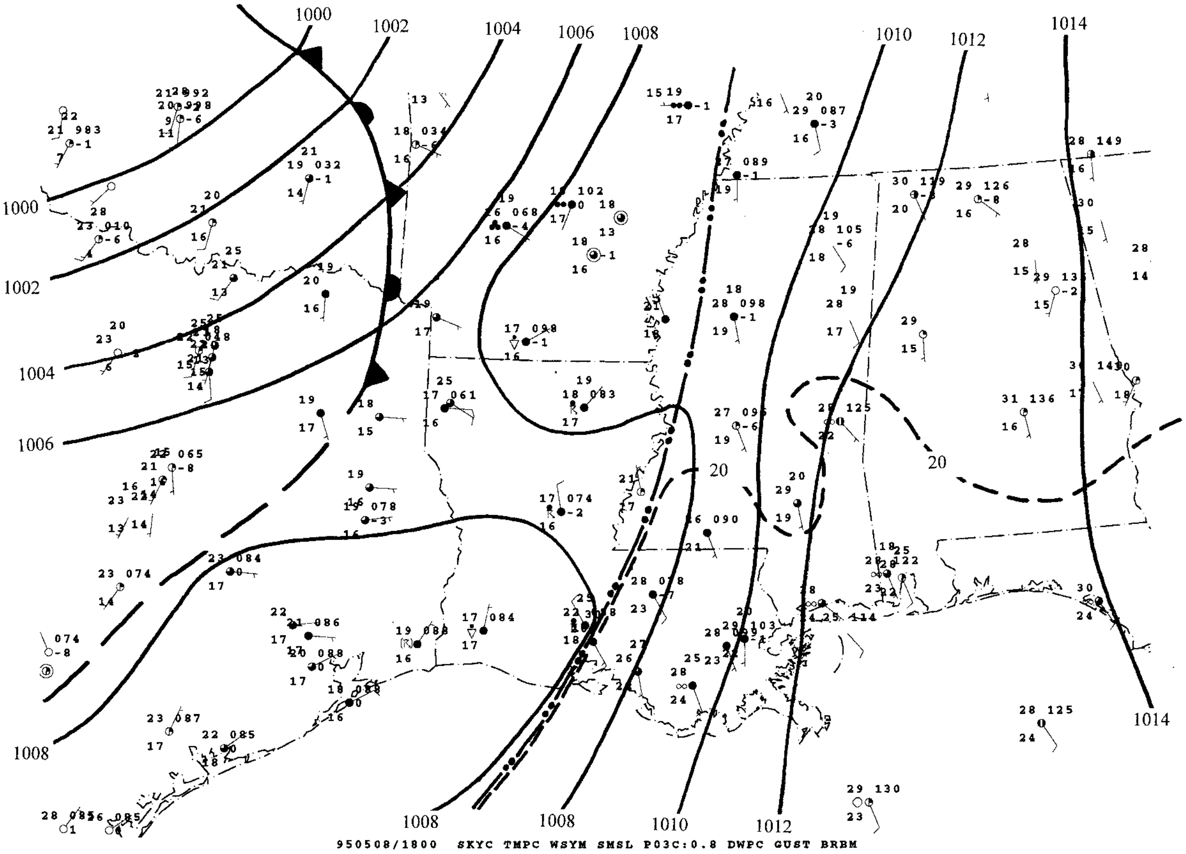
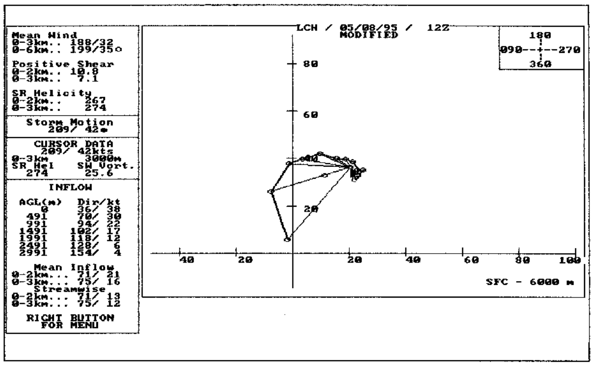


FIG. 8. Same as Fig. 7 except for 1800 UTC.

which is common in the dynamic bow echo pattern (Johns 1993), means that dry air would be available in the midlevels for downdraft entrainment, evaporative cooling, and enhanced downdraft speeds.

The hodograph analysis from LCH at 1200 UTC 8 May (Fig. 9) using the storm motion of the CHE (209° at 21 m s^{-1}) showed strong shear with a 0–3-km storm-relative helicity near 277 (m s^{-1})^2 and 0–3-km shear of 21.6 m s^{-1}. This is in the low to middle range of the Johns et al. (1993) scatter diagram for strong and violent tornadoes. These high helicity and shear values were mainly the result of strong speed shear, with winds veering from approximately 160° to 190° in the lowest 3 km, while wind speed increased from 2.4 to 21.1 m s^{-1} through the same layer. The CAPE and shear values for this case (3500 J kg^{-1} and 21.6 m s^{-1}, respectively) compare reasonably well with those (2500 J kg^{-1} and 25 m s^{-1}) used by Weisman (1990) in his idealized simulation of a long-lived bow echo.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Mean Wind
0-3km.. 188/32
0-6km.. 199/35o

Positive Shear
0-2km.. 10.8
0-3km..  7.1

SR Helicity
0-2km..    267
0-3km..    274

  Storm Motion
   209/ 42●

  CURSOR DATA
   209/ 42kts
0-3km      3000m
SR Hel    SW Vort.
 274       25.6

    INFLOW
 AGL(m)   Dir/kt
    0      36/ 38
  491      70/ 30
  991      94/ 22
 1491     102/ 17
 1991     118/ 12
 2491     128/  6
 2991     154/  4

   Mean Inflow
0-2km... 71/ 21
0-3km... 75/ 16
   Streamwise
0-2km... 71/ 13
0-3km... 75/ 12

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FIG. 9. Hodograph for Lake Charles, LA, 1200 UTC 8 May 1995. Actual storm motion used in analysis.

4. Doppler radar products

The convective system of which this CHE was a part began in southeast Texas before 1200 UTC 8 May 1995 (Fig. 10) and produced wind damage across much of Louisiana from 1400 to 1800 UTC (Fig. 11) before it began to affect Mississippi after 1800 UTC. The rotation associated with the CHE was evident at midlevels (2.8 km) more than 150 km from the Jackson Radar Data Acquisition (RDA) site even before the system moved into Mississippi. A small mesoscale circulation was evident on the southeast side of the highly reflective comma head itself. During the period from 1833 to 1909 UTC, this circulation varied in diameter (distance between velocity inbound and outbound maxima) from 9 to 13 km, varied in depth (within the limitations of the radar due to the earth's curvature)

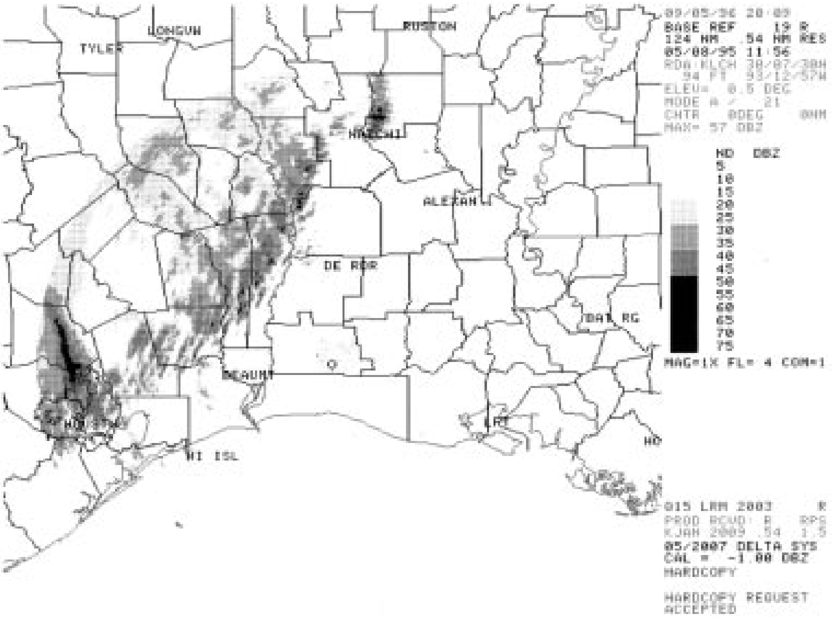

FIG. 10. Base reflectivity image from the Lake Charles WSR-88D 0.5° elevation at 1156 UTC 8 May 1995.

from 4 to 8 km, and displayed maximum rotational velocities of 13–22 m s^{-1} (Figs. 12a,b).

From 1909 to 1926 UTC, the magnitudes of maximum rotational velocities with the circulation slowly increased, but the core diameter maintained itself generally between 9 and 13 km. The base of the circulation throughout the event was at the lowest radar elevation angle. At 1921 UTC, the circulation showed a maximum rotational velocity of 21 m s^{-1} at a height of 3.1 km with a core diameter of about 12.9 km, which is larger than a traditional mesocyclone and better fits the concept of a bookend vortex. However, by 1941 UTC, the core diameter had shrunk to 6.4 km, which seemed to signal tornadogenesis (the exact time of the beginning of the first tornado is unknown, but

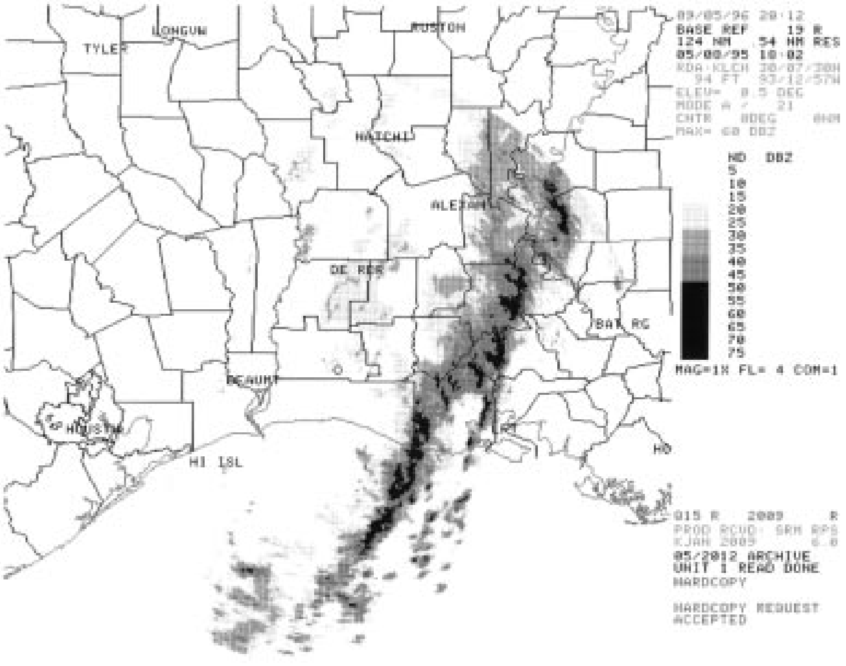

FIG. 11. Base reflectivity image from the Lake Charles WSR-88D 0.5° elevation at 1802 UTC 8 May 1995.

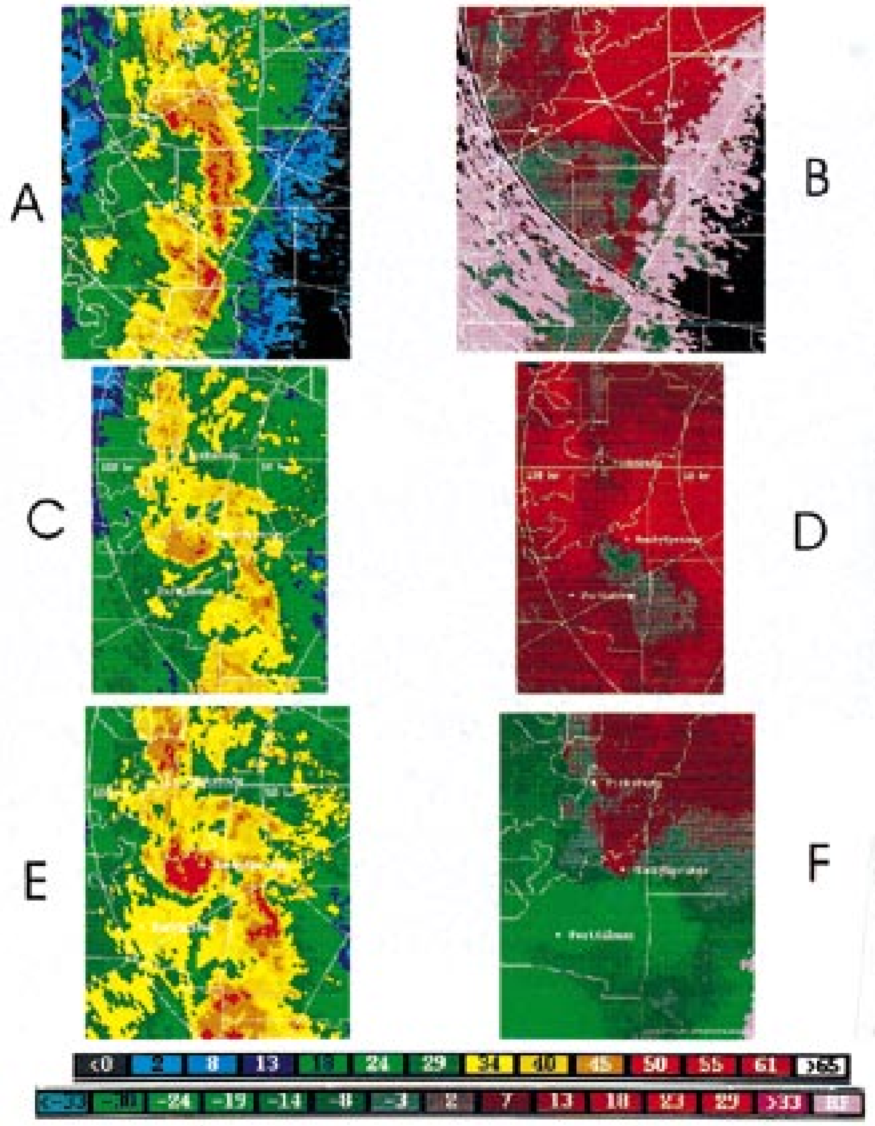

FIG. 12. WSR-88D data from the Jackson (KJAN) RDA. Reflectivity (dBZ, color scale at bottom of each page from <0 to >65 dBZ) and Doppler velocity (m s^{-1}, color scale at bottom of each page from -33 to $+33$ m s^{-1}). (a) base reflectivity (R) 0.5° elevation at 1904 UTC 8 May 1995, (b) storm relative velocity (SRM) 0.5° elevation at 1904 UTC 8 May 1995 (storm motion 209° at 21 m s^{-1}), (c) R 0.5° elevation at 1946 UTC 8 May 1995, (d) SRM 0.5° elevation at 1946 UTC 8 May 1995 (storm motion 209° at 21 m s^{-1}), (e) R 1.4° elevation at 1947 UTC 8 May 1995, (f) SRM 1.4° elevation at 1947 UTC 8 May 1995 (storm motion 209° at 21 m s^{-1}), (g) R 0.5° elevation at 1952 UTC 8 May 1995, (h) SRM 0.5° elevation at 1952 UTC 8 May 1995 (storm motion 209° at 21 m s^{-1}) (probable tornado location is indicated by red triangle), (i) R 0.5° elevation at 2007 UTC 8 May 1995, (j) base Doppler velocity image (V) 0.5° elevation at 2007 UTC 8 May 1995, and (k) base Doppler velocity cross section roughly along azimuth of 247° from the KJAN RDA showing structure of RIJ (2002 UTC).

it was likely around 1941 UTC from radar and eyewitness accounts). From 1941 to 2002 UTC, the core diameter remained around 6 km, and the base of the circulation continued at the lowest detectable height (Figs. 12c–f). During this period (1941 to 2002 UTC), tornadoes were occurring on the southeast side of the comma head, *behind* the bowing line. This apparently occurred due to increased shear as the rear inflow jet (RIJ), which was strongest (maximum observed inbound velocity was 39.5 m s^{-1} at 3.1 km at 1952 UTC) around 3–4 km throughout the event, descended, and approached the surface (Figs. 12g,h). While the tornadoes were occurring, maximum rotational velocity continued to increase from 26 m s^{-1} at a height of 0.9 km at 1946 UTC to a maximum of 33 m s^{-1} at a

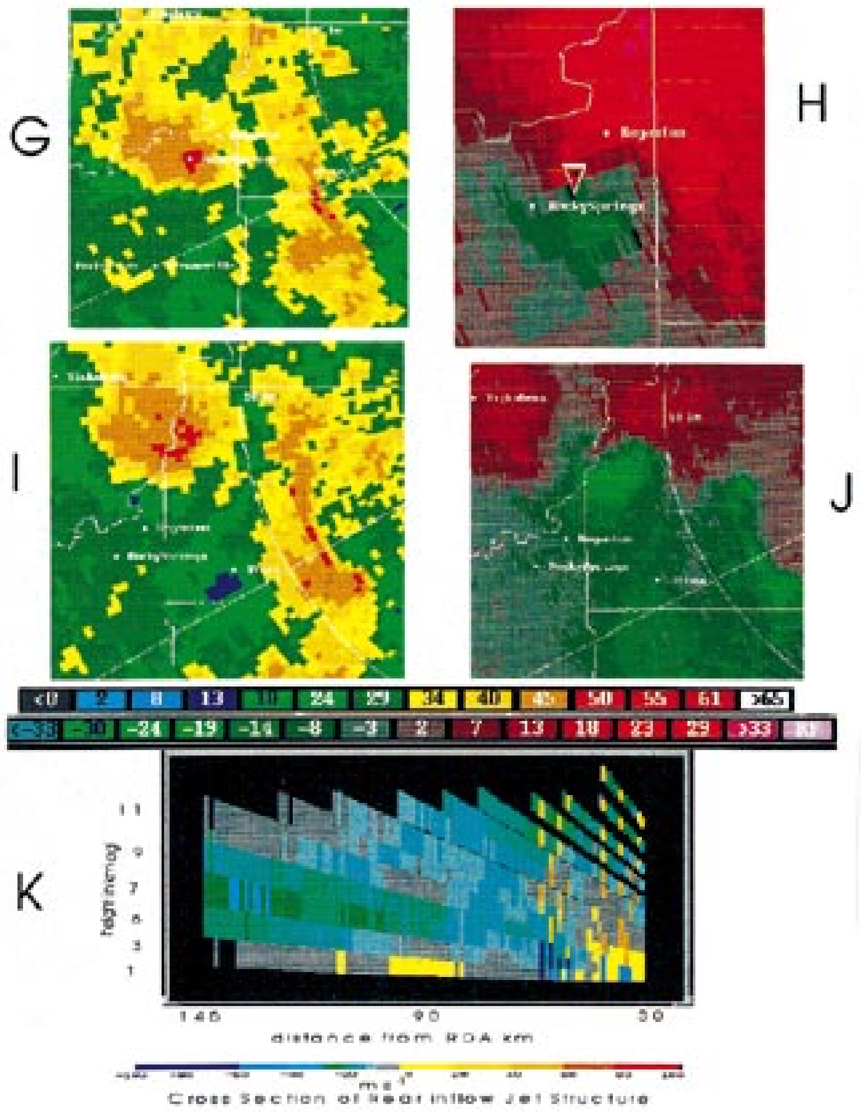

Fig. 12. (*Continued*)

height of 1.7 km at 2002 UTC. During this time, part of the RIJ appeared to move cyclonically around the highly reflective comma head, with a notch of lower reflectivity persisting on the southeast and east sides of the comma head from 1946 through 2013 UTC (Fig. 12e). Inbound velocities greater than 31 m s^{-1} were detected by radar on base velocity products less than 1000 m above ground level from 1957 through 2002 UTC.

The circulation associated with the comma head can be classified as very strong after 1859 UTC using mesocyclone depth and shear criteria. Prior to tornado touchdown (1921 to 1941 UTC), the core diameter decreased from 12.9 to 6.4 km, and rotational velocities increased from 21 to 27 m s^{-1}. During the tornadic event, the circulation was at least 4.5 km (15 000 ft) deep, and at 1941 UTC (around tornado touchdown time) the circulation was almost 7 km (22 900 ft) deep. The decrease in circulation core diameter, the increase in rotational velocity, and the fact that maximum circulation depth coincides with the approximate time of tornado touchdown followed by a decrease in circulation depth all correlate well with tornadic supercell findings (e.g., Burgess 1976).

Wind damage in western Hinds County near Utica between 2000 and 2015 UTC was due to the intensification of the RIJ 5–15 km south of the circulation. Potentially cold, dry air associated with the descending RIJ was evident in the reflectivity field as rear inflow notches (RIN) or areas of weaker reflectivity evolved along the trailing flank of the bowing line segment. A large area of inbound velocity with maxima around 26.5 m s^{-1} existed near the trailing flank of the bow echo itself (Figs. 12i,j). These RIN features have been identified by Przybylinski and Schmocker (1993) as equating to areas of stronger damaging downburst winds that reach the surface. A cross section of the RIJ is shown (Fig. 12k), with the cross section roughly along the azimuth of 247° and 30–145 km distance from the RDA.

The highest reflectivities observed during the storm's evolution occurred from 1833 to 1859 UTC, including 55 dBZ at a height of 8 km at 1844 UTC. The highest reflectivities were always located within the bowing segment of the line rather than in the comma head itself. Reflectivity values observed during the time of tornado occurrence were lower compared to earlier periods. The maximum reflectivity observed during the 1946 UTC radar volume scan was only 51 dBZ at a height of 2 km. Vertically integrated liquid values were also quite low during this time, generally ranging from 25 to 35 kg m^{-2} (no hail was reported during this event). Johns (1993) noted that reflectivity values associated with bow echoes are often relatively low in weak instability events. He also warned that methods of assessing severe weather based on reflectivity are not likely to be very effective in these situations. Even though the air mass in this case was already unstable, and higher instability air was moving north, the strong cap visible in the JAN 1200 UTC sounding may have inhibited convection somewhat as the system moved into Mississippi. Thus, velocity data combined with the overall reflectivity pattern from the WSR-88D was a more effective tool in the detection of severe weather.

5. Warning guidelines and conclusions

The recognition of an environment (as discussed by Weisman and Johns among others) favoring bow echoes is the first important step in a successful warning process. Given a favorable environment, the identification of bow echo patterns on the WSR-88D is immediate cause for severe weather warning based on the structure and movement of the phenomenon. The observation of a circulation (whether small enough to be called a mesocyclone, or large enough to be a bookend vortex) on either, but especially the northern, cyclonically rotating, end should result in immediate concern for a tornadic threat. Deepening and lowering of the circulation, tightening of the diameter, and increases in rotational velocities resulting in increasing shear often seem to signal the imminent development of a tornado. Using the WSR-88D to measure the trend of the overall depth and strength of the rotating circulation will help to finalize the tornado warning decision. Ground truth reports from spotters can help tremendously as well, but a tornado warning should generally not be delayed when radar analysis as described above indicates an increasing tornadic threat.

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