NOTES AND CORRESPONDENCE

WSR-88D Radar Depiction of Supercell–Bow Echo Interaction: Unexpected Evolution of a Large, Tornadic, ‘‘Comma-Shaped’’ Supercell over Eastern Oklahoma

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ABSTRACT

During a severe thunderstorm outbreak on 17 April 1995, a bowing line segment of severe thunderstorms intercepted an isolated supercell over eastern Oklahoma. The result of the supercell–bow echo interaction was unexpected. Instead of showing a weakening supercell, with diminished severe weather potential, as the bow echo's cold pool undercut, and spread in advance of, the supercell's updraft, WSR-88D imagery showed a different outcome. The bow echo rapidly weakened, while the supercell maintained its identity and severity for over an hour after the interaction took place. WSR-88D imagery showed the evolution of a large high-precipitation supercell with a ‘‘comma-shaped’’ echo appearance.

The archive II dataset from the WSR-88D radar at Inola, Oklahoma, was retrieved, and the reflectivity and velocity images for this event were reproduced and examined. The images showed the supercell–bow echo interaction and the changes to supercell structure and resultant weather that appeared to result from this interaction. This paper documents the remarkable evolution of a large, comma-shaped supercell, as shown by WSR-88D imagery, and illustrates an important scenario that can result from the interaction between a supercell and a bow echo.

1. Introduction

On 17 April 1995, an outbreak of severe thunderstorms occurred across Oklahoma. The outbreak featured both tornadic supercells (Doswell and Burgess 1993) and bowing convective line segments known as bow echoes (Fujita 1978). Late in the event, a bow echo intercepted a supercell thunderstorm over eastern Oklahoma. After the interaction between the two thunderstorm phenomena took place, the supercell apparently evolved into a large, low-topped ‘‘high-precipitation’’ (HP) supercell (Moller et al. 1990; Doswell et al. 1990) with a ‘‘comma-shaped’’ echo appearance. The structure of the supercell and the resultant severe weather changed substantially during this evolution.

The WSR-88D radar at Inola, Oklahoma, detected the supercell–bow echo interaction. Reflectivity and velocity images for this case were reproduced from archive II data and closely examined using the WSR-88D algorithm testing and display system (WATADS) program. Instead of showing the supercell as weakening and becoming absorbed by the approaching bow echo with the bow echo becoming the primary severe weather producer as its cold pool undercuts the supercell updraft, WSR-88D imagery showed a different outcome. The apparent result of the interaction was rapid weakening of the bow echo and the evolution of a large, low-topped, comma-shaped HP supercell that maintained its identity and severity for over an hour after the interaction took place. The radar images indicated a change in supercell structure, the formation of a large mesoscale circulation, and continued production of severe weather.

The atypical interaction between the two thunderstorm phenomena and the evolution of a large, comma-shaped HP supercell are presented here. The purpose of this paper is to present an important scenario of HP supercell evolution apparently associated with the passage of a bowing convective line segment around the southern periphery of a supercell, as shown by WSR-88D imagery. While similar studies (e.g., Sabones et al. 1996; Wolf et al. 1996) support the results of this case, further research is needed to determine if the HP supercell evolution presented here can be the expected result of bow–echo passage just to the south of a supercell.

2. Environment and storm-scale events prior to storm interaction

Atmospheric conditions supported severe thunderstorm development along and ahead of a cold front ad-

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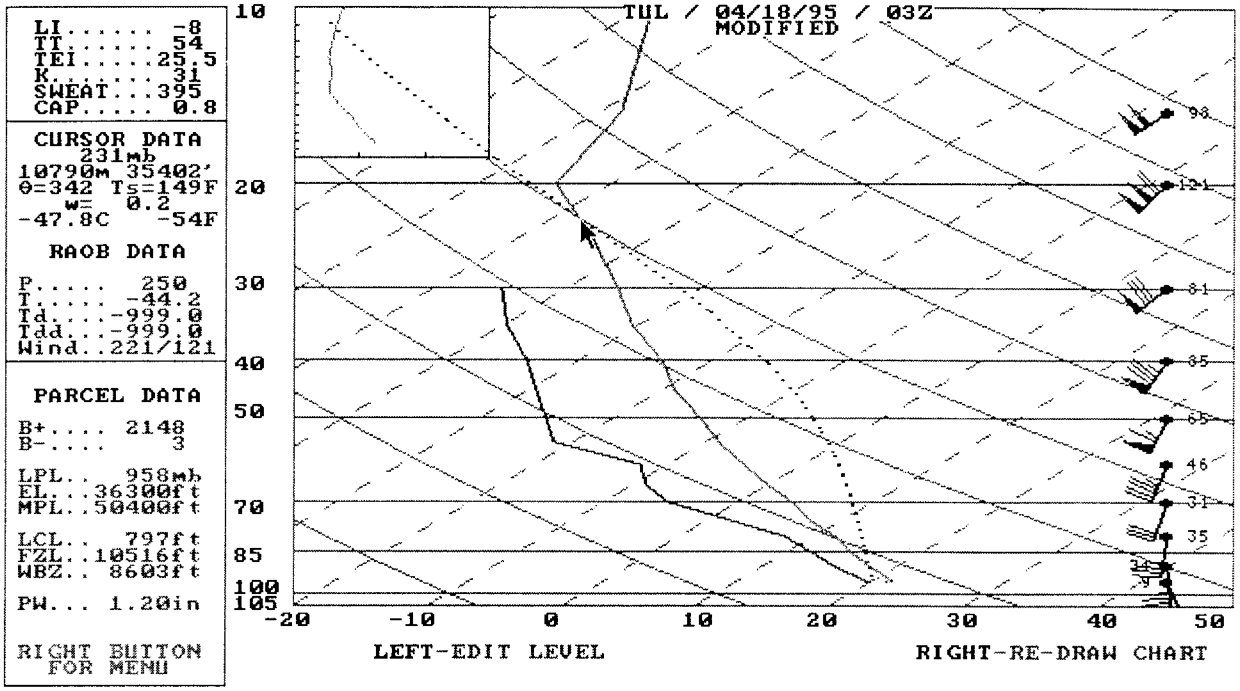


LI...... -8
TT...... 54
TEI.....25.5
K....... 31
SWEAT...395
CAP..... 0.8

CURSOR DATA
231mb
10790m 35402'
θ=342 Ts=149F
w= 0.2
-47.8C -54F

RAOB DATA

P..... 250
T..... -44.2
Td....-999.0
Tdd...-999.0
Wind..221/121

PARCEL DATA

B+.... 2148
B-.... 3

LPL.. 958mb
EL...36300ft
MPL..50400ft

LCL.. 797ft
FZL..10516ft
WBZ.. 8603ft

PW... 1.20in

FIG. 1. 0300 UTC 18 April 1995 sounding for Tulsa, OK, based on modified area 0000 UTC soundings and 0–6-h forecast data from the Eta Model.

vancing eastward over western Oklahoma during the afternoon and evening of 17 April 1995. A very unstable airmass existed over the eastern half of Oklahoma ahead of the cold front, with convectively available potential energy values of at least 2000 J Kg^{-1} (Fig. 1) for surface-based parcels.

The vertical wind profile (Fig. 2) showed substantial speed and directional shear, resulting in 0–3-km storm-relative helicity values of at least 250 m^2 s^{-2}, sufficient for the development of supercells (Johns and Doswell 1992; Davies-Jones and Burgess 1990). However, the Inola WSR-88D wind profile and the 0000 UTC 18 April sounding from Norman, Oklahoma, showed a layer 2–3 km above ground level where the wind speeds decreased with height, a potential negative factor for the development of strong rotation (Johns and Doswell 1992).

The combination of an unstable airmass, substantial vertical wind shear, the approach of an upper-level trough and associated jet streak, and convergence along the advancing cold front (Fig. 3) led to the severe thunderstorm event. Prior to 0300 UTC 18 April, an isolated, long-lived supercell tracked across south-central Oklahoma in advance of an eastward moving squall line. This study focuses on the portion of the event over eastern Oklahoma after 0300 UTC.

At 0300 UTC (Fig. 4), the supercell was located over eastern Okfuskee County and southern Okmulgee County, about 60 km south of Tulsa, Oklahoma. The supercell produced hail up to half-dollar size (32 mm), surface winds reaching 25 m s^{-1} or greater, and three short-lived FO tornadoes as it moved northeastward across southern Okmulgee County and western Muskogee County through 0330 UTC.

At the same time, a line of severe thunderstorms composed of several bow echo segments was moving steadily eastward over east-central Oklahoma. One of the bow echo segments was accelerating eastward and approaching the supercell. Damaging straight-line winds of 25 m s^{-1} or greater were reported along the path of this bow echo.

3. WSR-88D depiction of storm interaction and the result

Between 0330 and 0400 UTC, WSR-88D imagery showed the apex of the bow echo pass just to the south of the supercell (Figs. 5 and 6). Subsequently, the northern portion of the bow echo accelerated northeastward around the eastern periphery of the supercell and rapidly weakened (Fig. 7). The appearance of an outflow boundary to the east of the supercell (Fig. 7a) suggested the bow echo's cold pool was intercepting the supercell's low-level easterly inflow. This interaction typically weakens the supercell, and diminishes its severe weather potential, as the bow echo's cold pool undercuts the supercell updraft and spreads in advance of the storm. WSR-88D imagery indicated a different outcome. Substantial changes to the supercell's structure took place, but the supercell maintained its identity and severity for over an hour after the interaction between the supercell and bow echo took place.

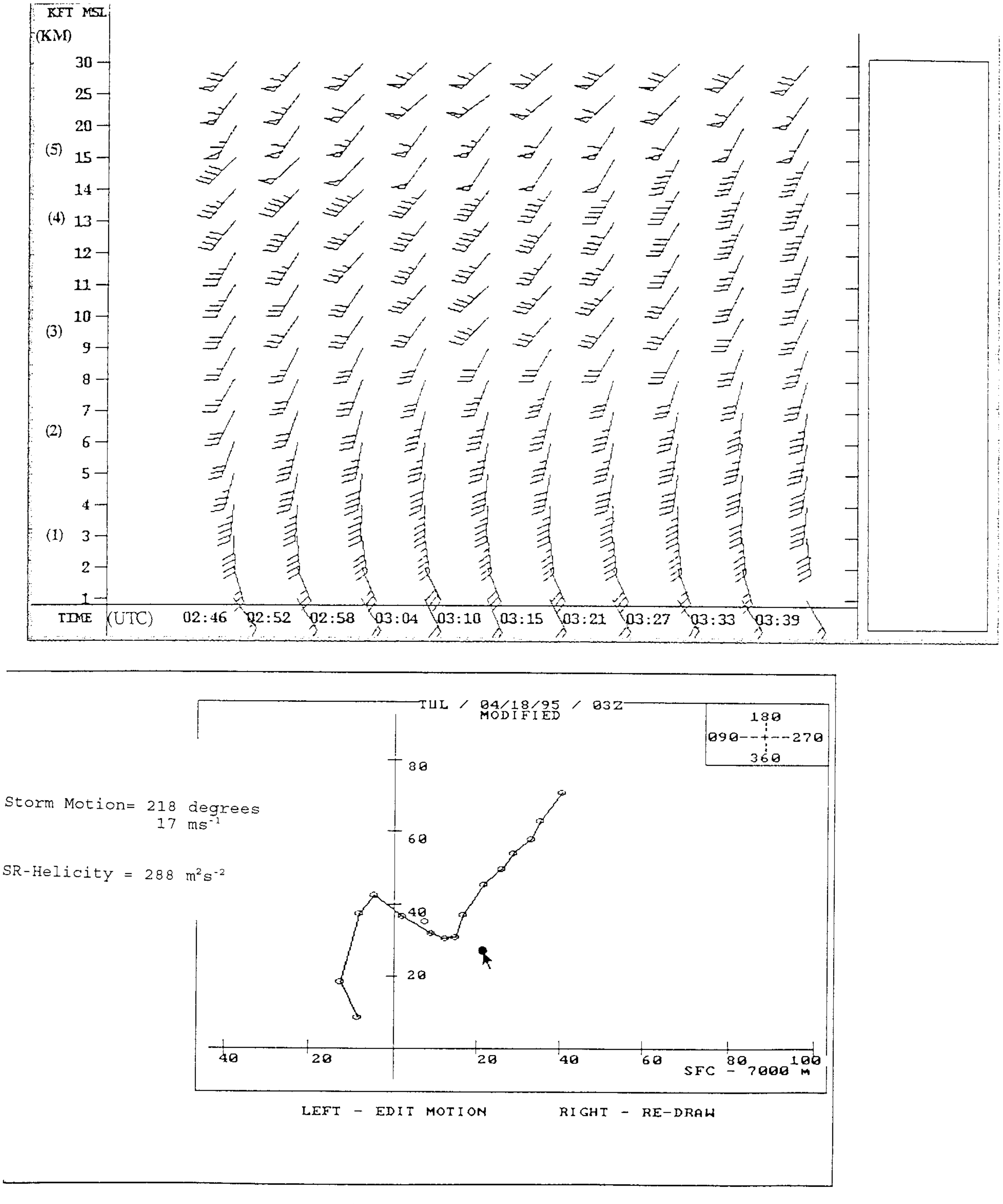


FIG. 2. (a) Inola, OK WSR-88D VAD wind profile during the evening hours of 17 April 1995; (b) hodograph produced by the WSR-88D VAD wind profile. Supercell motion is indicated by the arrow.

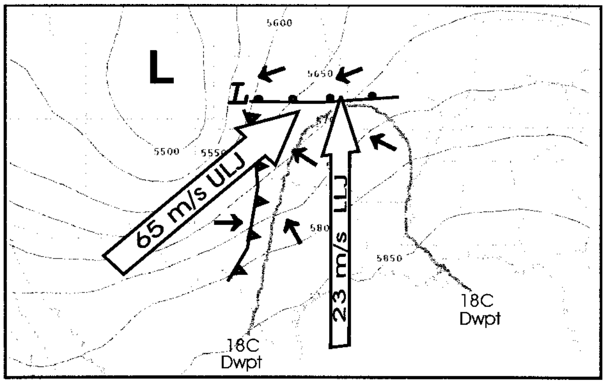


FIG. 3. 0000 UTC 18 April 1995 composite illustration showing the location of the upper-level trough (500-mb height contours) and jet streak (65 m s^{-1}), the low-level jet (23 m s^{-1}), surface flow (small arrows), surface low pressure center and associated fronts, and the low-level moisture ridge indicated by the 18°C surface dewpoint contour.

One of the more obvious changes to the supercell was the development of a 15–20-km-wide mesoscale circulation that engulfed the 5–8-km-wide mesocyclone of the supercell (Figs. 6c, 7c). As the 4 km-deep mesoscale circulation developed between 0345 and 0415 UTC, the depth of the smaller-scale mesocyclone decreased substantially from 9 km to ~4 km. These width and depth values were maintained after 0415 UTC. WSR-88D imagery suggested the mesoscale circulation developed as a result of the rapid passage of the bow echo, and associated strong low-level flow as indicated by spotter reports, to the south of the supercell. This may be a storm-scale example of cyclonic vorticity development observed on the cyclonic-shear side of a wind maximum, similar to the development of rotating comma-head features associated with bow echoes (Fujita 1978). In this case, the supercell appeared to become the rotating comma-head feature and maintained this identity after the bow echo dissipated. Changes in the reflectivity pattern support this observation.

The reflectivity pattern of the supercell, as displayed by WSR-88D imagery, changed substantially after the interaction with the bow echo. The merging of the northern portion of the bow echo with the supercell, and redistribution of precipitation around the developing mesoscale circulation, led to the formation of a large, rotating thunderstorm with a comma-shaped echo appearance (Figs. 5–7). Reflectivity cross sections (Figs. 4d–7d) indicated a decrease in the depth of the heavy precipitation core (50 d*BZ* or greater), dissipation of reflectivity values greater than 59 d*BZ* (also see Fig. 10c, later), and less impressive echo overhang after supercell–bow echo interaction. In addition, the height of the echo tops decreased from near 14 km before the interaction to around 10 km after the interaction (Fig. 10b). The result was a dramatic and permanent drop in vertically integrated liquid (VIL) values associated with the supercell from greater than 55 kg m^{-2} before the interaction to less than 30 kg m^{-2} after the interaction (Fig. 10a).

The altered structure of the supercell appeared to be associated with a cessation of hail occurrence at the surface. Hail was not reported after the supercell–bow echo interaction took place. The illustrations of VIL trend, echo-top trend, and maximum-reflectivity trend shown on Fig. 10 support this observation. Despite the suggestion of storm updraft weakening given by Fig. 10, the supercell maintained its strong rotation and continued to produce damaging winds and tornadoes.

Development of similar comma-shaped echo patterns and mesoscale circulations have been documented in other cases (e.g., Przybylinski et al. 1990; Wolf et al. 1996). This type of HP supercell evolution can occur without supercell–bow echo interaction, an example of which is provided by Przybylinski et al. (1990). For the case presented here, WSR-88D imagery strongly suggests passage of the bow echo just to the south of the supercell that played a role in the formation of a large comma-shaped HP supercell.

During the 20-min period after the development of the mesoscale circulation, WSR-88D reflectivity imagery indicated the formation of a rear-inflow notch (RIN) boundary over northern Muskogee County, which accelerated east-northeastward around the southern periphery of the mesoscale circulation (Fig. 7). This boundary appeared to be the leading edge of the rear-flank downdraft (Lemon and Doswell 1979).

As the RIN moved around the southern periphery of the supercell thunderstorm, WSR-88D imagery showed the development of a tornado vortex signature (an indication of tornado-like shear in Doppler radial velocity data) at a location where the RIN boundary appeared to intersect the supercell's main updraft (Fig. 7c). At this location of southeastern Wagoner County, near the community of Okay, an F2 tornado developed around 0415 UTC. It damaged many houses and mobile homes, and uprooted numerous trees. As the large comma-shaped supercell moved northeastward over western Cherokee County through 0430 UTC (Fig. 8), it produced another RIN boundary. An F1 tornado formed shortly after 0430 UTC over northwest Cherokee County just north of the RIN where the RIN boundary appeared to intersect the supercell's main updraft. Similar tornadic development north of a RIN has been documented (Pfost and Gerard 1997; Sabones et al. 1996; Przybylinski and Schmocker 1993; Przybylinski et al. 1990).

The apparent redistribution of precipitation around the mesoscale circulation led to the unusual formation of a reflectivity minimum (Fig. 9) on WSR-88D reflectivity products after 0445 UTC. This feature, located near the center of the mesoscale circulation, lasted nearly 20 min. After it dissipated, the HP supercell gradually weakened, though it continued to produce damaging winds and a brief F0 tornado as it moved northeast across Delaware County.

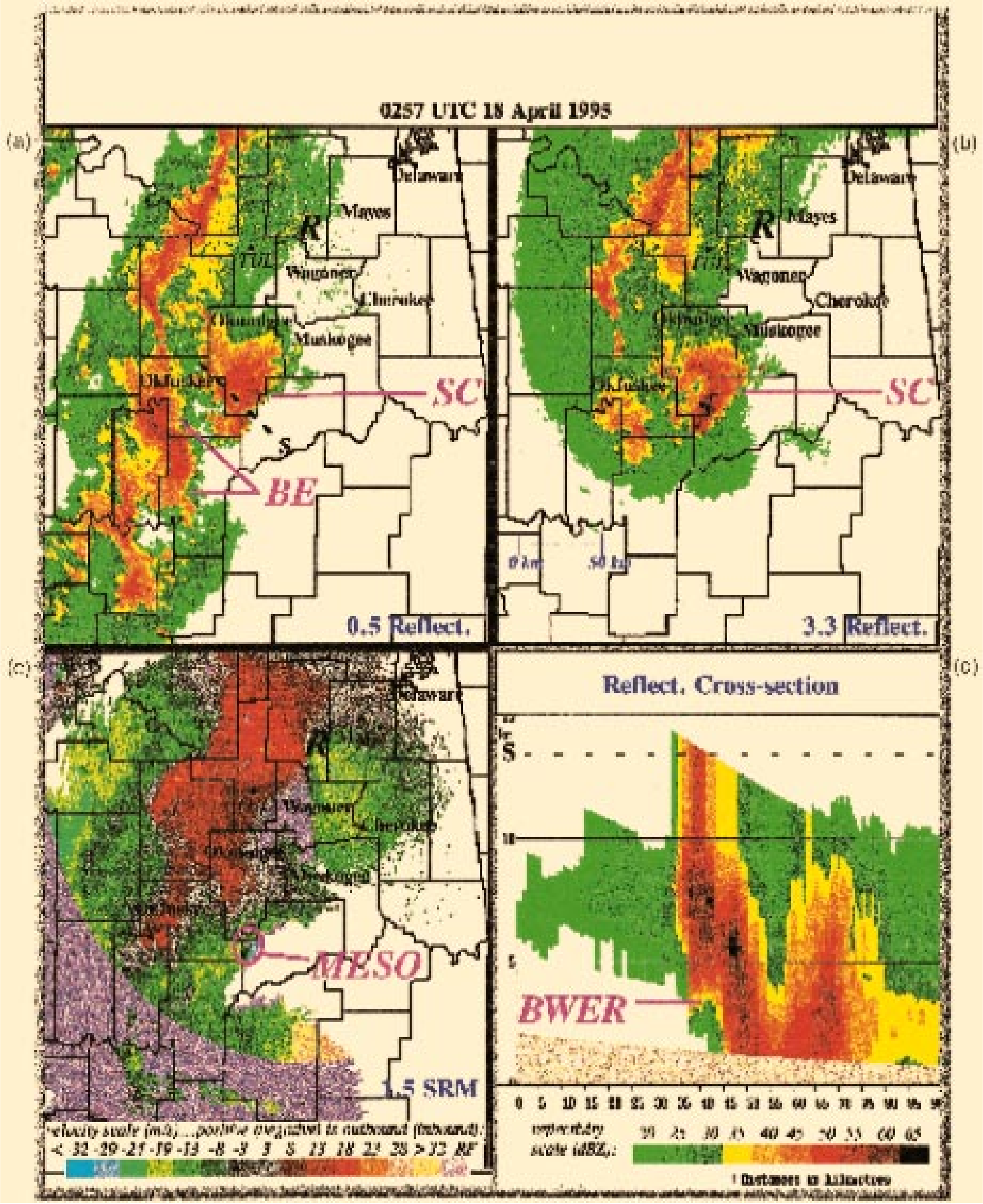


FIG. 4. (a) WSR-88D 0.5° base reflectivity, (b) 3.3° base reflectivity, (c) 1.5° storm-relative mean velocity, and (d) and reflectivity cross section products for 0258 UTC 18 April 1995. Here, ''R'' indicates the WSR-88D location, ''SC'' means supercell, ''BE'' means bow echo, ''MESO'' refers to mesocyclone, and ''BWER'' refers to bounded weak echo region. The label ''S - - - '' indicates how the cross section in (d) was cut, with ''S'' indicating the starting point. A horizontal length scale is given in the lower-left corner of (b). Reflectivity and velocity scales are provided.

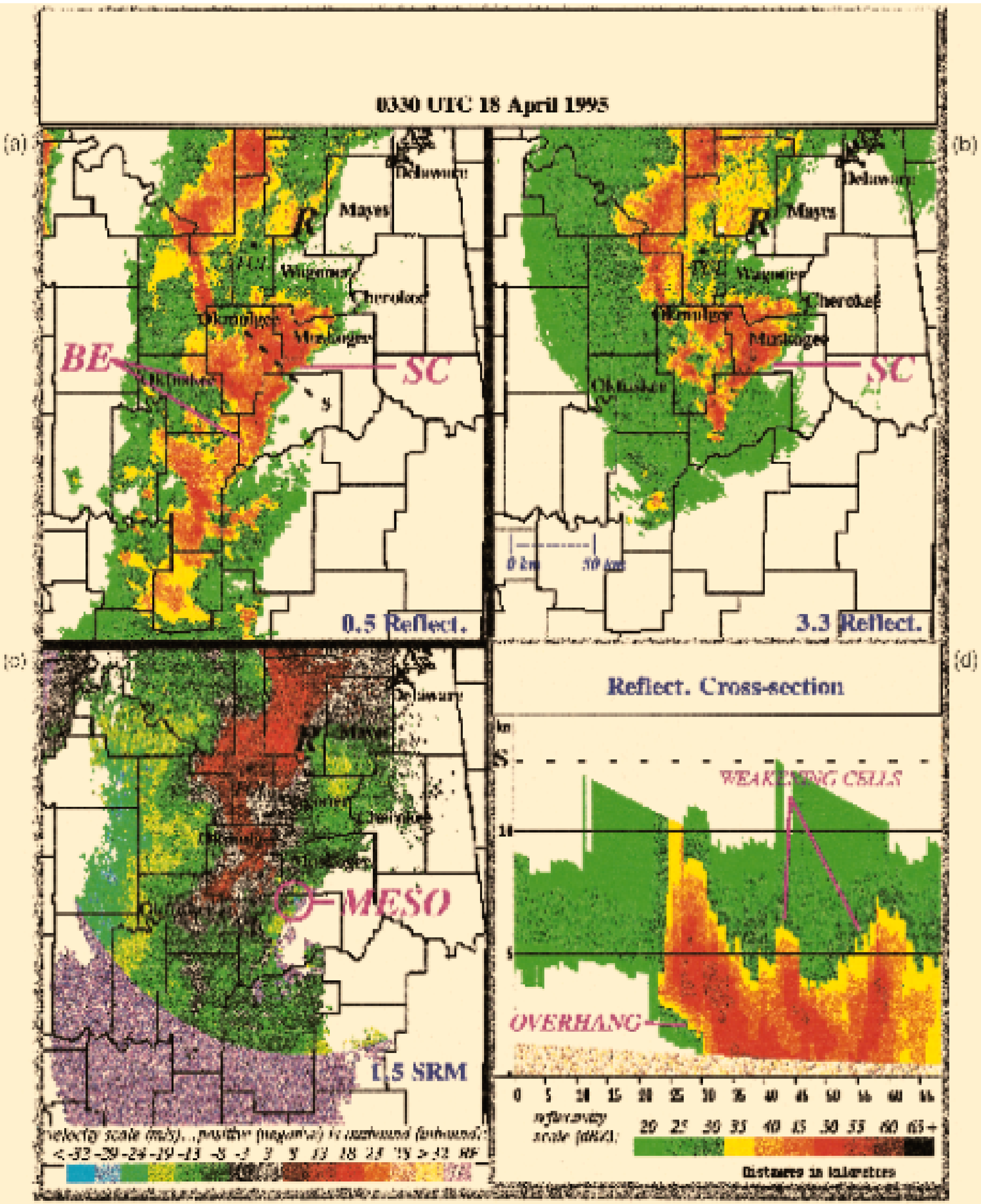


FIG. 5. Same as Fig. 4 except for 0327 UTC.

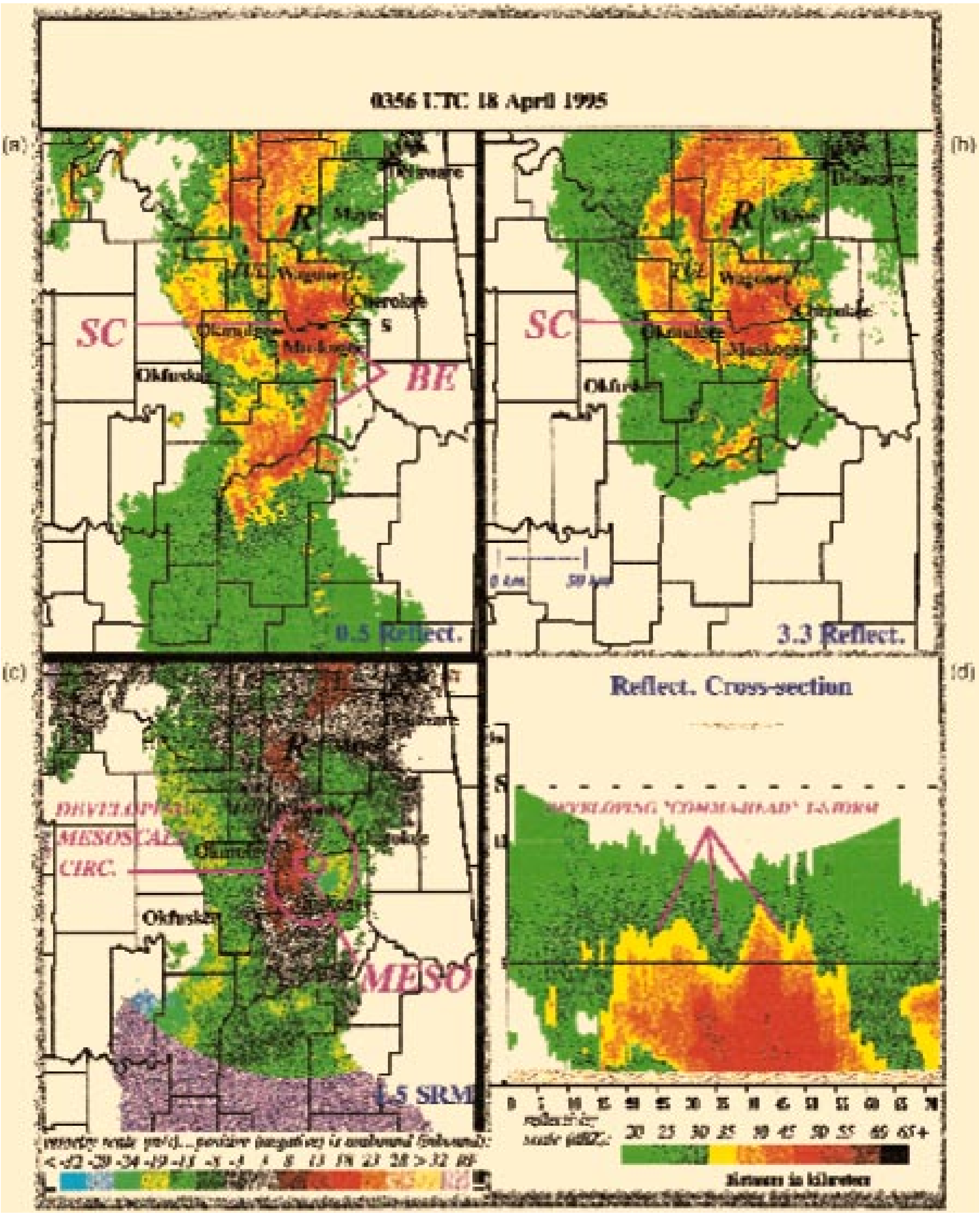


FIG. 6. Same as Fig. 4 except for 0358 UTC.

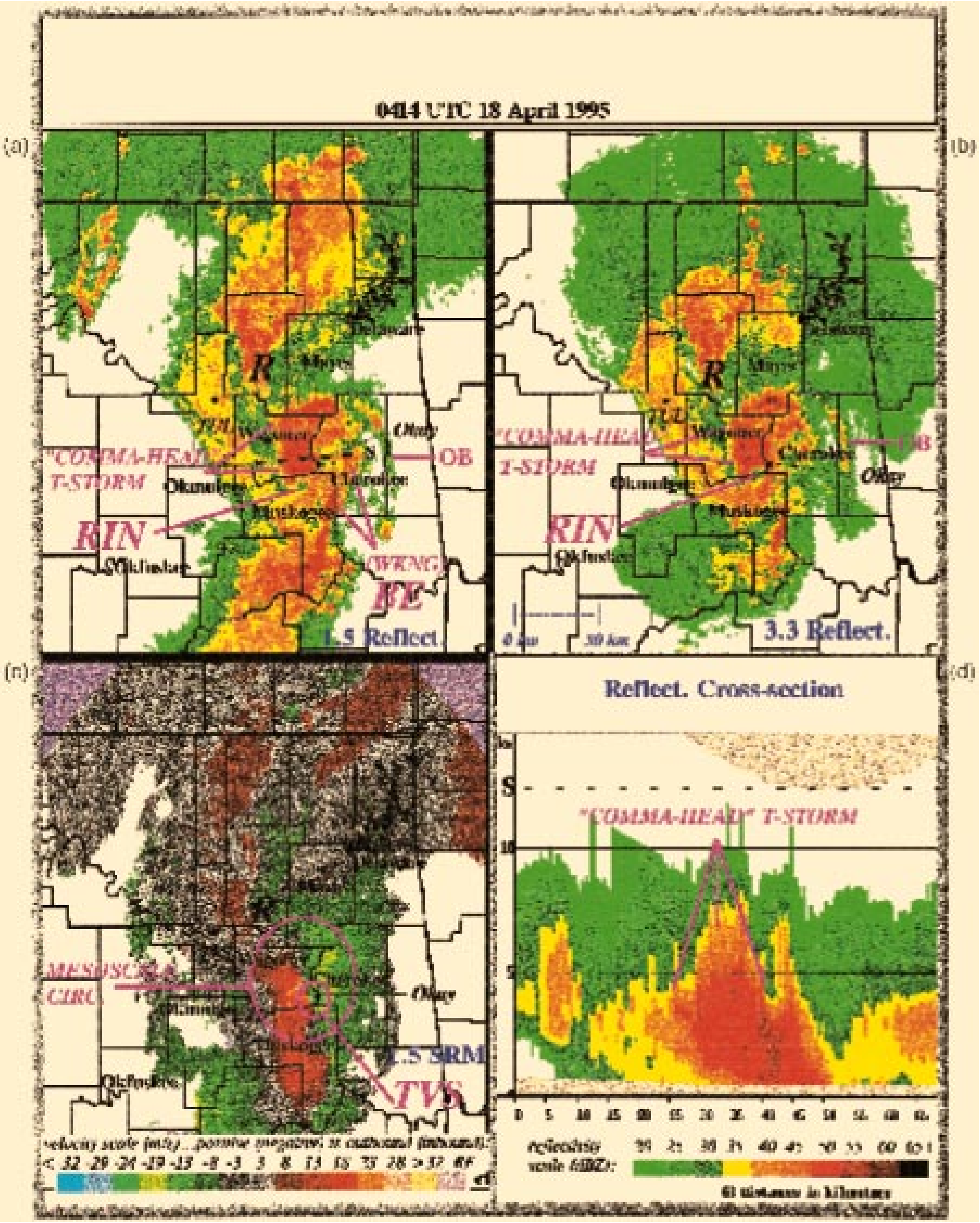


FIG. 7. Same as Fig. 4 except for 0414 UTC and shows 1.5° base reflectivity in (a). ''RIN'' refers to rear-inflow notch, ''TVS'' refers to tornado vortex signature, and ''OB'' indicates an apparent outflow boundary.

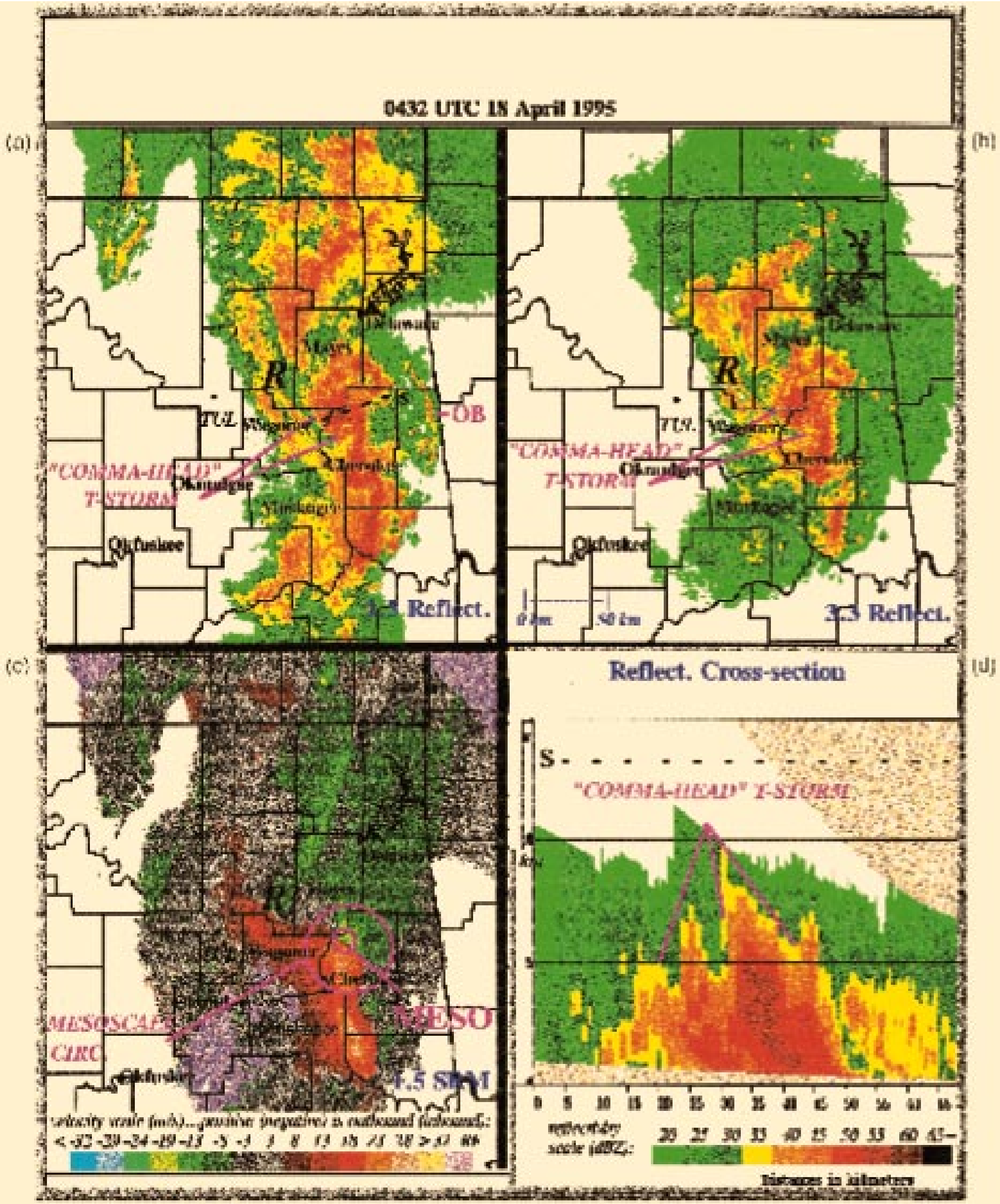


FIG. 8. Same as Fig. 7 except for 0432 UTC.

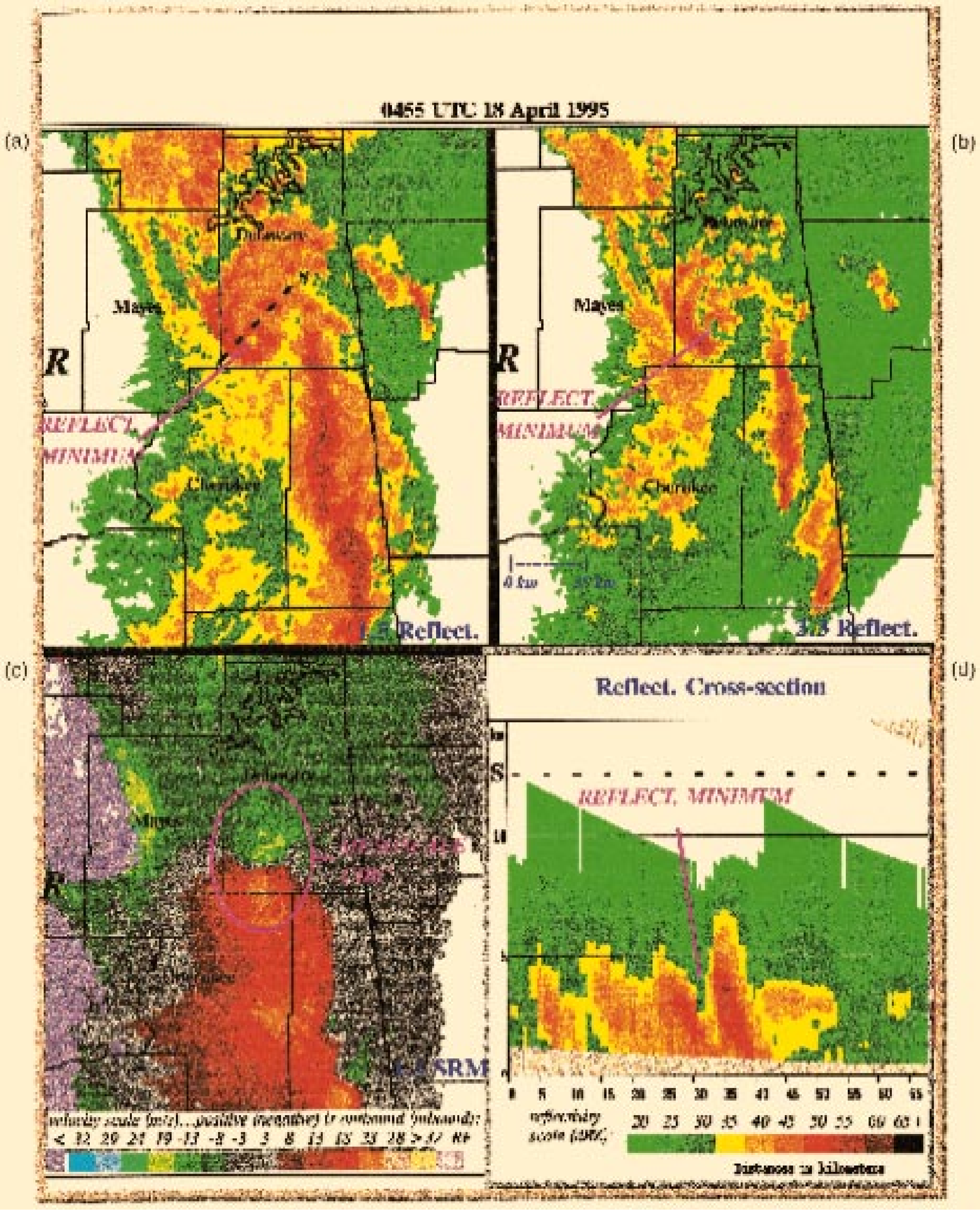
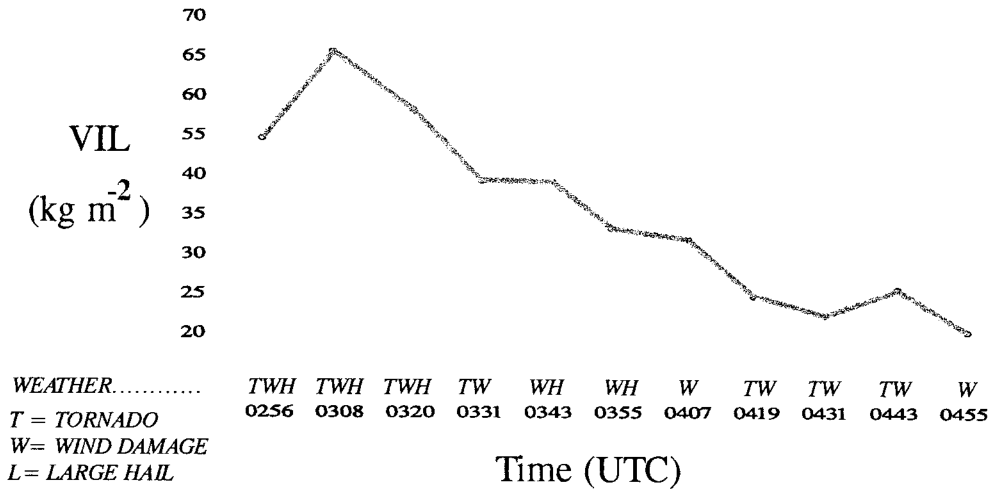
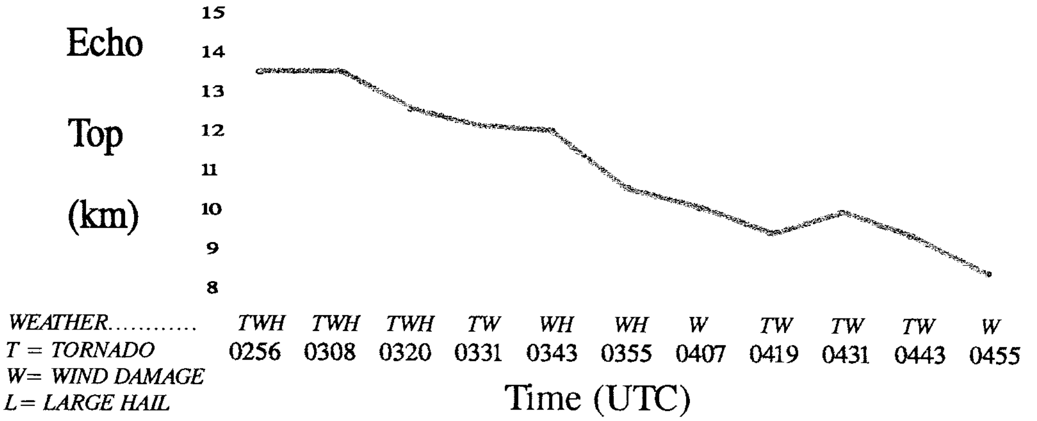


FIG. 9. Same as Fig. 7 except for 0455 UTC. The images are magnified here to more clearly show the reflectivity minimum.

a) VIL Trend



b) Echo Top (estimated) Trend



c) Maximum Reflectivity Value Trend

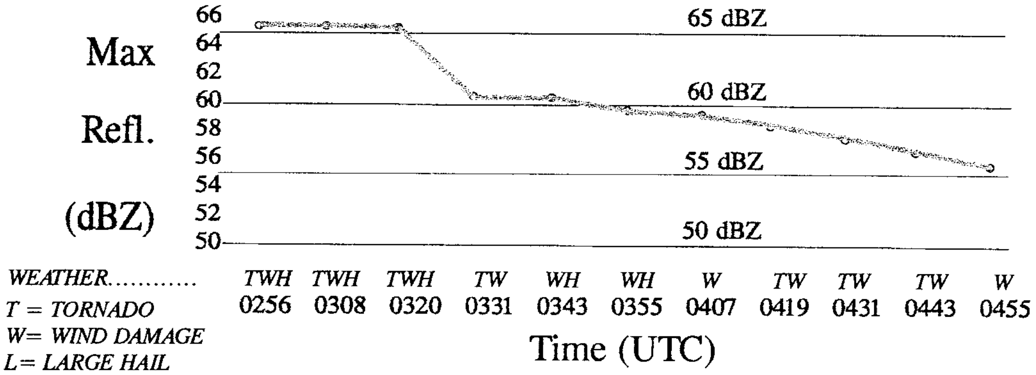


FIG. 10. Trend plots for (a) VIL, (b) estimated echo top, and (c) maximum reflectivity values. The trend plots cover a 2-h period from 0258 to 0454 UTC. Note that supercell–bow echo interaction occurred between 0330 and 0400 UTC. Weather reports obtained near the time of each radar scan are included to show the continuation of severe weather production after the interaction occurred.

4. Discussion

WSR-88D imagery provided a fascinating look at the interaction between two different convective phenomena: a supercell and a bow echo. The detailed reflectivity and velocity products from the WSR-88D showed the apparent result of this interaction. Instead of showing the supercell weakening and becoming a part of the advancing bow echo, as the bow echo's cold pool undercut the supercell and spread out in advance of the storm, the WSR-88D showed a different outcome. The bow echo weakened, while the supercell evolved into a large, comma-shaped thunderstorm, with a large mesoscale circulation, that continued to produce severe weather.

This case illustrates a member of a large spectrum of potential outcomes when a thunderstorm line segment intercepts a supercell. It also illustrates a member of a large spectrum of HP supercell structures and appearances as suggested by Doswell et al. (1990). This case shows a fascinating HP supercell evolution that apparently results from bow echo passage just to the south of a supercell. Other studies of similar supercell–bow echo interactions yielded similar results. Different outcomes would be anticipated for scenarios in which a thunderstorm line segment passes to the north of a supercell, or directly merges with a supercell. Wolf et al. (1996) described an example of a supercell thunderstorm that weakened shortly after directly merging with an approaching squall line.

An interesting feature of the evolving HP supercell was the formation of a large mesoscale circulation with a 15–20-km diameter. Perhaps similar to the formation of a cyclonic circulation on the cyclonic-shear side of a wind maximum, a cyclonic mesoscale circulation formed to the north of strong low-level flow associated with the passing bow echo. As this circulation developed, and the northern portion of the bow echo merged with the supercell, a large, comma-shaped HP supercell evolved. The supercell, which appeared to be similar to a rotating comma-head feature commonly observed with bow echoes, maintained its identity and severity for over an hour after the supercell–bow echo interaction took place. At one point, apparent precipitation redistribution around the broad mesoscale circulation led to the formation of an unusual reflectivity minimum near the center of the circulation.

Tornado development from the HP supercell continued for over an hour after the supercell–bow echo interaction occurred. Tornadoes were associated with 5–8-km-wide low-level mesocyclones embedded within the larger mesoscale circulation. The existence of low-level mesocyclones within the mesoscale circulation may have been associated with the continued influx of strong horizontal streamwise vorticity into the main updraft of the supercell from the cool side of the forward flank downdraft boundary (Lemon and Doswell 1979), a process described by Davies-Jones and Brooks (1993).

WSR-88D images also showed the development of two successive RIN boundaries around the southern periphery of the supercell. Tornado development occurred where each of these boundaries appeared to intersect the main updraft of the supercell. WSR-88D imagery suggested there may be some association between the RIN boundaries, or shear induced by passage of these boundaries just to the south of the supercell, and tornado development. The exact role the RIN boundaries may have played in tornadogenesis, if any, is not clear. Interestingly, the tornadoes produced in the vicinity of the RIN boundaries were somewhat stronger than those produced by the supercell during the 1-h period prior to the supercell–bow echo interaction.

Supercell demise may not necessarily be the result when the storm is intercepted by a thunderstorm line or line segment. Bow echo passage to the south of a supercell can lead to the evolution of a large comma-shaped HP supercell with continued production of severe weather, including tornadoes. Tornado development occurred before and after supercell–bow echo interaction in the case presented here, but apparently did not occur during the interaction. Other studies (e.g., Sabones et al. 1996; Goodman and Knupp 1993) have documented the formation of strong tornadoes during supercell–bow echo interactions.

This case and similar cases indicate that operational meteorologists should be especially alert for severe weather production, including tornado development, during and after passage of a thunderstorm line segment just to the south of a supercell. Severe weather production can continue from the supercell after the interaction occurs, even when the supercell shows signs of weakening (Fig. 10). Further research is needed on interactions between various thunderstorm phenomena to determine if the HP supercell evolution presented here, and in similar cases, can and should be the expected result of bow echo passage around the southern periphery of a supercell in future events.

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