THE INITIATION AND EVOLUTION OF A MINI-BOW ECHO OCCURRING BEHIND A PREFRONTAL SQUALL LINE

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Abstract

Early on 13 April 1996, a mini-bow echo moved through parts of south central Mississippi. This bow echo produced one report of severe weather, namely $10K in wind damage near the town of Bassfield in Jefferson Davis county. The evolution of this bow echo was somewhat unusual, in that the storm developed within the southern part of the enhanced stratiform rain region of a well developed prefrontal squall line. This paper will examine the development of this small bow echo, beginning with the synoptic and mesoscale environments. This will be followed by the storm evolution as observed by the WSR-88D Doppler radar in Jackson, Mississippi.

1. Introduction

During the early morning hours of 13 April 1996, a mini-bow echo (as defined by Forbes et al. 1998) moved through parts of south central Mississippi. In spite of moving through a relatively unpopulated area, some wind damage was reported, namely a report of $10K in damage at 0325 CDT near the town of Bassfield in Jefferson Davis county (Fig. 1). The occurrence of this damage was observed by a county sheriff on the scene. He reported strong winds, lightning, and a funnel cloud passing overhead (although based on the time of night the validity of this funnel cloud report could be considered suspect).

Rather than occurring along the leading edge of a mesoscale convective system (MCS), this bow echo formed **behind** the squall line, in an area characterized by generally stratiform rainfall with just a few embedded convective cells. This region in which the convection formed had also been stabilized significantly in the boundary layer by evaporational cooling and thunderstorm outflow associated with the passage of the squall line. Although the bow echo formation in this event occurred in a location different than that proposed by conceptual models (e.g., Przybylinski 1995; Johns 1993), the synoptic environment showed many features conducive to the development of bow echoes. Additionally, many of the radar signatures identified in previous research (e.g., Forbes et al. 1998; Przybylinski 1995; Przybylinski and Schmocker 1993) such as rear inflow notches (RIN), the "bow" formation of the reflectivity pattern, as well as shear zones and circulations along the leading edge of the convection, were observed by the Jackson, Mississippi (KJAN) WSR-88D.

2. Synoptic Environment

During the early evening hours of 12 April 1996, synoptic features and parameters came together for an active severe weather event over the western Gulf Coast region (Fig. 2). At 0000 UTC 13 April 1996, an upper-level shortwave trough had become negatively-tilted over north Texas as a 30 m s^{-1} 500 mb wind maximum lifted out of the base of the trough and into the mid-Mississippi valley region. A 300 mb polar jet streak in excess of 50 m s^{-1} was located downstream from the trough axis from eastern Oklahoma to southeastern Iowa. Meanwhile at 200 mb, an active subtropical jet stream extended from southwest of Brownsville, Texas to south of Pensacola, Florida with a jet streak in excess of 55 m s^{-1} embedded within the mean flow. At the surface, a weak cold front was draped across north Texas and extended northeastward to a low pressure center over the Great Lakes region.

With the approach of the upper-level trough, a surface low pressure area developed along the cold front over north Texas with an attendant dryline extending southwestward to just east of San Antonio, Texas. Surface dewpoints of 20 °C east of the dryline resulted in surface-based Convective Available Potential Energy (CAPE) values to as high as 3200 J kg^{-1} over southeast Texas (see Fig. 3). This low-level instability axis was mainly confined to southeast Texas and western Louisiana where rich low-level moisture return occurred under 700-500 mb lapse rates of around 7.3 °C km^{-1}, leading to the high, surface-based CAPE values.

Observed and model forecast vertical wind profiles to the east of the surface cold front were characterized by a low-level (0-3 km) veering pattern with uniform southwesterly flow increasing with height through the middle and upper troposphere (e.g., see Fig. 4). The magnitude of the 0-5 km wind shear vector over Louisiana and Mississippi was on the order of 20 m s^{-1}. Numerical modeling work from Rotunno et al. (1988) has shown that, given sufficient initial buoyancy conditions, long-lived (4-6 hours) lines of convective cells can develop in environments where the vertical wind shear is on the order of

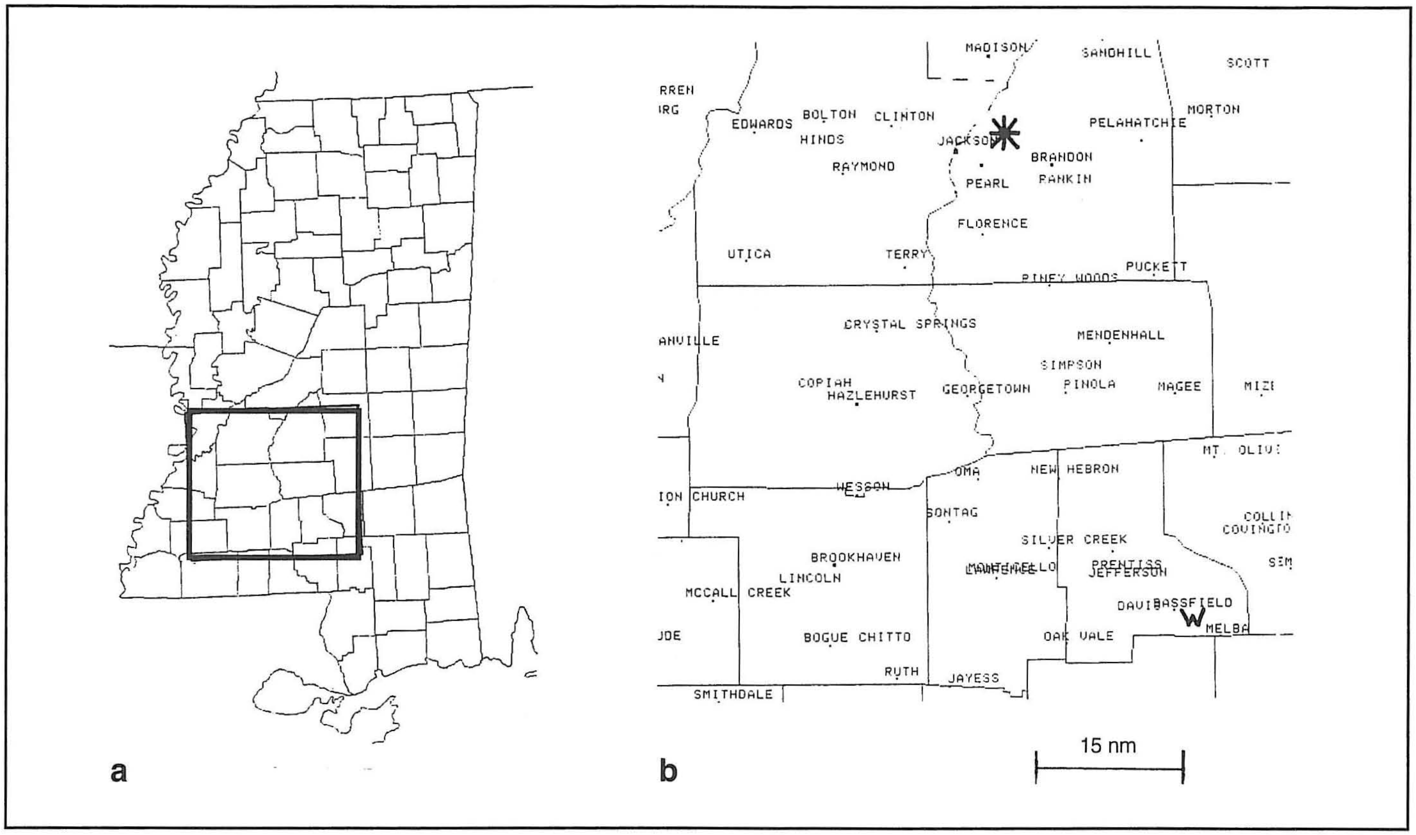

Fig. 1. Reference maps: a) State of Mississippi with counties outlined and b) magnification of boxed area in Fig. 1a with Bassfield in the lower right hand corner and W indicating the location of wind damage which occurred at 0825 UTC 13 April 1996. Lincoln County is in the lower left hand corner, Jackson is in the top center with the WSR-88D RDA location marked by a star.

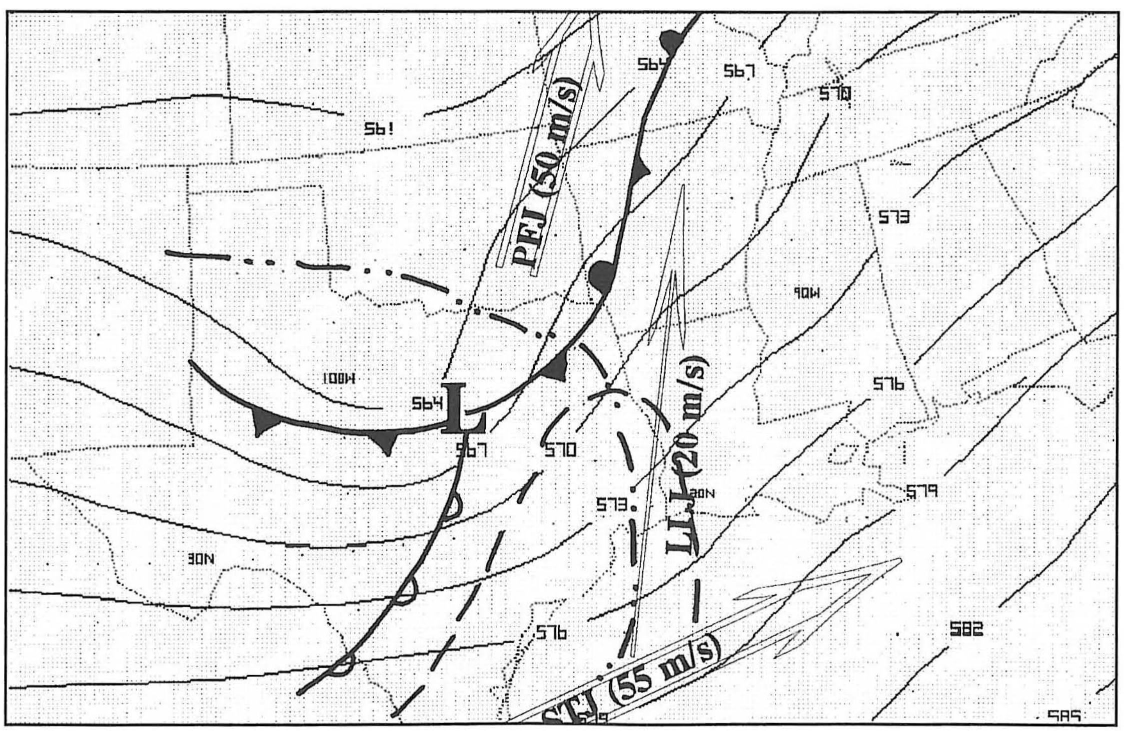

Fig. 2. Composite chart valid at 0000 UTC 13 April 1996. The 500 mb height contours (in decameters) are indicated by the solid thin lines. The branches of the polar jet (PFJ) at 300 mb, subtropical jet (STJ) at 200 mb, and low-level jet (LLJ) at 850 mb are shown along with the surface fronts. The location of the 20 °C surface isodrosotherm is marked by the dashed line, and the location of the leading edge of 700 to 500 mb layer mean dewpoint depressions greater than 20 °C is marked by the dash-dot-dot line.

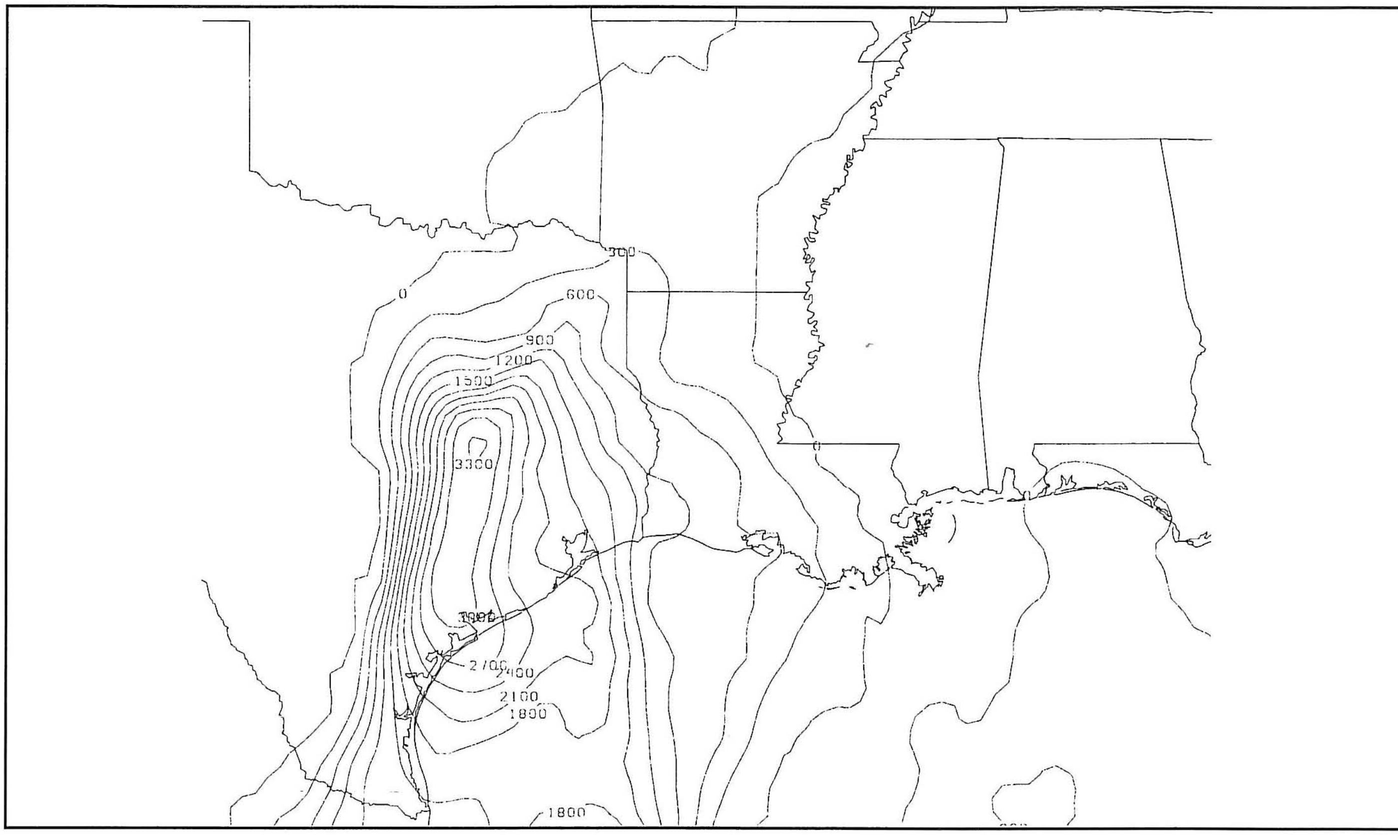

Fig. 3. 00-hour CAPE (J kg^{-1}) forecast from the 0300 UTC 13 April Meso-Eta model.

20 m s^{-1} through the 0-5 km Above Ground Layer (AGL). The character of the shear vector profile for this event was linear (i.e., a nearly straight line hodograph from 1 to 10 km), which is conducive to the formation of derechoes and straight line wind damage.

The combination of the approach of the upper-level trough, sufficient instability, and strong wind fields yielded a favorable environment for the formation of severe convection ahead of the eastward moving dryline. Specifically, the proximity of the upper-level trough and the strong wind profiles describes a synoptic pattern similar to the "dynamic" bow echo pattern discussed by Johns (1993). Although not necessarily a characteristic of the "dynamic" pattern, the impinging dry air in the mid- and upper-levels of the atmosphere (to be discussed in the next section) is a factor conducive to the development of bow echoes and is more common in the "dynamic" bow echo pattern than the warm season bow echo pattern (Johns 1993; Przybylinski and Schmocker 1993).

3. Convective Initiation

The initial development of the bow-echo producing MCS occurred shortly after 0000 UTC on 13 April 1996 to the east of a surface dryline located across eastern Texas. Low-level convergence in the vicinity of the dryline and surface-based CAPE values to 3200 J kg^{-1} aided rapid thunderstorm development across extreme eastern Texas and western Louisiana (Fig. 5a). The convection quickly moved east of the main low-level instability axis and into central Louisiana by 0300 UTC. Even with the convection moving into a "seemingly" more stable environment, GOES-8 infrared satellite imagery indicated a cooling trend in the cloud-top temperatures along with a rapid expansion of the cirrus canopy (Fig. 5b) at this time. The 00-h initialization and the 03-h forecast of 500 mb geopotential heights and absolute vorticity from the 0300 UTC 13 April Meso-Eta model (not shown) indicated that the rapid eastward movement of this convection was well correlated with the location and movement of the vorticity maximum associated with the southern plains shortwave trough. The 0300 UTC Meso-Eta 500-300 mb Q-vector fields for these times suggested that synoptic scale vertical motions in advance of this developing convective complex were acting to destabilize the local environment over the eastern two-thirds of Louisiana and Mississippi. Large-scale upward vertical motion appeared to be enhanced by secondary ageostrophic circulations associated with the coupling of the polar and subtropical jet streaks over eastern Louisiana and Mississippi (Fig. 6). The coupling of the polar and subtropical jet streaks is similar to observations documented by Junker et al. (1990) in the development of large MCSs.

By 0700 UTC, GOES-8 infrared satellite imagery indicated that cloud-top warming was occurring with the MCS as it moved across Mississippi (Fig. 5c). At this time, the convective complex had moved well east of the main low-level instability axis, with only minimal surface-based CAPE values of 200-300 J kg^{-1} present along the coasts of Mississippi, Alabama, and Florida. By 0800 UTC, satellite imagery indicated dissipation of the cold

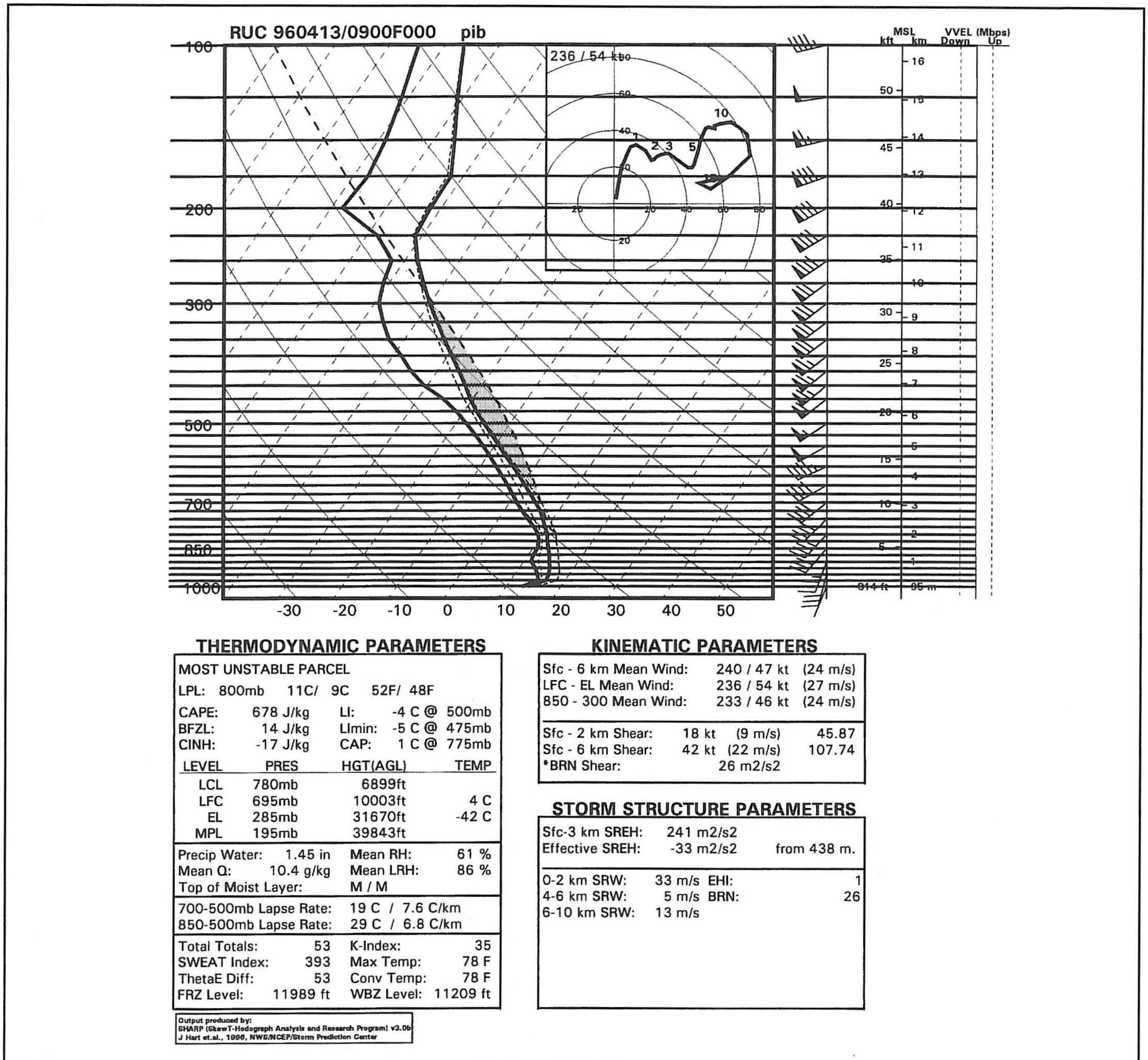

Fig. 4. 00-hour Rapid Update Cycle (RUC) sounding valid 0900 UTC 13 April 1996 for a location near Bassfield, Mississippi. The surface data has been modified to reflect observed surface conditions. Sounding produced by the N-SHARP computer program (Hart et al. 1999).

cloud tops, likely indicative of a deep layer of sinking associated with a mid-level dry intrusion (Fig. 5d). Indeed, the 6-h forecast of the 0300 UTC Meso-Eta model indicated that 700-500 mb dewpoint depressions in excess of 20 °C were being advected into the area by a mid-level (500 mb) westerly wind maximum in excess of 30 m s^{-1}. Although the MCS was in a state of decay, Smull and Houze (1987) have shown that the momentum from the environment can enhance the downburst potential of any individual convective elements comprising the system.

While satellite imagery indicated a general warming of cloud tops with the MCS at 0800 UTC, a few colder tops associated with active convection remained over south central Mississippi. This convection likely developed due to the synoptic scale vertical motion and destabilization discussed previously occurring in an area of elevated convective instability. A sounding obtained from the 0900 UTC Rapid Update Cycle (RUC) model valid at the initial 0900 UTC time (Fig. 4) for the area near Bassfield, Mississippi, indicated an area of convective instability based about 800 mb. This convective instability was above a weak surface based inversion with a conditionally stable boundary layer. Radar indicated the development of a convective cell around 0730 UTC over south central Mississippi, and its further evolution after this time will be discussed in the following section.

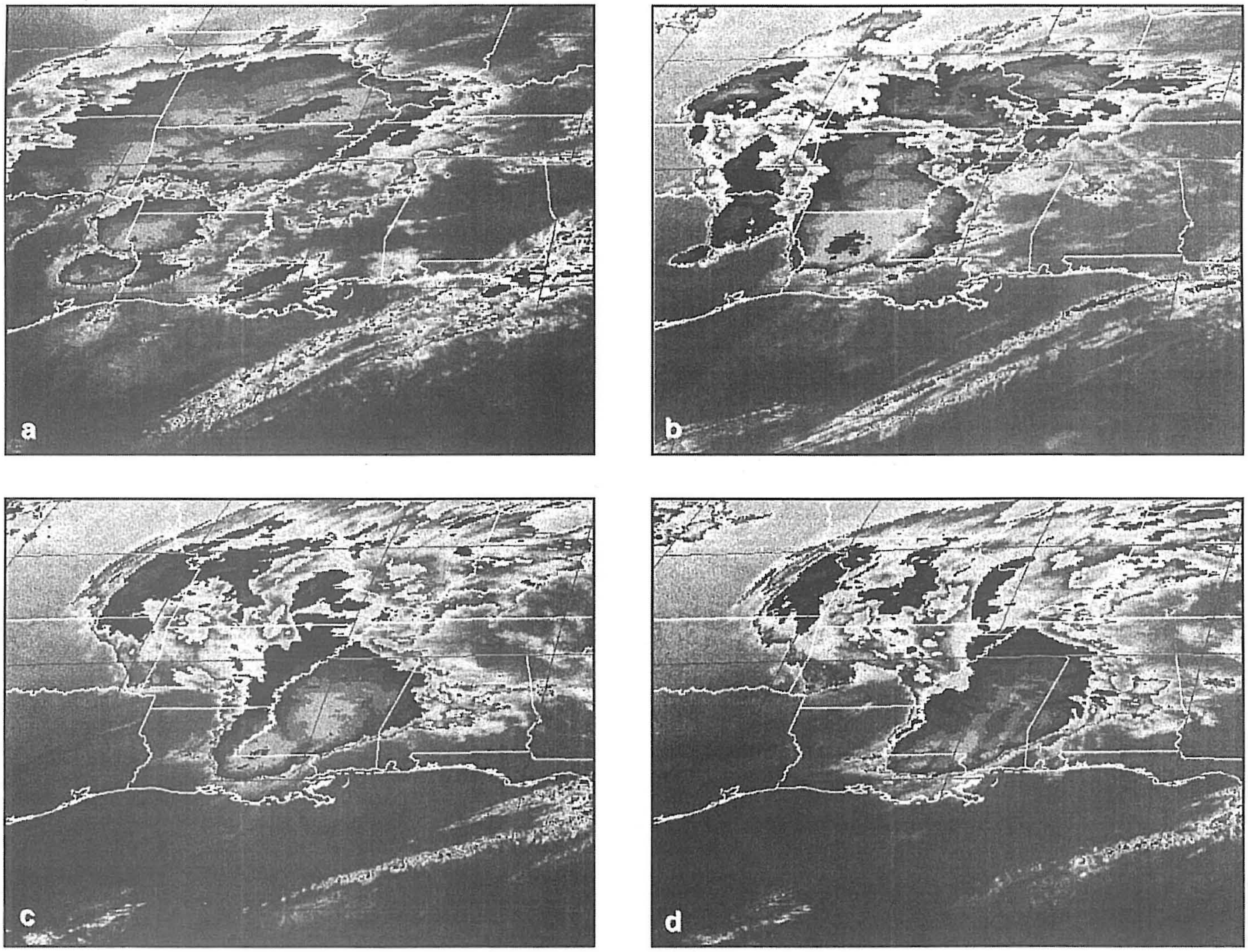

Fig. 5. GOES-8 Infrared satellite imagery sequence on 13 April 1996 valid: a) 0015 UTC, b) 0315 UTC, c) 0702 UTC and d) 0802 UTC.

4. Evolution of the Bow Echo

By 0719 UTC, WSR-88D radar products indicated that a prefrontal squall line had advanced as far as the Mississippi/Alabama border, while much of the rest of the precipitation area over the region appeared to be mainly stratiform in nature. As can be seen in Fig. 7, at 0719 UTC a large enhanced stratiform rain area was occurring across much of Mississippi, while the remnants of the convective line extended from near Meridian to just west of Hattiesburg. A few convective cells were present within the widespread stratiform precipitation area over southern Mississippi to the rear of the squall line. One of these convective cells developed over south central Mississippi around 0730 UTC (Fig. 8), with reflectivity of 45 dBZ present over Lincoln County, Mississippi, southeast of Brookhaven and approximately 90 km from the Jackson Radar Data Acquisition (RDA) site. Already at this time, a weak reflectivity minimum containing intensities of 15 dBZ was apparent behind the convective cell, with a small Rear Inflow Notch (RIN) and associated bulge in the forward side of the convection. This structure appeared similar to that observed in early stages of bow echo development as discussed by Przybylinski (1995). At the same time, WSR-88D storm-relative velocity data at 0.5° (an elevation of about 1.5 km) indicated a weak shear zone associated with the leading edge of this convection. Echo tops with this cell were quite low, around 9 km.

The convection changed little in reflectivity or velocity structure from 0730 UTC to 0754 UTC. By 0759 UTC, however, reflectivity values began to increase in the convection, with areas of 50 dBZ appearing on the 0.5° and 1.5° elevation angles (Fig. 9). Also, a defined core of 35 dBZ appeared at 2.4° (around 5 km) for the first time (not shown). This increase in reflectivity values indicates that the updrafts associated with the convection had become more vigorous by this time, although the RIN and bulge near the leading edge of the bow were not as pronounced at this time as at 0730 UTC. By 0804 UTC, the leading edge of the convection again began to bow out (Fig. 10), with a weak reflectivity minimum present to the rear of the echo at 0.5°. An erosion of the stratiform precipitation

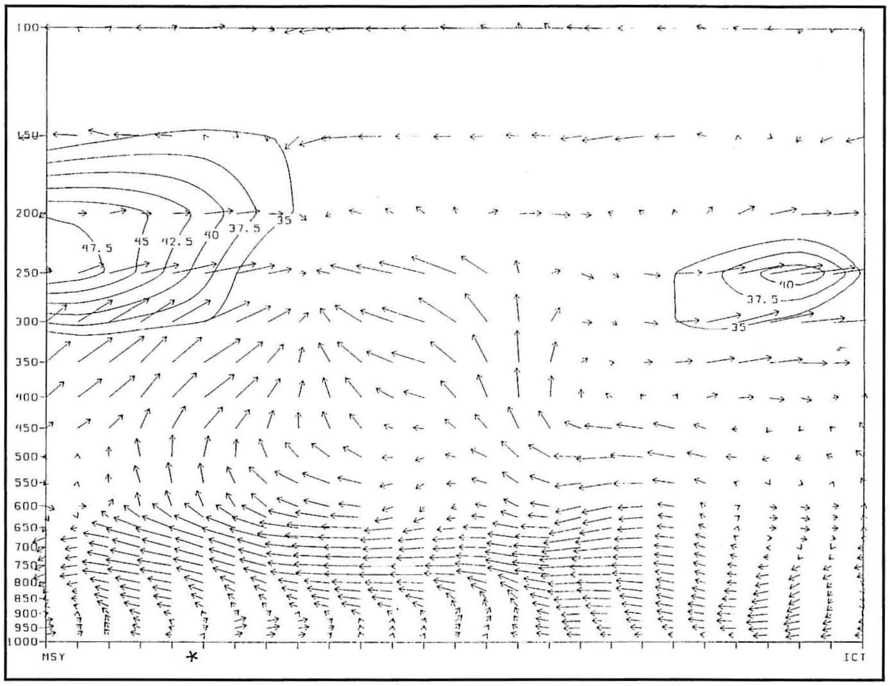

Fig. 6. 00-hour cross section (New Orleans, Louisiana to Wichita, Kansas) from the 0300 UTC 13 April Meso-Eta model. The vectors depict the ageostrophic circulation (m s^{-1}) along the cross section and the solid lines are isotachs (m s^{-1}) of the total wind speed showing the position of the jet stream cores. The asterisk indicates the approximate location of southwest Mississippi.

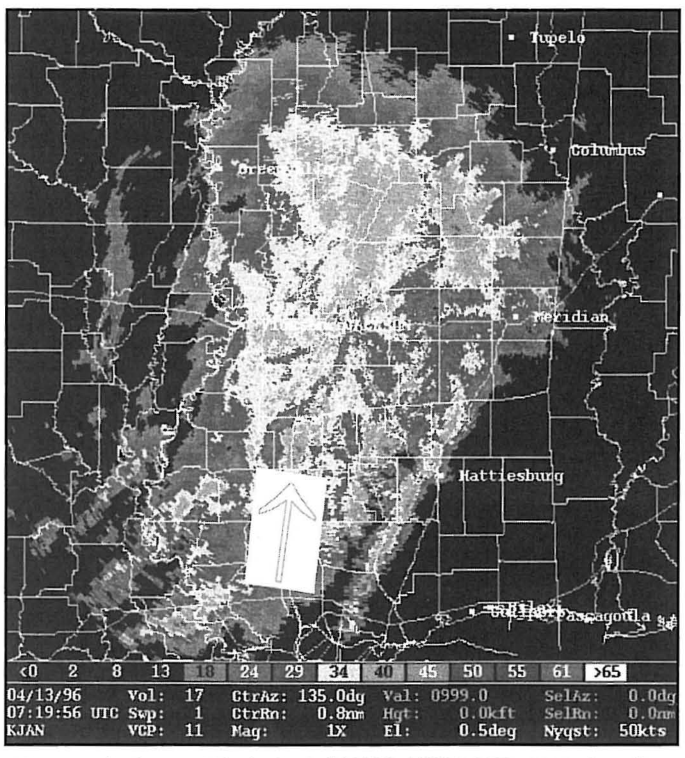

Fig. 7. Jackson, Mississippi (KJAN) WSR-88D 0.5° elevation, base reflectivity valid at 0719 UTC 13 April. Arrow points to the developing convective cell.

shield, upwind of the bowing structure, commenced shortly thereafter as well, indicating a region of mesoscale descent (Fig. 11).

While the reflectivity structure was becoming better defined, storm-relative velocity data was showing an increasingly identifiable circulation along the leading edge of the echo. At 0804 UTC (Fig. 10), the 0.5° storm-relative velocity image showed a cyclonically convergent pattern, while at 1.5°, the first hint of a broad, poorly defined circulation appeared along the leading edge of the echo with 10 m s^{-1} of rotational velocity and a diameter of 13 km. By 0809 UTC (Fig. 12), this circulation became a well defined velocity couplet at 1.5°, with the rotational velocity increasing to 15 m s^{-1} and the diameter decreasing to 7 km. The shear had also strengthened at 0.5°, with the maxima of inbound and outbound velocity becoming closer together and showing an even better defined cyclonic convergent pattern. The rotational velocity across this shear zone at 0.5° had also increased to 15 m s^{-1} at 0809 UTC from 10 m s^{-1} at 0804 UTC. The rapid strengthening of this circulation from 1.5 km up to near 3 km was likely due to a process outlined by Wakimoto and Wilson (1989), where a circulation develops along the outflow boundary and is then stretched vertically by vigorous updrafts and the presence of vertical vorticity. The boundary serves as a focus for strong horizontal shears and the initial development of low-level circulations.

By 0814 UTC, the 0.5° base reflectivity data showed the area of lower reflectivity behind the bowing structure continuing to increase in size, with a weak RIN apparent in the trailing flank of the echo at 0.5° (Fig. 13). These features reflect the presence of storm and mesoscale descent, thereby increasing the potential for wind damage due to the production of intense downdrafts. The base reflectivity data also showed a better defined bowing structure with reflectivity values of 55 dBZ or greater detected on the lowest two slices for the first time. Through 0824 UTC, the most interesting evolution of the bow echo structure was evident at 1.5°. At this elevation angle, the weak echo hole, identified directly upwind of the storm's high reflectivity core region, continued to grow from 0814 UTC to 0824 UTC. The storm showed the most noticeable bulge and most intense reflectivity values at this time (Fig. 14). The continued growth of the weak echo hole and forward bulge of the echo is consistent with the conceptual model of the bow echo, and is indicative of an imminent downburst capable of producing wind damage. It was around this time (0825 UTC) that wind damage was indeed reported with this storm.

The circulation identified earlier along the storm's leading edge maintained its intensity through 0814 UTC (Fig. 13). Rotational velocities of 15 m s^{-1} were noted at the lowest two elevation slices. After 0819 UTC, the vortex weakened at the 1.5° slice and exhibited a cyclonic divergent velocity pattern after 0824 UTC (Fig. 14). The magni-

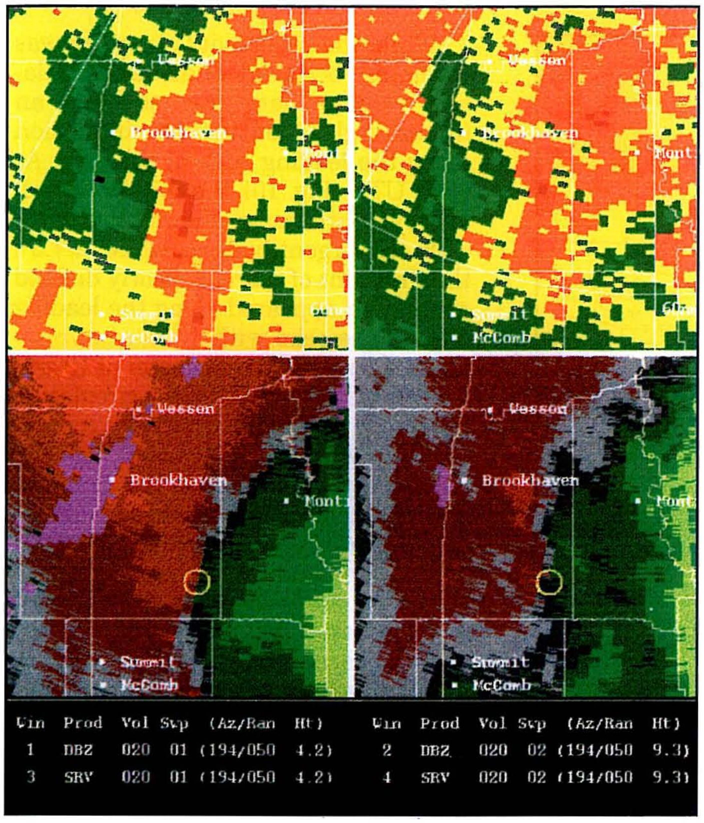

Fig. 8. KJAN WSR-88D 4 panel product valid at 0730 UTC 13 April. Upper left hand corner contains 0.5° base reflectivity, upper right hand corner contains 1.5° base reflectivity, lower left hand corner contains 0.5° storm-relative velocity, and lower right hand corner contains 1.5° storm-relative velocity. Circle on storm-relative velocity products highlights the circulation/shear zone along the leading edge of the cell as detected by the WATADS software.

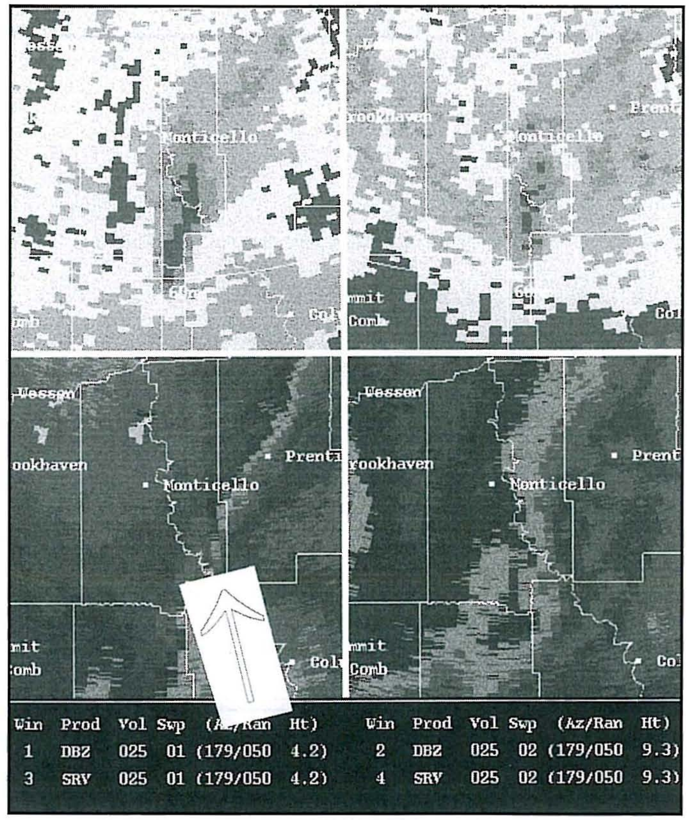

Fig. 9. Same as Fig. 8, only for 0759 UTC 13 April. Arrow on 0.5° storm-relative velocity product highlights the location of the shear zone along the leading edge of the cell.

tude of rotational velocities fell from 15 m s^{-1} to 10 m s^{-1} during this period. At the lowest elevation slice, the velocity structure changed from a cyclonic convergent pattern to one of a shear axis. During this period (0814-0824 UTC), the vortex appeared to play a role in enhancing the downward transport of momentum from the rear of the storm's mid-level region as the weak echo hole expanded in size.

After 0824 UTC, the bow echo began to slowly weaken, with less of a bowing structure apparent and a gradual decrease in reflectivity values. By 0839 UTC, a distinct echo core was no longer apparent on the 2.4° elevation angle reflectivity data, and by 0844 UTC the echo had become indistinct at 1.5°. A similar weakening was noted in storm-relative velocity data, with the circulation at 1.5° quickly becoming indistinct after 0824 UTC. A gradual weakening of the shear zone was also noted at 0.5°. No severe weather was reported with the bow echo after 0825 UTC (0325 CDT) 13 April 1996.

5. Warning Decision Implications

As has been discussed above, the combination of an approaching strong short-wave trough, favorable wind profiles, and an encroaching mid-level dry air intrusion, led to an environment favorable for severe convection and bow echoes over the lower Mississippi Valley region during the early morning of 13 April 1996. This fact was well recog-

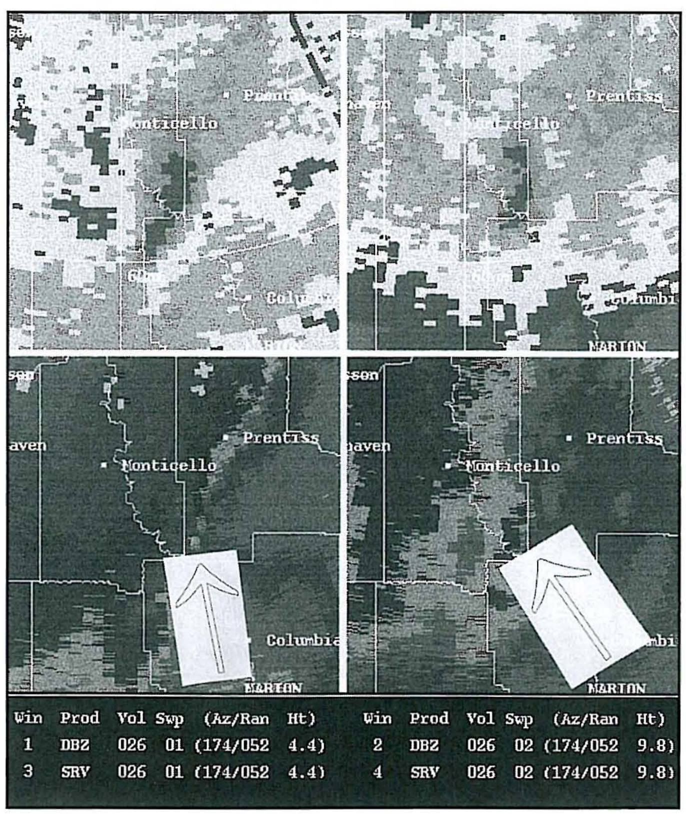

Fig. 10. Same as Fig. 8, only for 0804 UTC 13 April. Arrows on 0.5° and 1.5° storm-relative velocity products highlight the location of the shear zone along the leading edge of the cell.

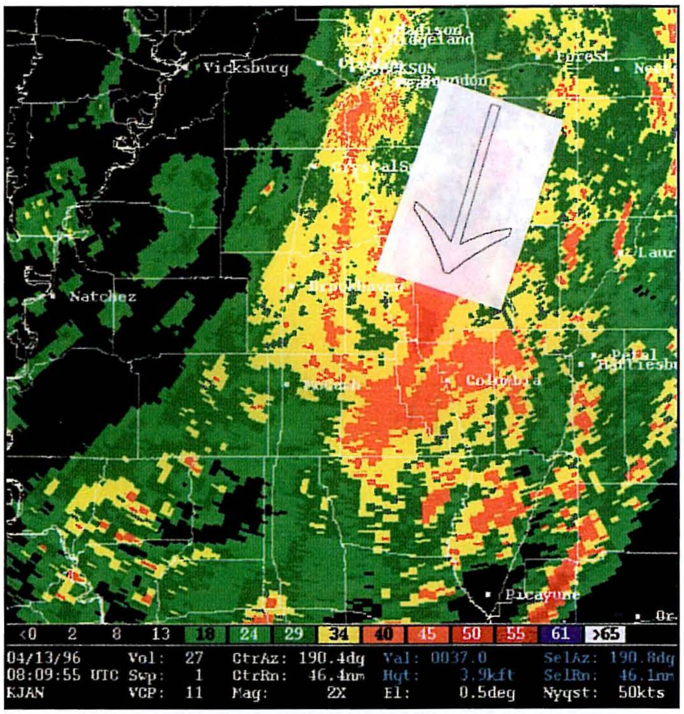

Fig. 11. Same as Fig. 7, only for 0809 UTC 13 April.

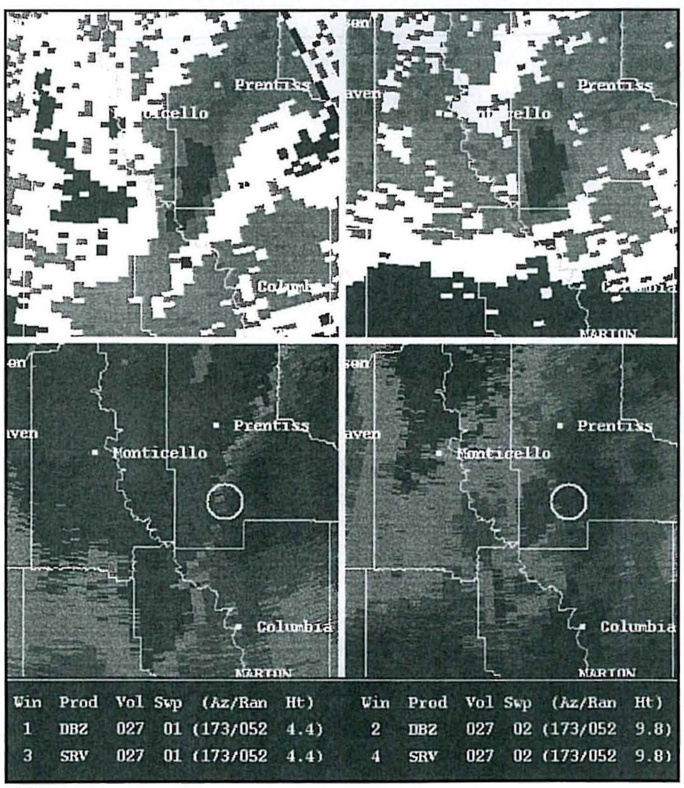

Fig. 12. Same as Fig. 8, only for 0809 UTC 13 April. Circles on storm-relative velocity products highlight the location of a circulation identified as a mesocyclone by the WSR-88D MDA using the default value of 10 for the Threshold Pattern Vector.

nized by forecasters both at local National Weather Service (NWS) offices and at the NOAA/NWS Storm Prediction Center (SPC), who had issued a Tornado Watch for central and southern Mississippi as well as southeast Louisiana valid from 0600 UTC through 1200 UTC.

However, conceptual models of severe convection would indicate that the most significant risk of severe weather would be with the main squall line, with little threat after the passage of the line due to stabilization of the lower levels of the atmosphere due to cooling of the boundary layer through evaporative cooling and convective downdrafts. Even if elevated upright convection developed in the wake of the line, in an area of elevated instability, studies (e.g., Grant 1995) and conceptual models would indicate the most common threat of severe weather would be from large hail. Damaging winds and tornadoes tend to be limited in such storms as the presence of a cool, moist boundary layer keeps the storm from being "rooted" in the boundary layer. Hence, the initial stages of bow echo development as outlined above might be overlooked by a warning meteorologist who would likely be focused on the main squall line, especially when one considers the rare nature of an event such as this.

Warning decisions were further complicated by the low topped nature of the bow echo. Algorithm derived echo tops from the WSR-88D Algorithm Testing and Display System (WATADS; National Severe Storms Laboratory 1997) software were consistently below 7 km, with manual identification of the tops never exceeding 9 km. Furthermore, Vertically Integrated Liquid (VIL) values, both cell-based and grid-based, never exceeded 25 kg m^{-2}. Johns (1993) and Pfost and Gerard (1997) have suggested that low topped convection and low VIL values are not uncommon in "dynamic" bow echo cases. Hence, the three-dimensional reflectivity structure is a more important factor in making warning decisions than reflectivity at one elevation or VIL values. In this particular case, the reflectivity structure of the convection clearly identified it as a bow echo, with classic features such as RIN's and weak echo holes.It should be noted that the difficulty in warning for low topped events such as this are made even greater when the convection is further from the radar. In this event, the echo was generally around 90 km from the RDA, and some detail in the lower levels of the storm was able to be discerned. At a greater distance from the RDA (e.g., 100 nm or 180 km), at the 0.5° elevation angle the radar beam would be at a height of approximately 10 K ft, making any detailed examination of the low levels of the storm impossible, and thereby making any warning decision based solely on radar extremely difficult.

The presence of the low-level shear axis along the leading edge of the bow echo is a common feature of bow echoes as described by Przybylinski (1995). The WSR-88D Mesocyclone Detection Algorithm (MDA; Stumpf and Marzban 1995) might have helped draw the attention of a radar operator to this feature. During the 0809 UTC volume scan, the MDA indicated a mesocyclone with the bow echo (Fig. 12). Furthermore, lowering the MDA's Threshold Pattern Vector number to the optimal value of 7 as discussed by Margraf et al. (1997) would have yielded a second detection of a mesocyclone on the 0814 UTC volume scan (Fig. 13). Although it did not indicate a mesocyclone after this time or at the time of damage, the alarm associated with the mesocyclone would have helped focus attention on the storm, leading to fur-

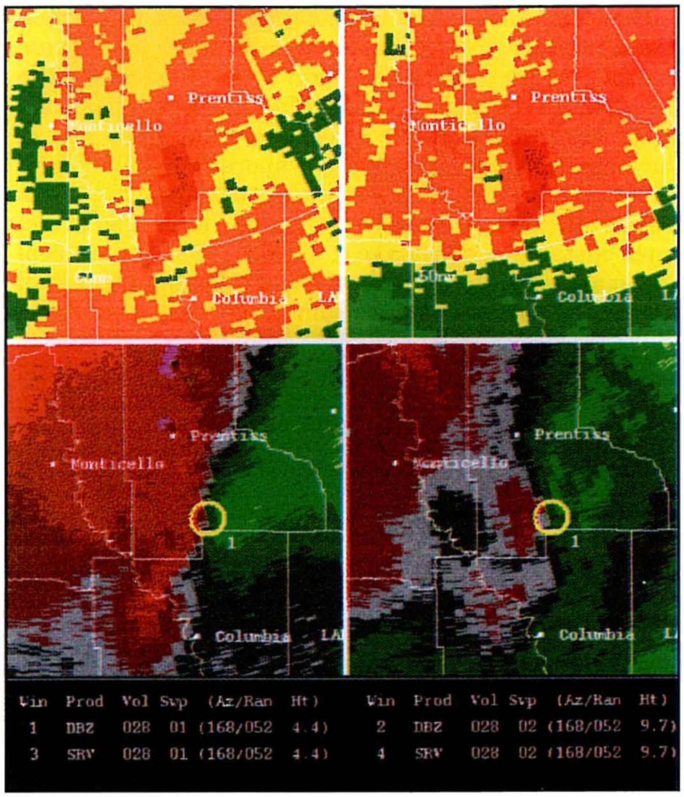

Fig. 13. Same as Fig.8, only for 0814 UTC 13 April. Circle on storm-relative velocity products highlight the location of a circulation identified as a mesocyclone by the WSR-88D MDA using a Threshold Pattern Vector value of 7.

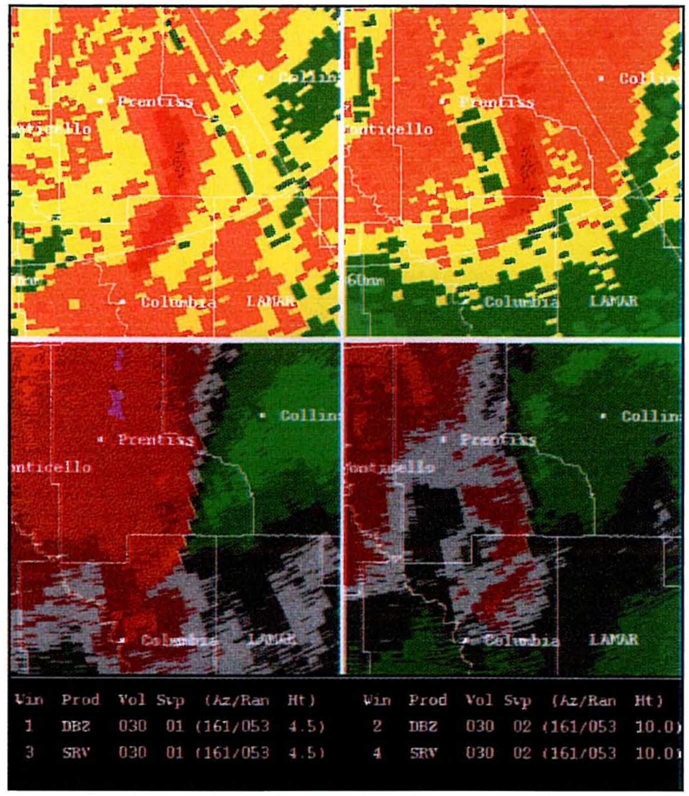

Fig. 14. Same as Fig. 8, only for 0824 UTC 13 April.

ther investigation of the bow echo. In fact, during this event at the NEXRAD Weather Service Forecast Office (NWSFO) in Jackson, the triggering of the mesocyclone alarm helped draw the warning forecaster's attention to this storm, and after further radar analysis a warning was issued with 9 minutes of lead time.

However, it should be stressed that algorithms only offer guidance, and are not a replacement for continuous, vigorous interrogation of the radar data. This is particularly true in a low topped event such as this when the algorithm may have difficulty in identifying mesocyclones. It should also be noted that base velocity products would be of little use in detecting strong straight-line winds during this event, due to the fact that any such wind maxima would have been oriented perpendicular to the radar beam, thereby giving a very small component of the wind toward or away from the radar.

Once a bow echo structure was identified, the decision on whether or not to issue a warning would partially rest on the determination of whether damaging winds would, in fact, reach the ground in spite of the presence of the cool and moist boundary layer left by the passage of the squall line. As can be seen in Fig. 4, the low-level inversion does not appear particularly strong, although the boundary layer is certainly conditionally stable. However, it should also be noted that the RUC low-level winds on this sounding were not consistent with observations, as surface data valid for this time indicated that the outflow boundary associated with the squall line had caused winds to shift to the northwest in this area, while the RUC still showed southwesterly winds. This suggests that a deeper stable layer than the RUC suggested might have existed at the time of the bow echo.

6. Conclusion

Even with high temporal resolution model data sets such as the RUC, it would have been difficult in real time to determine the depth of the cool and moist boundary layer in the vicinity of Bassfield at the time of the damage. In the end, the warning decision rests on the warning meteorologist's interpretation of radar data and knowledge of 3-dimensional storm structure. Waiting for damage reports in this event would have resulted in a negative lead time. Furthermore, with the storm occurring in rural Mississippi at 0325 local time, the probability of receiving real-time damage reports is small. The bowing reflectivity structure with an expanding RIN, identification of an intensifying circulation along the system's leading edge, and MDA algorithm output of a mesocyclone were critical features and signals of a severe thunderstorm. Warning forecasters need to be cognizant of these features during warning situations.

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