3A.4

ANALYSIS OF A TEXAS TORNADO OUTBREAK INVOLVING THREE MODALITIES OF ENHANCED TORNADOGENESIS

Lon Curtis
KWTX-TV
Waco, Texas

A cold front moved southward across Oklahoma and into northern Texas on Mar. 29, 2002, becoming quasi-stationary across southern portions of north central Texas as surface pressures fell across southwest and west Texas ahead of a tightly-wound mid- and upper-level low. Increasingly warm, moist, and unstable air pooled south of the surface front in Texas. These features set the stage for an outbreak of 23 tornadoes over Texas on Mar. 30th. The tornadoes occurred in three distinct clusters or zones (Fig. 1) and post-event analysis suggests that tornadogenesis was enhanced by distinct factors in each zone.

I. INTRODUCTION

Objectively analyzed upper air data at 12 UTC on the 30th (Fig. 2) found the system approaching from west Texas with the 850 mb and 700 mb centers vertically stacked near Midland, while the 500 mb and 250 mb centers were still to the west near Guadalupe Pass. A strongly diffluent mid- and upper-level flow was depicted downstream over central and eastern Texas, enhanced by a 95 knot subtropical jet stream feature just south of Brownsville, and a >150 knot jet in the polar jet stream over the Great Lakes.

At 12 UTC surface analysis (Fig. 3) found the quasi-stationary front along a line from just north of Shreveport (SHV) to near Waco (ACT) to southwest of San Angelo (SJT), where it was anchored by a surface low. A dryline was located southward from the low to near Del Rio (DRT). West of the surface low the front was diffuse, but appeared to lie near a line south of Fort Stockton to north of Marfa. A boundary separating northwesterly flow from northeasterly flow ran from San Angelo to Hobbs.

An overnight squall line was decelerating while approaching Austin (AUS) and San Antonio (SAT), with the flow west of it temporarily disrupted and erratic. Strengthening outflow from an on-going convective mass over the Red River Valley of Texas and Oklahoma, eastward into Arkansas, was reinforcing the front over northeast and north central Texas.

Corresponding author address: Lon Curtis, KWTX-TV, P.O. Box 2636, Waco, TX 76702-2636; email: lon.curtis@kwtx.com

The 13 UTC Storm Prediction Center (hereafter, SPC) Day-1 outlook placed a moderate risk of severe thunderstorms over parts of central and eastern Texas, as well as northern and central Louisiana, southern Arkansas, and most of northern and central Mississippi, citing the stalled front across central Texas into the southern Appalachians as a focus for widespread thunderstorms. The upper low over western Texas was expected to move eastward across northern Texas into northern Louisiana by evening, inducing a low pressure wave along the stalled front tracking from southeast Texas into northern Mississippi during the overnight hours.

The SPC forecaster also noted that the ETA model was indicating the possibility of a triple-point developing with a surface low between Houston (HOU) and San Antonio (SAT) during the afternoon, although the models differed on the location of the surface low. The airmass south of the stalled front was expected to become very unstable (MLCAPE of 2000-3000 J kg^{-1}), and a coupled jet structure was expected to evolve from southeast Texas into Mississippi toward evening.

In the ensuing 14 hours, 23 tornadoes occurred in Texas, including two with damage rated F3 and path lengths of 30 to 50 miles and one producing damage rated F2[1]. The first tornadoes developed before 19 UTC southeast of Waco and north of College Station (CLL) in association with the quasi-stationary front. Storms near this front continued to produce isolated tornadoes until well after sunset.

2. EVENT OVERVIEW

The surface analysis at 1500 UTC (Fig. 4) found low pressure just northwest of San Angelo

[1] All F-scale references are to Fujita, 1981.

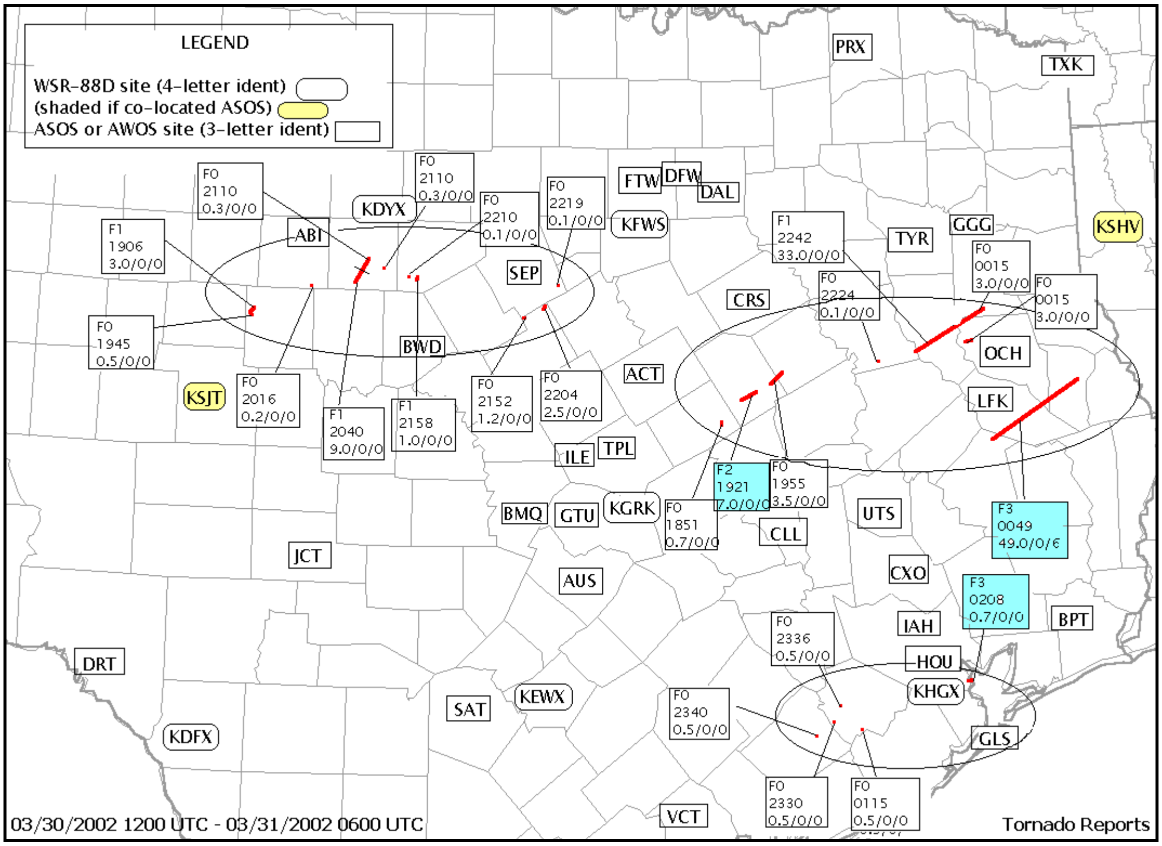

Fig. 1. Map showing location of tornadoes on Mar. 30, 2002, selected WSR-88D sites, and selected ASOS and AWOS stations.

with a dryline southward to east of Del Rio, the quasi-stationary front extending eastward near a Temple (TPL)-Palestine-Shreveport (SHV) line, and a poorly-defined warm front surging inland from the Texas coast to near a Burnet (BMQ)-Austin-College Station line. That boundary separated dewpoints in the low 60s from dewpoints near 70. Surface observations and radar data indicated a non-severe squall line moving west to east across the eastern Texas Hill Country into central Texas near a Waco-Austin-San Antonio line. Rain and thunderstorms covered northeastern Texas, eastern Oklahoma and much of Arkansas. Cooling associated with this broad area of precipitation continued to reinforce the baroclinic boundary that defined the quasi-stationary front in northeast Texas and Louisiana.

By 1800 UTC, a surface low was analyzed between San Angelo and Abilene (ABI) (Fig. 5). A cold front stretched southwestward to near Fort Stockton. A dryline feature stretched southward to east of Junction (JCT) and Hondo (HDO). A surface trough stretched southeast to a developing secondary low northwest of Burnet. The quasi-stationary front was draped across the area east and southeast of the primary low to north of Temple and eastward to near Nacogdoches (OCH). The dryline was somewhat diffuse from the secondary low southward to near San Antonio.

Objective analysis (not shown) indicated strong surface convergence in the warm sector east and southeast of the secondary low, as well as with the primary low between San Angelo and Abilene. Composite radar data revealed a large area of rain and imbedded thunderstorms over the Texas South Plains and northern Permian Basin, and over portions of Oklahoma, Arkansas and northern Louisiana. Several strong thunderstorm cells were developing west and southwest of Waco to northeast of Austin, ahead of the secondary surface low northwest of Burnet. At 1807 UTC SPC issued a Tornado Watch (#57) for a large portion of central and eastern Texas effective at 1830 UTC. A severe storm moved over KGRK and continued to the northeast, spawning the first tornado of the day near Reagan in Falls County before 1850 UTC. The same system produced a tornado near Thornton in Limestone County shortly after 1915 UTC, which produced damage rated F2. The same storm produced a weak tornado on the Limestone-Freestone county line shortly before 20 UTC.

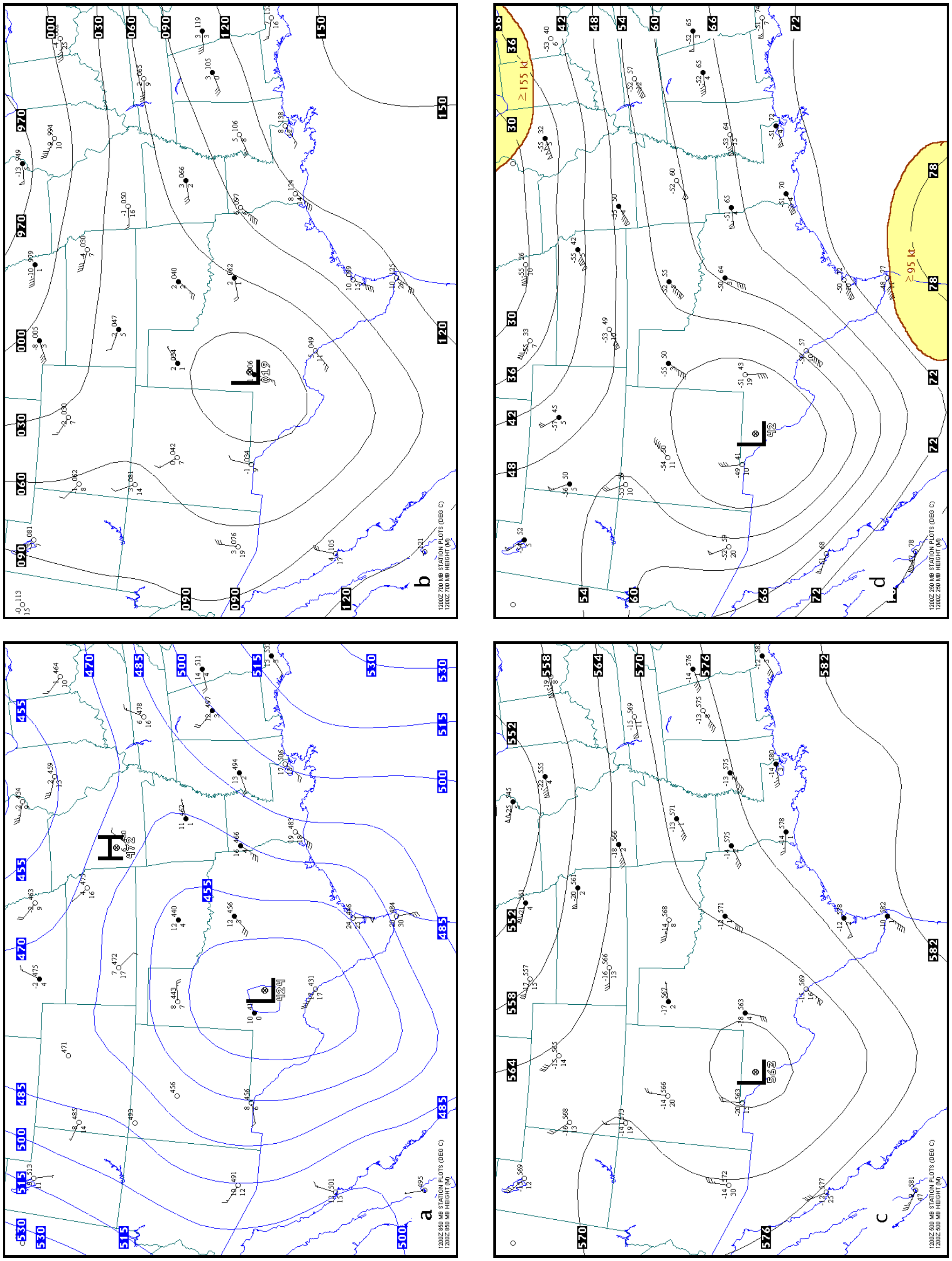

Fig. 2. Upper air analyses (objectively analyzed) at 12 UTC on Mar. 30, 2002. Analyses are as follows: (a) 850 mb; (b) 700 mb; (c) 500 mb; (d) 250 mb (includes isotachs of maximum winds only).

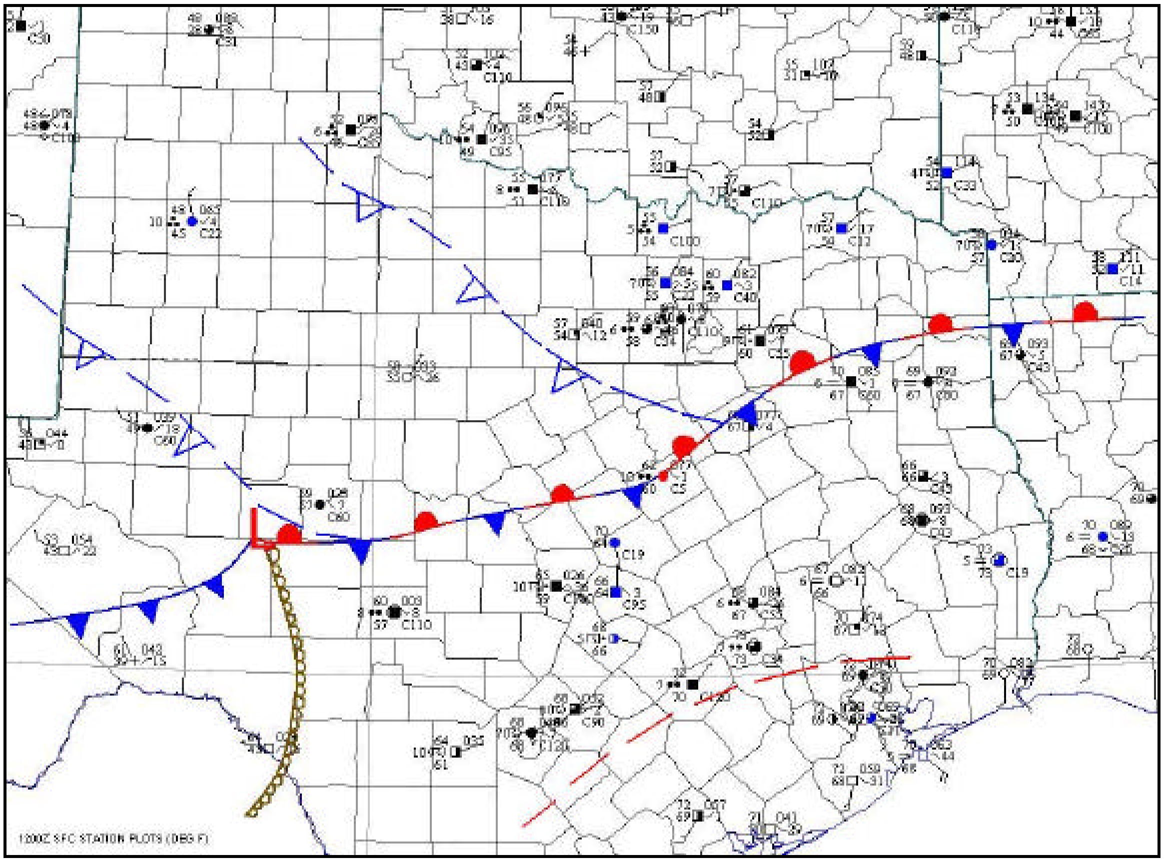

Fig. 3. Surface analysis at 12 UTC Mar. 30,2002.

The storm ceased tornado production as it crossed Freestone County (perhaps as a result of moving well north of the surface boundary), but additional severe convection continued developing across portions of Robertson, Leon and Madison counties. These cells moved to the northeast and produced at least three tornadoes in Anderson, Cherokee, Rusk and Nacogdoches counties between 2200 and 0000 UTC.

At 1842 UTC, SPC issued a Tornado Watch (#58) for a large portion of north central and northeastern Texas, citing an increasing threat of severe storms and a few tornadoes in areas west and southwest of Fort Worth. Almost simultaneous with the development of the tornadic storms southeast of Waco, other tornadic cells evolved between San Angelo and Abilene. These storms developed in proximity to the original surface low as the dry slot just ahead of the midlevel vorticity center produced erosion of the mid- and upper-level clouds, permitting strong surface insolation and rapid destabilization of the lower atmosphere.

By 21 UTC, surface analysis indicated a rapidly evolving situation. Although a cyclonic circulation center was still present near Abilene, the primary low appeared to have redeveloped into the area west of Waco, with a complex array of boundaries shown on the map (Fig. 6). Although the circulation remained, the low that had been between Abilene and San Angelo was obviously filling. There was also a suggestion of a developing subsynoptic low near LaGrange (southeast of Austin) along the bulging dryline that stretched from the low west of Waco to La Grange to west of Victoria (VCT). The quasi-stationary boundary stretched from the low west of Waco along a line north of Temple to near Nacogdoches.

The area of storms east and southeast of Abilene continued to produce an occasional tornado, while tornadogenesis in the storms east and southeast of Waco was in a temporary lull. SPC issued a Mesoscale Discussion (MD) for north central through east central Texas indicating that severe storms with isolated tornadoes would persist for several more hours. The MD mentioned that a surface low was located near Fort Hood with an arcing boundary from just southwest of Abilene to the surface low to just east of Austin. The discussion noted that low clouds had mixed out of the area in the dry slot region north and east of the arcing boundary southeast of Abilene, with MLCAPES around 1500 J kg^{-1} , noting that the flow north of the surface low continued to be backed.

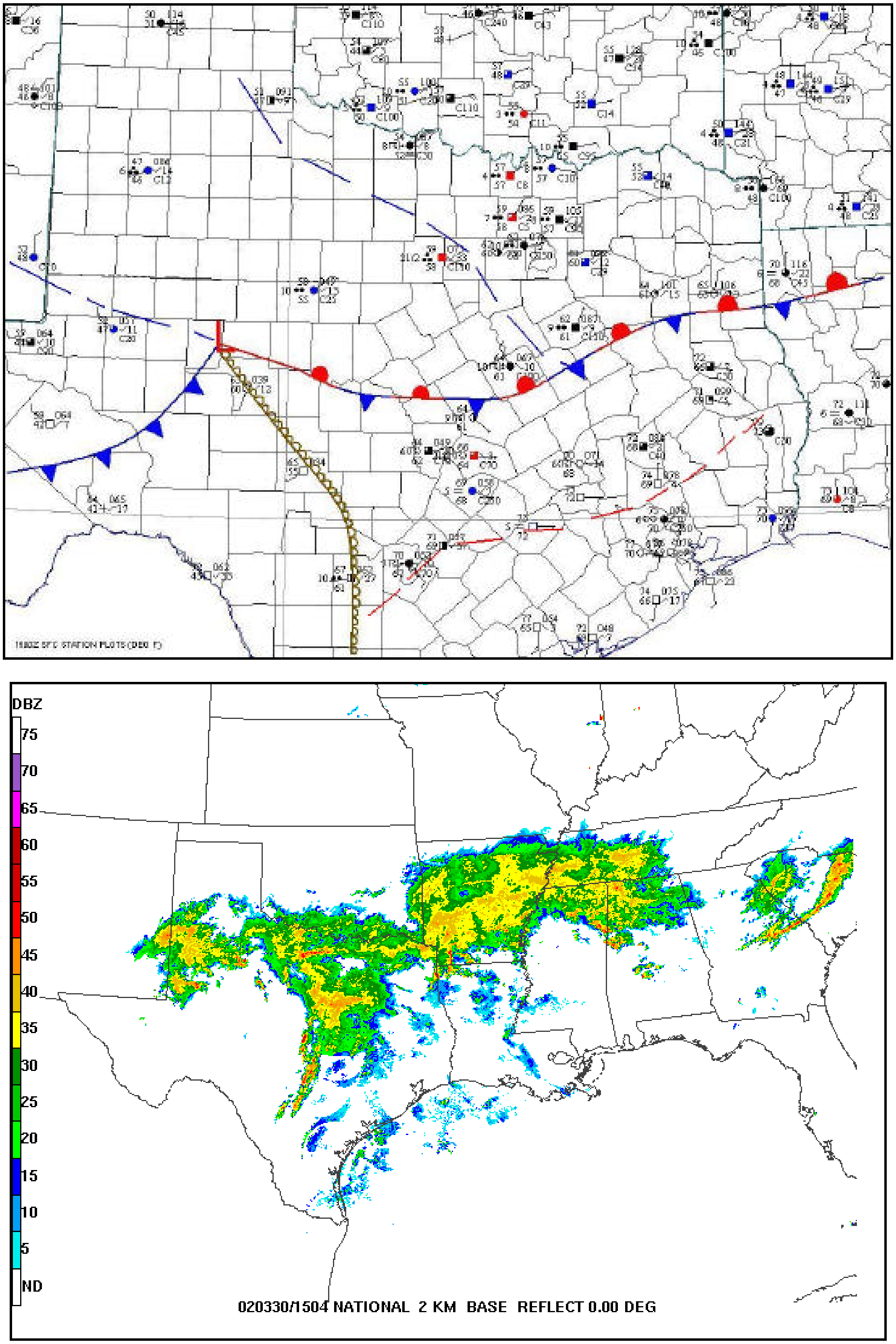

Fig. 4. Surface analysis (top) and NEXRAD 2 km 0.5° base reflectivity mosaic (bottom) at 15 UTC.

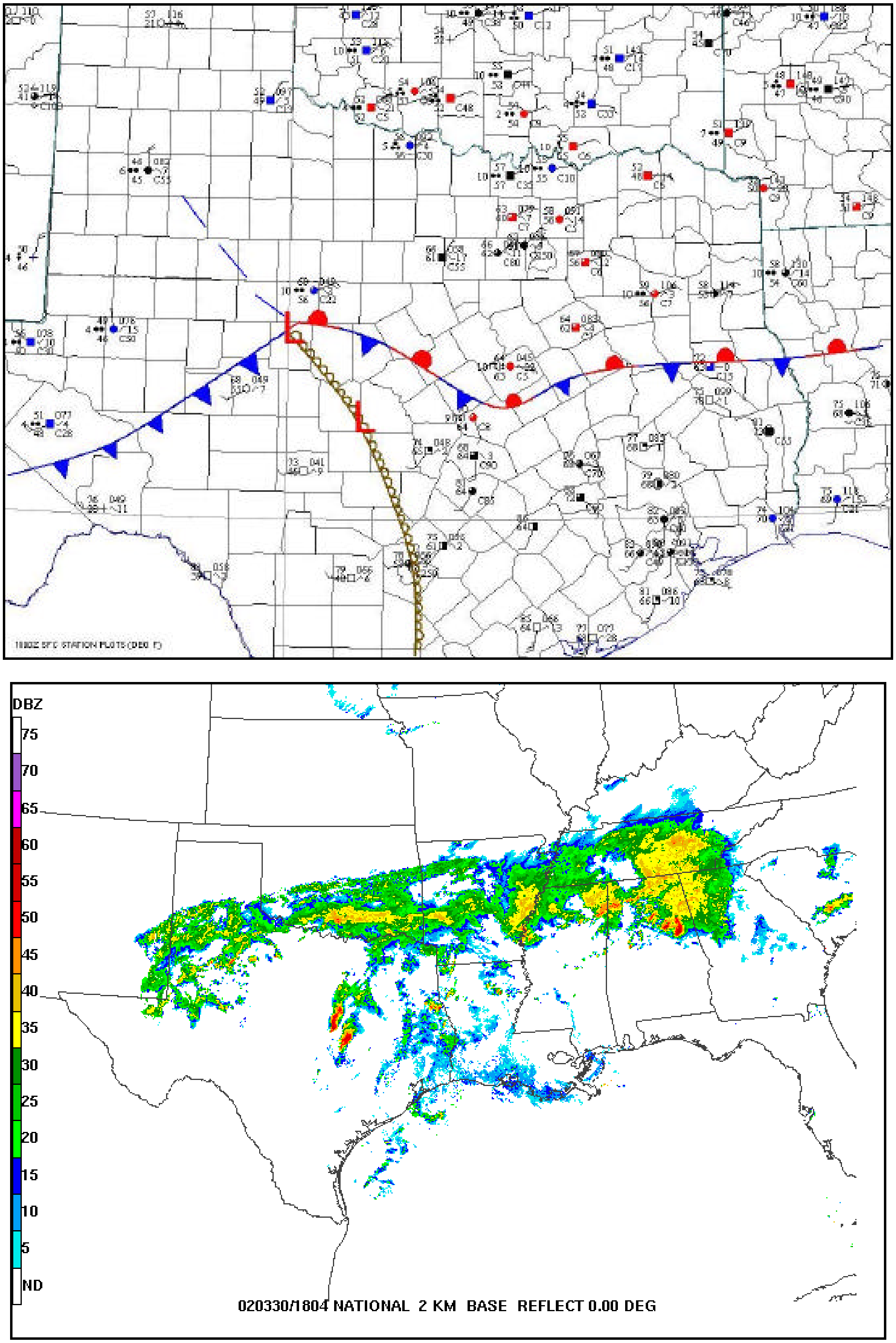

Fig. 5. Surface analysis (top) and NEXRAD 2 km 0.5° base reflectivity mosaic (bottom) at 18 UTC.

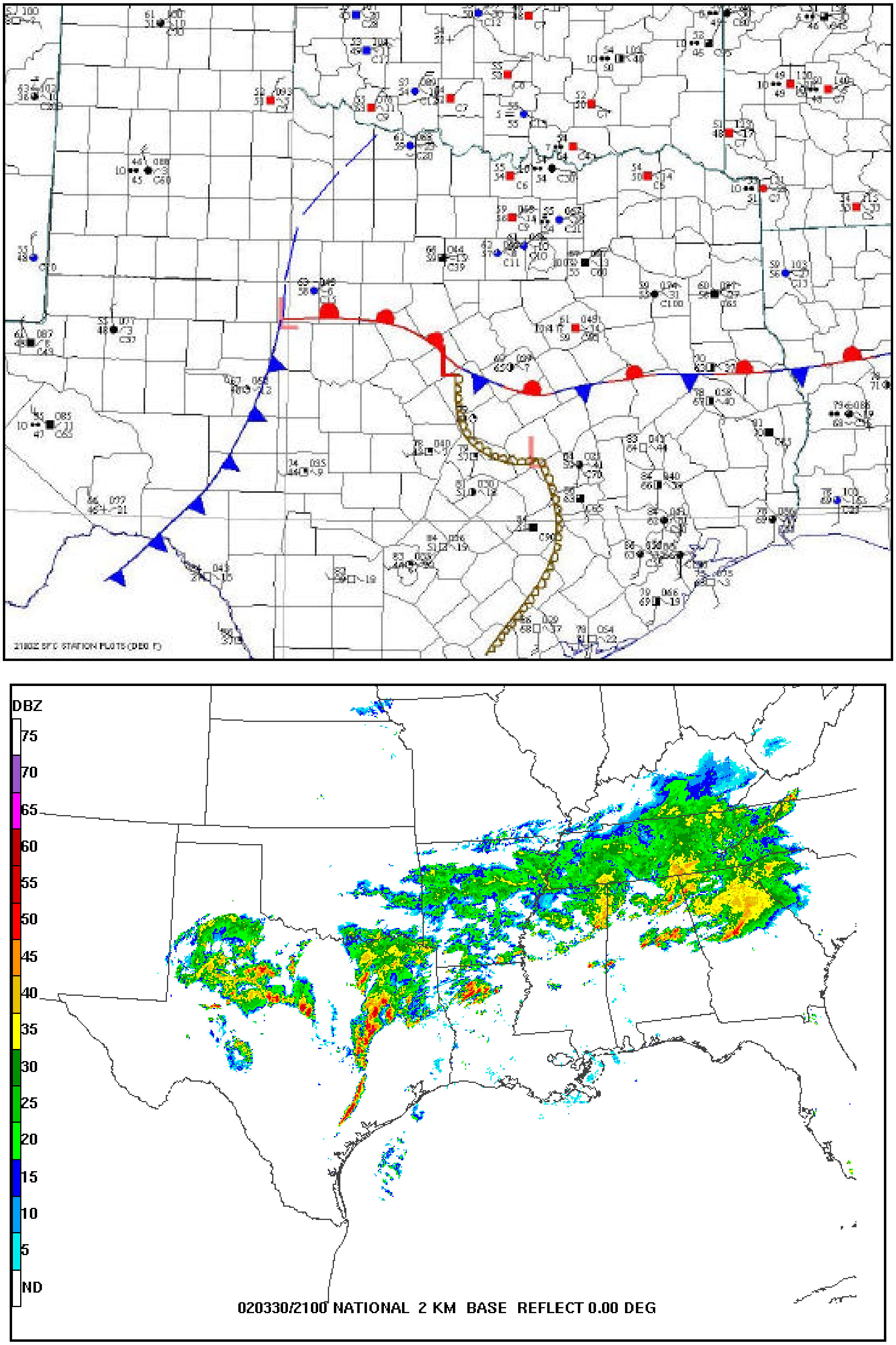

Fig. 6. Surface analysis (top) and NEXRAD 2 km 0.5° base reflectivity mosaic (bottom) at 21 UTC.

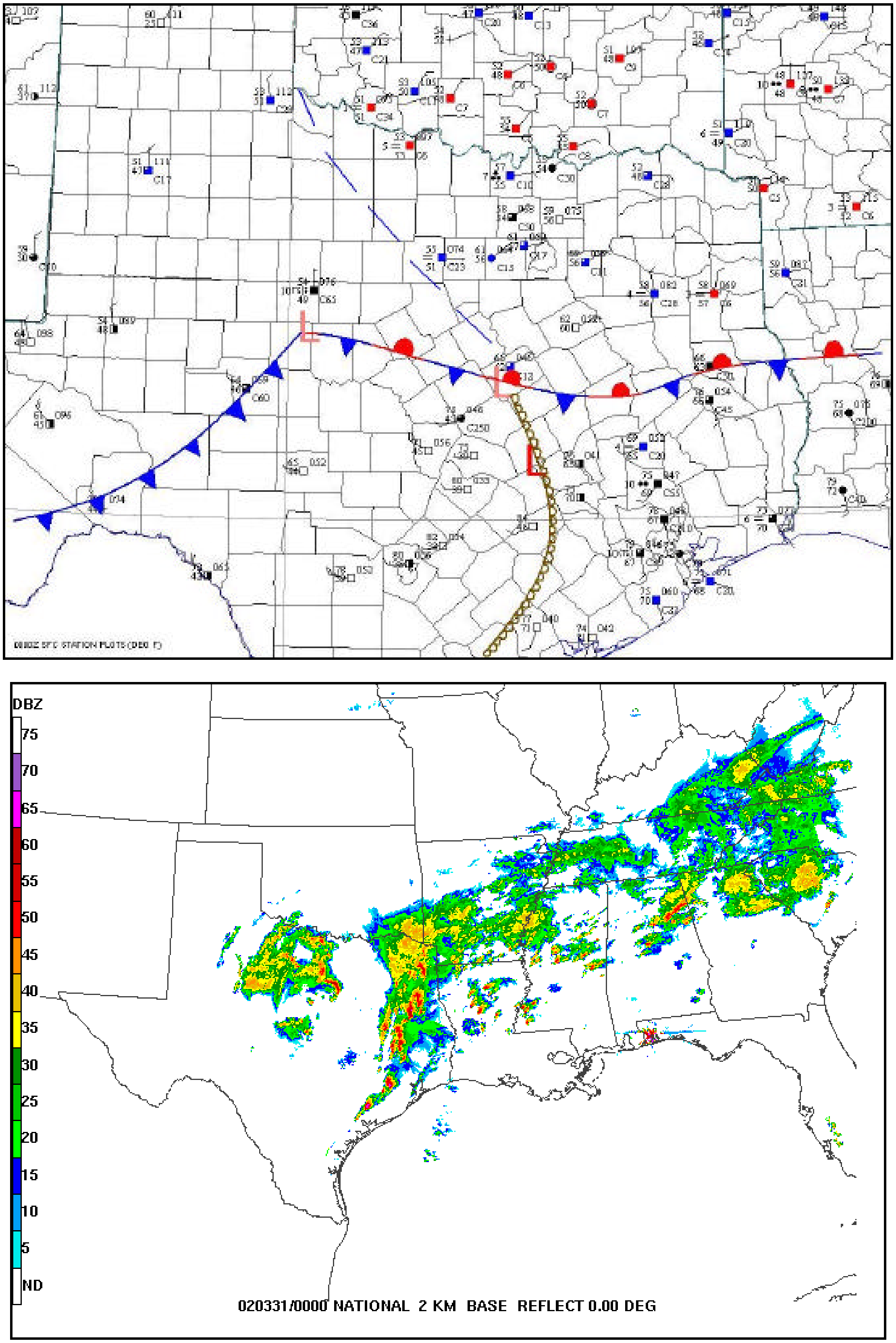

Fig. 7. Surface analysis (top) and NEXRAD 2 km 0.5° base reflectivity mosaic (bottom) at 00 UTC.

SPC issued a new Tornado Watch (#60) for portions of eastern Texas and central and northern Louisiana (#59) shortly after 23 UTC, replacing the original watch (#57). The discussion issued with the watch noted that a broken line of intense supercell storms extended from west of Houston to west of Shreveport, with the activity expected to develop eastward through the evening hours in the vicinity of the surface baroclinic zone. The discussion also mentioned that strong instability and increasing low-level vertical shear profiles would sustain the potential for tornadoes as well as very large hail.

By 00 UTC, surface analysis (Fig. 7) indicated the occluding surface low just southwest of Abilene, another occluding low just southwest of Waco, and a primary low center developing west of College Station along the dryline that stretched from near Waco to east of LaGrange to west of Victoria. The quasi-stationary boundary was located from the occluding low near Abilene to the occluding low near Waco, then eastward to near Nacogdoches, and on eastward into central Louisiana.

Well to the east of Waco, tornado production resumed between 22 and 23 UTC and five tornadoes occurred in the area between the Trinity and Sabine rivers before 02 UTC, including two long-track tornadoes. One of these developed around 2242 UTC and produced damage rated F1 as it crossed Cherokee County. This tornado had a path length of 33 miles. Another long-track storm developed a little before 01 UTC in Polk County and crossed portions of Angelina and Nacogdoches counties, before terminating in San Augustine County. The damage from this tornado was rated F3, the maximum path width was 440 yards and the path length was 49 miles. Six persons were injured by this tornado.

Intense thunderstorm development was also underway between 21 and 00 UTC in the area between Houston and Victoria. Most of this area was covered by a Severe Thunderstorm Watch issued earlier in the afternoon, but Tornado Watch #60 extended as far south as Harris County (the greater Houston area). The intense storms produced several weak, brief tornadoes between 2330 and 0115 UTC in Fort Bend and Wharton counties, southwest of Houston.

Shortly after 02 UTC, the same intense storm system produced a tornado about 3 miles south of La Porte (very close to KHGX), on the northwest shoreline of Galveston Bay. Although producing a track less than 1 mile in length, and having a path width of ~60 yards, the tornado produced F3 damage. Soon after 02 UTC, SPC issued a new tornado watch for portions of southeastern Texas and southern and central Louisiana, as well as adjacent coastal waters, replacing Tornado Watch #60. However, there were no additional tornadoes reported through the evening and overnight hours.

3. SATELLITE AND RADAR IMAGERY

As previously noted, a dry slot developed ahead of the eastward moving mid-level circulation over portions of west central Texas by around 18 UTC. The evolution of this feature is seen in Fig. 8 from 1745 UTC. Pronounced surface insolation produced an extensive deep convective response in an arc northwest through northeast of San Angelo. (Refer to Figs. 5 and 6 for surface analyses and radar imagery corresponding to 18 UTC and 21 UTC respectively.) Figure 8 also shows the intense convection developing near and southeast of Waco around 18 UTC.

As previously shown (Fig. 2), tornadoes occurred in three distinct and relatively widely separated areas. As noted heretofore, tornadogenesis evolved more or less simultaneously in the area east and southeast of Waco and in the area from San Angelo northeastward. Different mechanisms appear to have been involved in promoting or enhancing tornadogenesis in these two areas.

An examination of the tornadic storms north and northeast of San Angelo is undertaken first. Eleven tornadoes occurred in the area extending from ~40 miles northeast of San Angelo east and northeast to ~50 miles southwest of Fort Worth between ~19 UTC and 2230 UTC. Four tornadoes produced damage rated F1. All others produced F0 damage. The thunderstorms that produced these tornadoes appear to have developed just south of the slowly-retreating boundary that extended eastward from the surface low that was between San Angelo and Abilene from ~15 UTC to ~21 UTC. During this period, the boundary lifted slowly northward as a warm front.

WSR-88D Level III data from San Angelo (KSJT) and from Fort Worth (KFWS) was examined for details of the western portion of the outbreak (see Figure 9). The portion of the outbreak east and southeast of Waco fell within the coverage of KGRK and the continuation of that activity eastward into deep eastern Texas was within the coverage of KSHV and KPOE (not shown on Fig. 1, but located at Fort Polk, LA, south of Shreveport and north of Lake Charles). Finally, the portion of the outbreak near Houston was within the coverage of KHGX, and the tornado that produced F3 damage at La Porte occurred within 10 miles of the radar site.

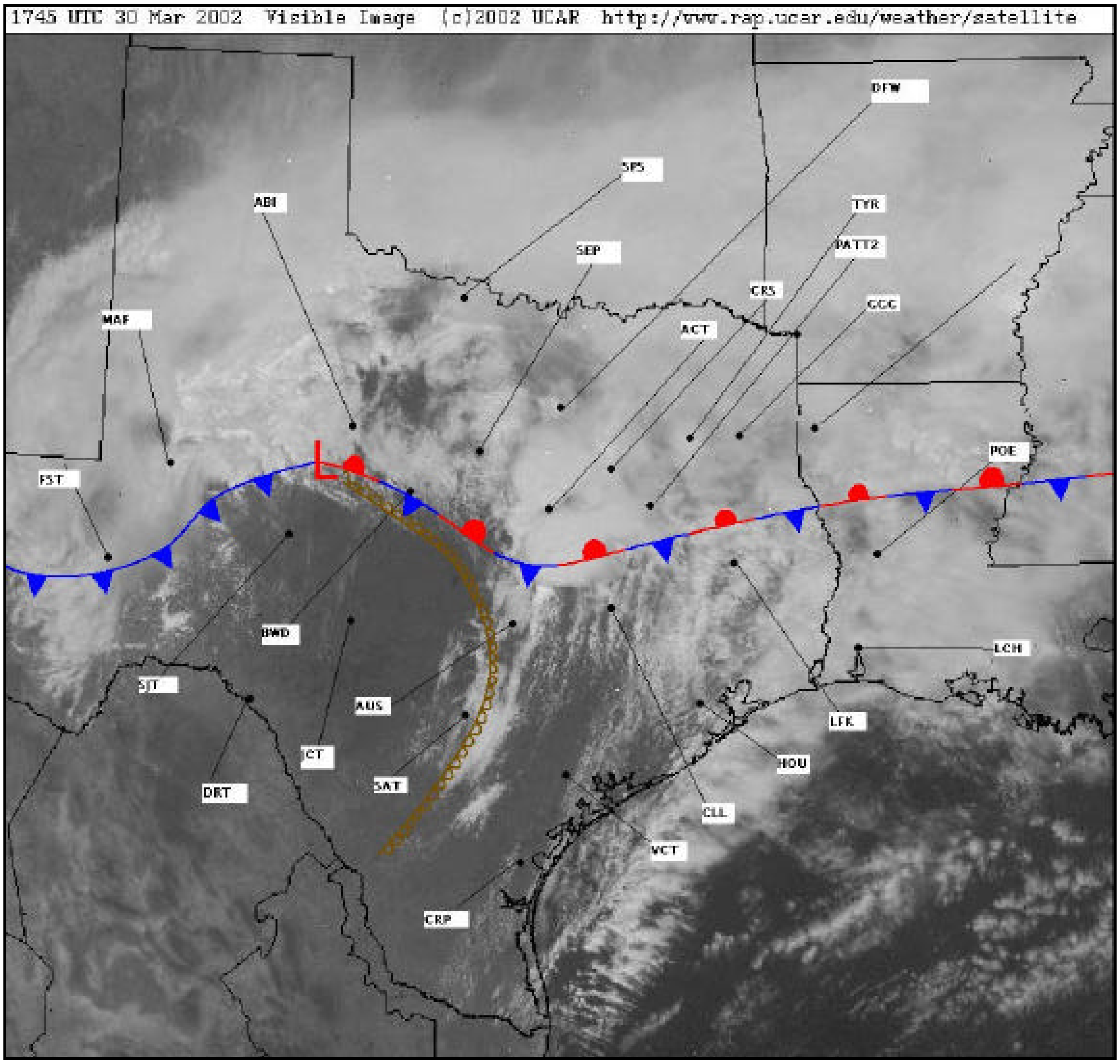

Fig. 8. Visible satellite image from eastern GOES at 1745 UTC on Mar. 30, 2002 annotated with the location of features from 18 UTC surface analysis (see Fig. 5). (Image used with permission of UCAR. © 2002)

All storms that produced tornadoes were examined using the Level III data displayed on Digital Atmosphere Work Station.[2] Selected images of storms over the area between San Angelo and Fort Worth are presented in Figure 9. Selected images of storms over the area east and southeast of Waco are presented in Figure 10. Selected images of the storms over deep eastern Texas are presented in Figure 11. Two of the storms north and northeast of San Angelo developed tornadoes that produced damage rated F1. Shortly after 19 UTC, a storm developing over northwest Runnels County (Fig. 9a) produced a tornado that had a path 3 miles in length. Two stronger cells just to the west of the Runnels County storm did not produce documented tornadoes. The middle storm did have a low-level mesocyclone at the time of this image, and the left-most cell of the three appears to have a pendant formation on its southwest corner. Note the presence of several fine-line boundaries in the image. Surface observations on the hour are plotted where available.

Within the hour, a new storm developed over the same area of northwestern Runnels

[2] Digital Atmosphere Work Station, © 2004, Weather Graphics Technologies.

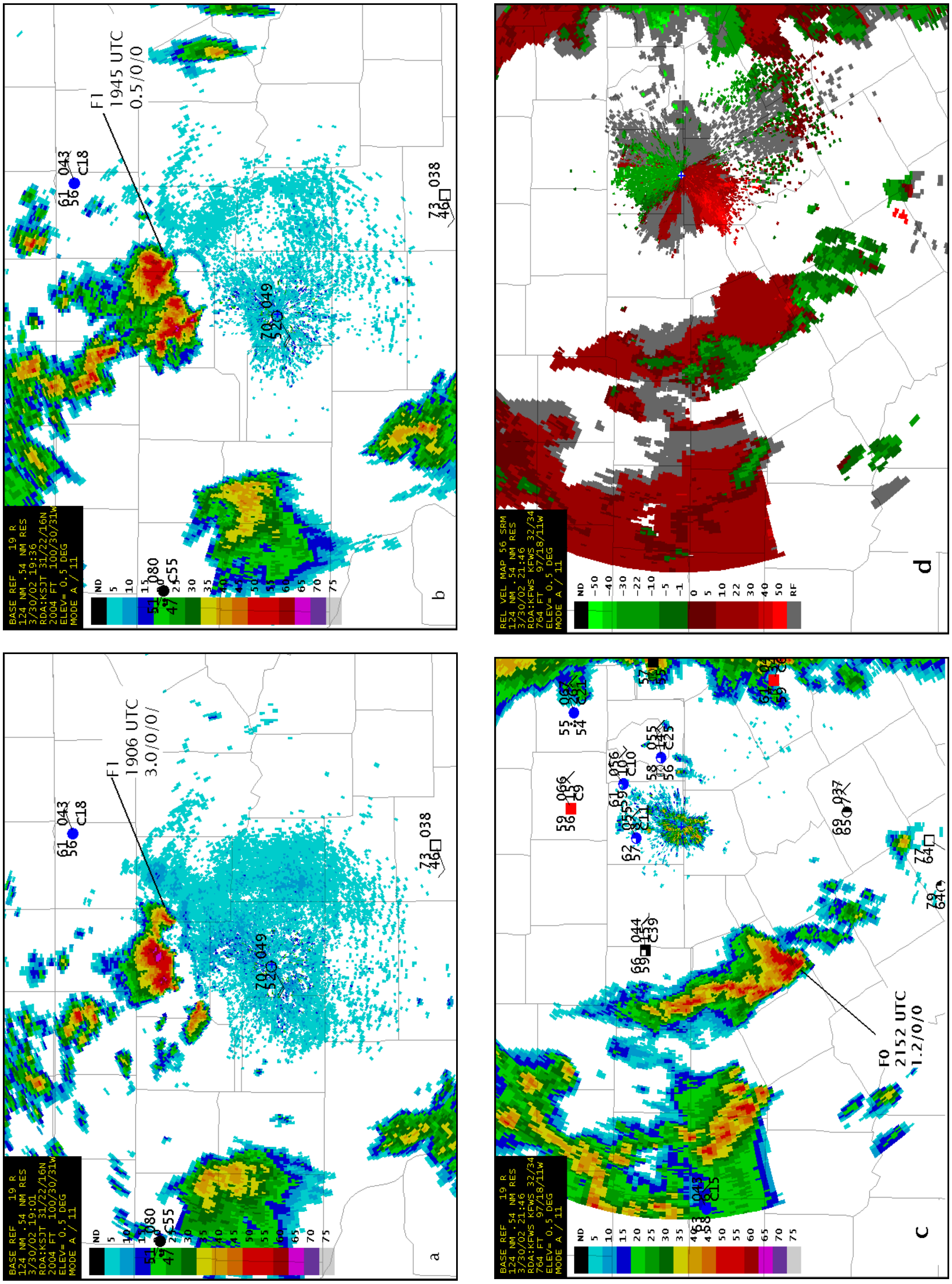

Fig. 9. 0.5° base reflectivity from KSJT for (a) 1901 UTC and (b) 1936 UTC; (c) 0.5° base reflectivity and (d) 0.5° storm-relative velocity from KFWS for 2146 UTC on Mar. 30, 2002.

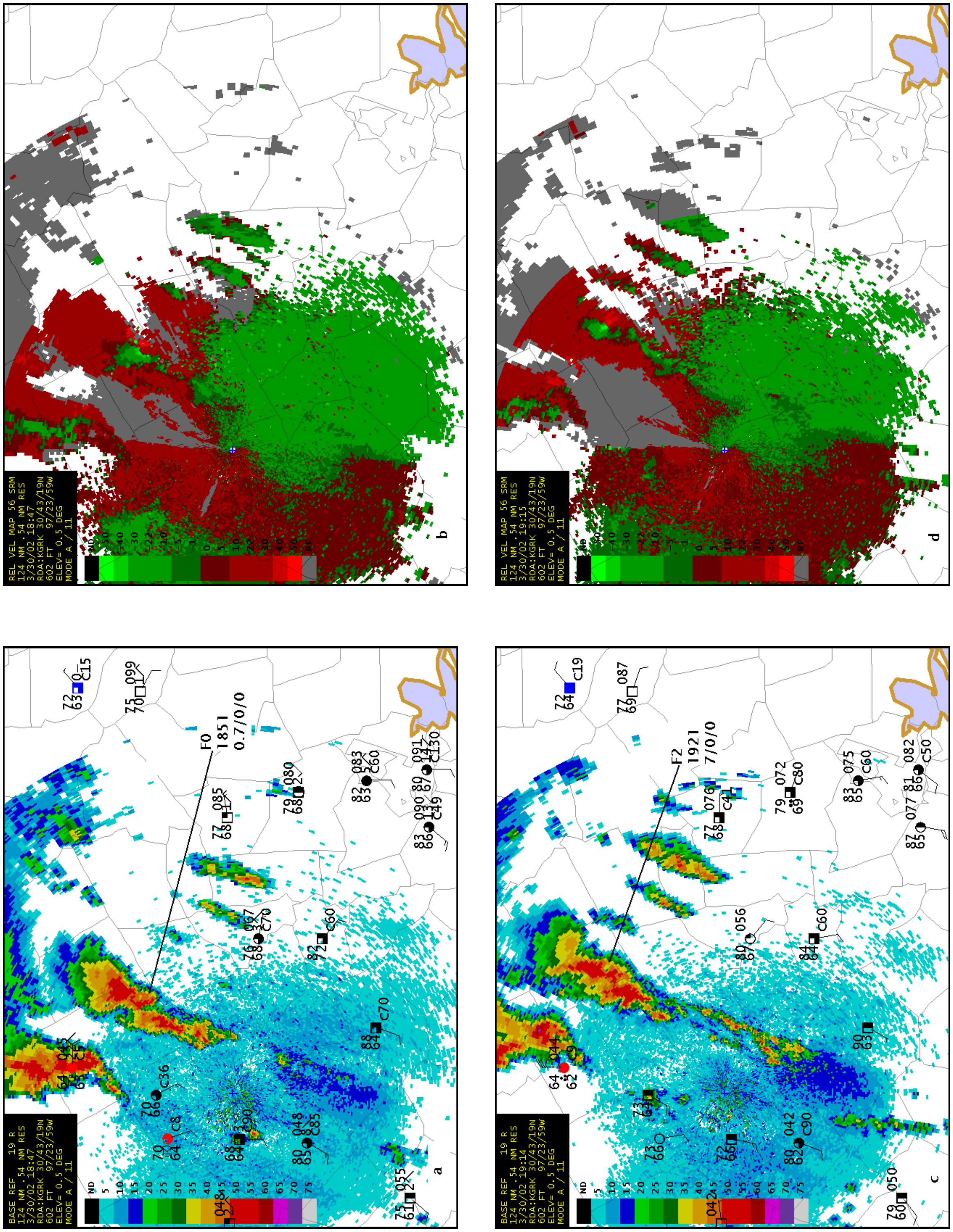

Fig. 10. (a) KGRK 0.5° base reflectivity and storm-relative velocity (a) and (b) at 1847 UTC; and the same respectively (c) and (d) at 1915 UTC.

County (Fig. 9b) and developed a tornado that produced F1 damage and had a path length of 0.5 miles. Note the fine-line boundary wrapping into the cell that produced the tornado within minutes of this scan. Surface observations are from 19 UTC. The storm-relative product from KSJT (not shown) does not reveal a mesocyclone at the 0.5º tilt but the automated algorithm did detect the presence of a mesocyclone with this storm.

Two other tornadoes northeast of San Angelo produced damage rated F1 (as shown in Fig. 1) but these occurred at a greater distance from the radar site and no conclusions could be drawn regarding the thunderstorms that produced those tornadoes. These storms occurred not far from the KDYX nexrad site, but the KDYX Level III archive contained no data for the applicable time period and there was no Level II archive at NCDC because KDYX was (and is) a Dept. of Defense unit that did not archive Level II data.

Additional thunderstorms developed eastward toward Stephenville after 2130 UTC along or south of the same boundary. Several tornadoes occurred with damage rated F0. Fig. 10c shows the thunderstorm that appears to have spawned all three of these tornadoes, and Fig. 10d shows the storm-relative velocity data. The three tornadoes had relatively short path lengths.

The thunderstorms in all of the foregoing cases were moving primarily toward the north or north-northeast. All of the tornadoes appear to have occurred as the parent thunderstorms approached and encountered the baroclinic boundary which arced from the low centered initially near San Angelo first to the northeast, then to the east and finally to the southeast, and which was lifting slowly northward. This area is easily visualized by reference to visible satellite imagery (Fig. 8).

An attempt was made to obtain Level II data so that additional qualitative judgments could be made regarding storm structure, but the NCDC HAS system indicates that no Level II data is archived for this event from KSJT, and the Level II archive from KFWS was very incomplete during the critical time period involved herein. A general impression of the storms is that they produced smaller radar footprints and had lower maximum tops than the storms that occurred east and southeast of Waco. Some of these storms were clearly supercells, while for others no conclusive classification could be made. It is likely that the slowly retreating boundary provided a source of abundant baroclinically-generated streamwise horizontal vorticity; it may also have furnished a focus for the development of pre-existing vertical vorticity, in which case some tornadogenesis may have been non-mesocyclonic.

The tornadoes east-southeast of Waco initiated a little before the San Angelo to Fort Worth tornadoes. A general impression for most of the storms in this zone is that they had radar footprints larger than those to the northwest and they did have maximum tops of at least 45,000 feet (versus ~35,000 feet for the previously discussed storms).

Fig. 10 presents two sets of images of the same storm which moved from over KGRK northeastward across portions of Milam, Falls, Limestone and Freestone counties between 18 UTC and 2030 UTC. The storm produced at least three tornadoes, and in that regard may have been a cyclic supercell.

The first tornado occurred over southeastern Falls County between 1830 UTC and 1900 UTC and produced weak damage over a narrow path 0.7 miles in length. The reflectivity signature (Fig. 10a) shows a rather meaty pendant echo and the storm-relative product (Fig. 10b) shows a strong low-level mesocyclone coincident with the pendant echo. This same cell had earlier displayed a well-developed hook echo at a time when the storm-relative velocity signature was not as well defined.

The next tornado developed ~1915 UTC near Thornton in Limestone County and had a path length of 7 miles and produced damage rated F2. The maximum path width was 440 yards. Figure 10c shows the storm in 0.5° base reflectivity just prior to tornadogenesis. Note that a BWER is associated with the storm. The storm-relative product (Fig. 10d) shows a strong mesocyclone and manually-defined tornado vortex signature (TVS). The third tornado developed after the occlusion of the second and tracked across the southeastern corner of Limestone County into Freestone County, with a maximum path width of 30 yards.

It is hypothesized that the second tornado occurred as the cyclic supercell, moving to the northeast, encountered the baroclinic surface boundary that stretched west to east from north of Temple to between Nacogdoches and Lufkin. This boundary was reinforced during the day and actually drifted toward the south as a result. The slow-moving boundary likely provided a source of abundant baroclinically-generated streamwise horizontal vorticity for storms encountering the boundary.

As noted previously, there was a lull in tornado production in this area after ~20 UTC through ~2225 UTC. The lull likely represents a period during which the initial storms had moved far enough north of the boundary that tornadogenesis was inhibited by the increasing depth of a rain-cooled stable layer near the surface. Additional storms developed to the southwest during the lull period and advanced northeastward toward the boundary, encountering it after 22 UTC.

Radar data from several nexrad sites shows that additional intense thunderstorms, moving northeastward, reached the vicinity of the quasi-stationary boundary between 22 UTC and 23 UTC in the area along and east of a line from Palestine to Huntsville. A severe thunderstorm produced a brief, weak tornado just prior to 2230 UTC near Elkhart in Anderson County south of Palestine. The same thunderstorm subsequently produced a long-track tornado (33 miles) that developed about 2240 UTC and crossed Cherokee County, the northwest corner of Nacogdoches County, and ended in Rusk County. Maximum path width was 150 yards, with virtually all damage involving felled and broken pine trees. Figs. 11a and 11b show the storm as viewed from KSHV in the 0.5° base reflectivity and 0.5° storm-relative velocity modes, respectively at 2309 UTC. The 23 UTC surface data plotted on the base reflectivity image (Fig. 11a) shows the storm positioned between very cool, damp air to the north and very warm, moist air to the south.

The most intense tornadoes of the outbreak developed shortly before 01 UTC in northern Polk County, then moved northeastward across portions of Angelina, Nacogdoches and San Augustine counties. The total path length was 49 miles, with a maximum path width of 440 yards. Six injuries were recorded. Figs. 11c and 11d show the storm as viewed from KPOE (Fort Polk, La) in the 0.5° base reflectivity and 0.5° storm-relative velocity modes, respectively at 0131 UTC. To the north, the storm that produced the 33-mile long path across Cherokee and nearby counties earlier can be seen crossing the Sabine River northeast of Center.

The third zone of tornadogenesis was located over the coastal plains near and west of Houston. Several brief, weak tornadoes occurred between 2330 and 0115 UTC over portions of Wharton and Jackson counties. The severe storm mode was somewhat different from that seen in the other two zones, as linear convection was more prevalent in this zone. The most intense tornado of this segment of the outbreak occurred just after 02 UTC as a line of intense storms with imbedded supercells pushed across the Harris County area. A tornado produced F3 damage 3 miles south of La Porte. The tornado was relatively brief, with a path length on land of less than 1 mile, although the tornado may have continued eastward over the waters of Galveston Bay. Maximum path width was 60 yards. Property damage from this tornado was estimated to be $350,000.

Radar imagery at the time of the tornado is hampered by the proximity (<10 miles) of the storm to the KHGX radar site. Even the higher elevations of base reflectivity and storm-relative velocity are difficult to interpret. As an alternative, Fig. 12 displays the 0.5° base reflectivity product from approximately 30 minutes prior to the occurrence of the tornado. The surface data overlay shows 01 UTC data, which shows very warm, moist air flowing into the linear system and the imbedded supercell.

4. PARCEL TRAJECTORY ANALYSIS

In an attempt to understand the role, if any, of the quasi-stationary boundary that was in proximity to two of the three zones in which tornadoes occurred, 24-hour backward parcel trajectories were computed using the HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model available at the NOAA Air Resources Laboratory "READY" website.[3]

In addition to computing the trajectory of a parcel, the model also generates a selected meteorological field for points along the trajectory. The selected meteorological field in this case was potential temperature (θ). The computed field represents the meteorological variable surrounding the parcel, not that of the parcel itself. Archived data from the 80-km Eta Data Assimilation System (EDAS), available at the ARL-READY website, was used for the computations.

Plots of backward trajectory were generated as of 18 UTC on Mar. 30th for points of origin located at the intersection of whole one-degree units of latitude and longitude bounded by and including 33°N, 93°W; 30°N, 93°W; 30°N, 102°W' and 33°N, 102°W. This resulted (generally) in a geographical coverage bounded by El Dorado, AR; Lake Charles, LA; Dryden, TX; and Jayton, TX. All parcel origins were set to 250 m AGL.

Some general observations regarding the 24-hour trajectories are as follows: (1) along 33°N and west of 97°W, all parcels originated over Oklahoma and were in an environment characterized by lower θ values than 24 hours earlier; (2) along 33°N and east of 97°W, parcels originated in Missouri 24 hours earlier and were in an environment characterized by lower θ values than 24 hours earlier; (3) along 32°N and west of

[3] For a description of the HYSPLIT model, see NOAA Technical Memorandum ERL ARL-224, "Description of HYSPLIT-4 Modeling System" at the following URL: http://www.arl.noaa.gov/ready/hysplit4.html

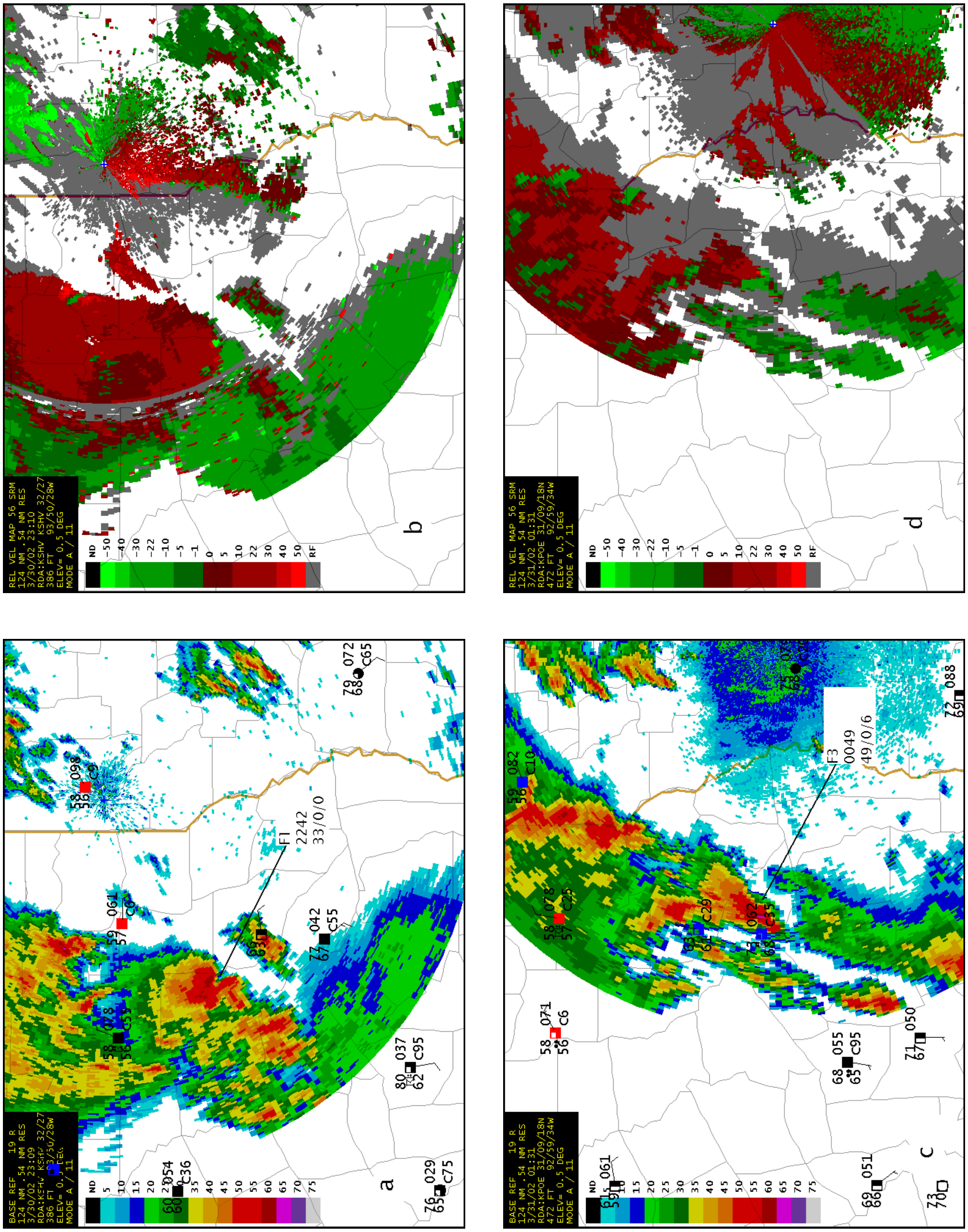

Fig. 11. KSHV (a) 0.5° base reflectivity and (b) 0.5° storm-relative velocity at 2309 UTC on Mar. 30, 2002, and KPOE (c) 0.5° base reflectivity and (d) 0.5° storm-relative velocity at 0131 UTC on Mar. 31, 2002.

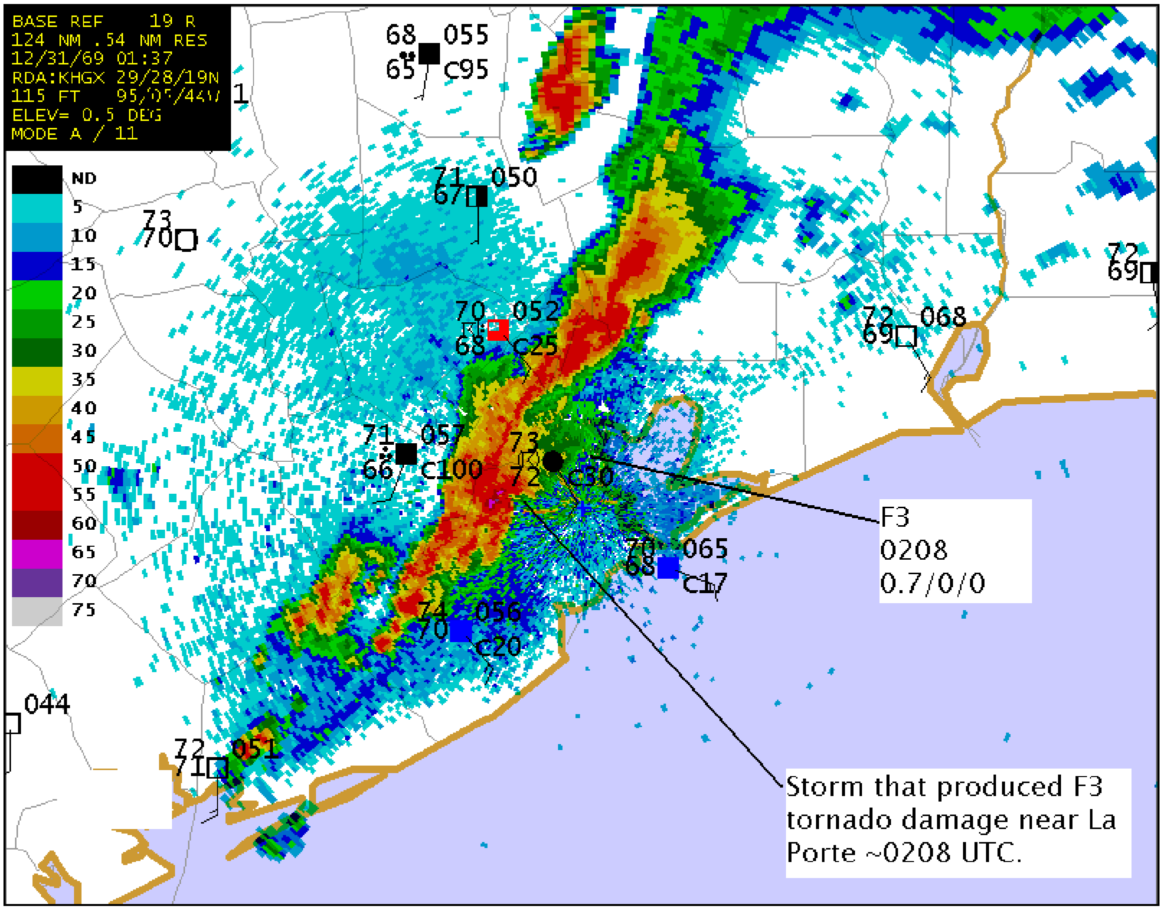

Fig. 12. KHGX 0.5° base reflectivity from KHGX at 0137 UTC on Mar. 31, 2002. The locations of the imbedded supercell and of the subsequent tornado are both indicated on the image.

99°W, parcels originated over Oklahoma and were in an environment characterized by either lower or unchanged θ values than 24 hours earlier; (4) along 32°N eastward from 99°W, parcels originated over the Gulf of Mexico or the immediate coastal plains of Texas and were in an environment characterized by either unchanged or lower θ values than 24 hours earlier; (5) along 31°N and westward from 100°W, parcels originated in the westernmost Red River Valley between Texas and Oklahoma were in an environment characterized by very little change in θ over the past 24 hours; (6) eastward along 31°N from 100°W, parcel trajectories were from the coastal bend area around Corpus Christi, then (farther east) from the waters of the Gulf of Mexico and were in an environment characterized by lower θ values than 24 hours earlier; (7) along 30°N westward from 99°W, parcel trajectories were from far western Texas around El Paso and were in an environment characterized by mostly unchanged θ than 24 hours earlier; and (8) eastward along 30°N from 99°W, parcel trajectories were from the Gulf of Mexico at or south of 26°N and were in an environment characterized higher θ values than 24 hours earlier, except for the area immediately along the upper Texas coast, where they were lower..

An interesting pattern of trajectories was found in the vicinity of the quasi-stationary front. This was most clearly seen in parcels along 32°N east of 100°W. Along this zone, trajectory plots all indicated parcel trajectories that were primarily from south to north until approaching ~32°N, then turning ~90° counter-clockwise and flowing westward. A fair inference from this pattern is that the parcels (at least according to the HYSPLIT model), encountered the quasi-stationary front and began to flow east to west (as opposed to south to north) along the north side of the front. This was, of course, a zone of increasingly strong baroclinity as the temperature gradient was reinforced by continued flow from the convective precipitation mass over Oklahoma, Arkansas, and northeastern Texas. Figure 13 displays four of the trajectory plots along 32°N from 95°W to 98°W.

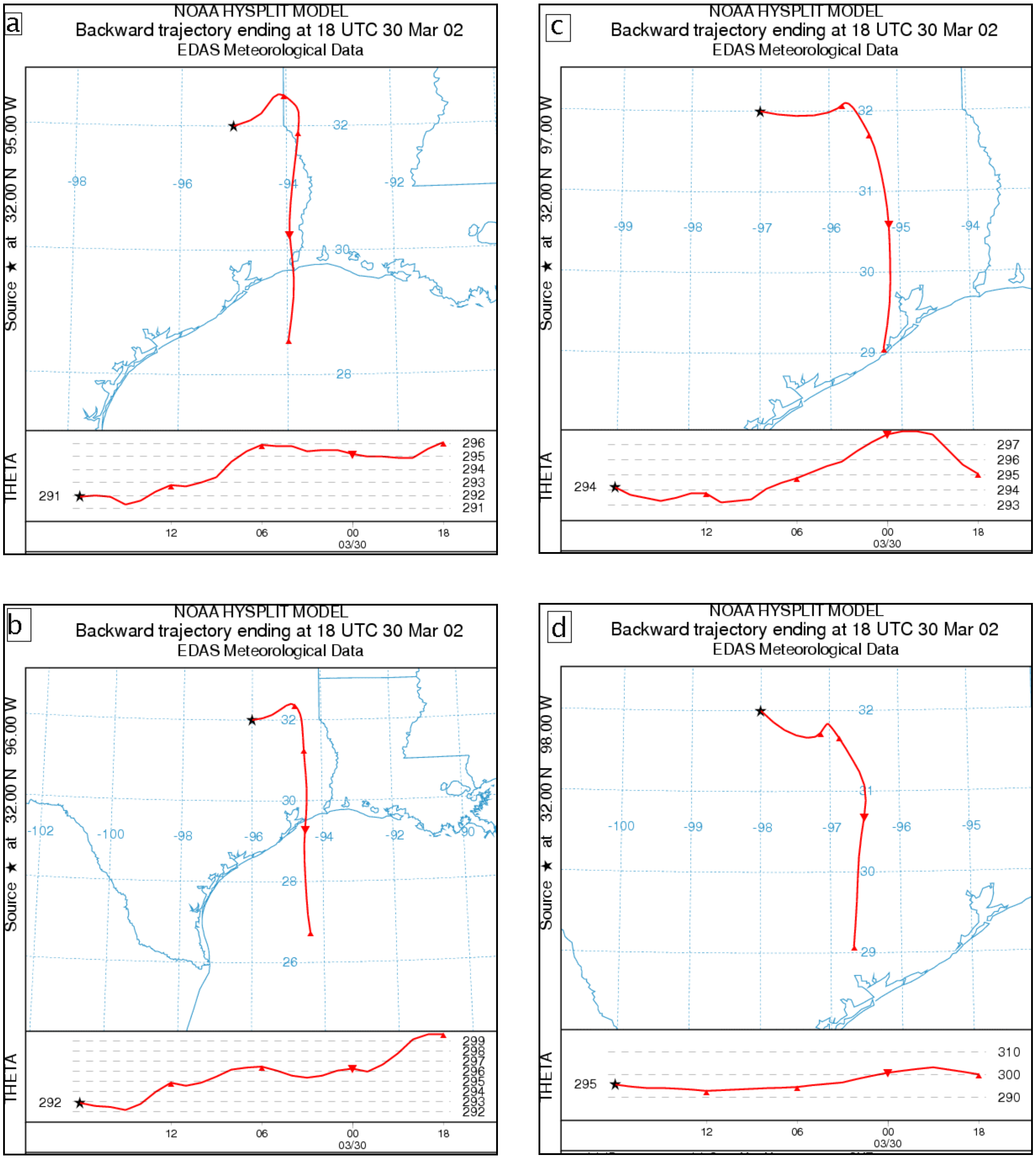

Fig. 13. Backward 24-hour trajectories and environmental potential temperature (θ) for parcels at 250 m AGL at 18 UTC on Mar. 30, 2002 for the following locations: (a) 32°N/95°W, (b) 32°N/96°W, (c) 32°N/97°W, and (d) 32°N/98°W. Plots generated using the NOAA Air Resources Laboratory HYSPLIT model.

Figure 14 is a plot showing the HYSPLIT-calculated value of θ at each of the grid points for which trajectories were computed. Given the pattern seen in the trajectory plots and keeping in mind the increasingly pronounced temperature gradient on the north side of the quasi-stationary front, it is speculated that the east to west flow north of the front was developing significant baroclinically-generated streamwise vorticity which may have enhanced the tornado potential there.

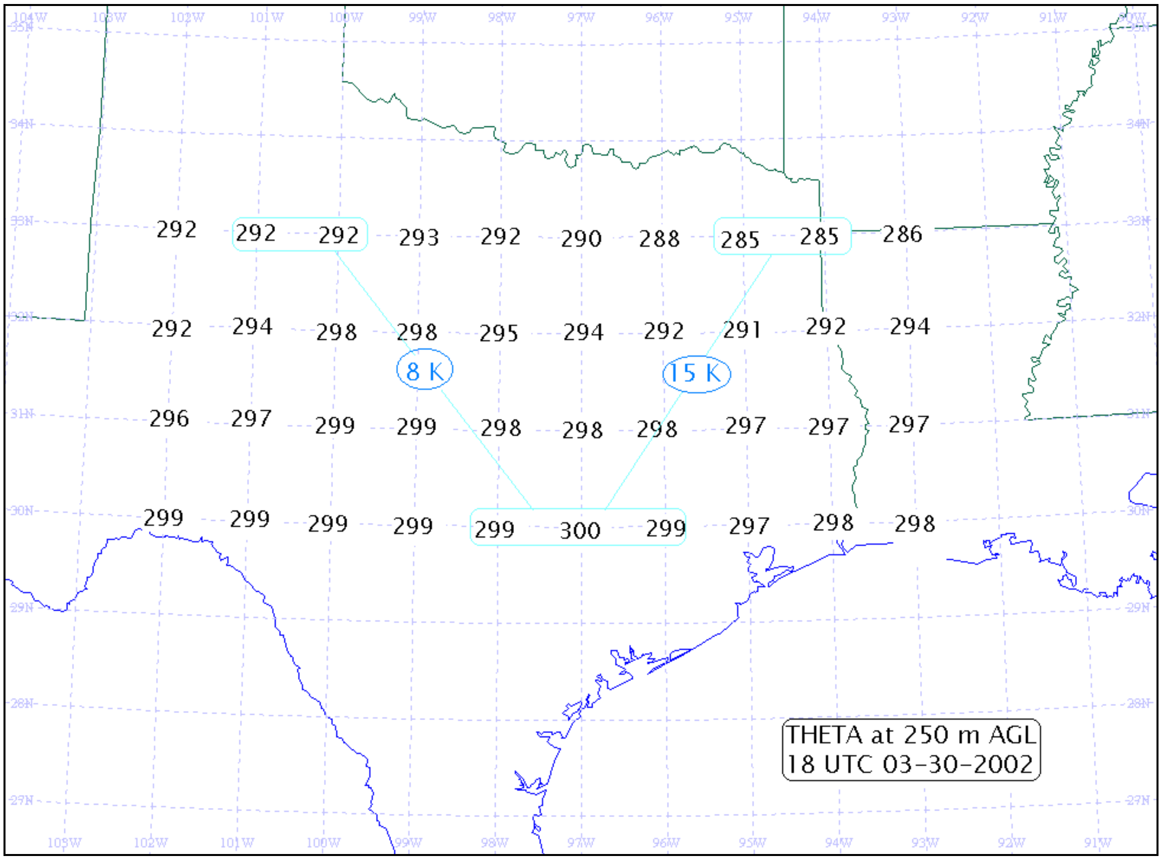

Fig. 14. HYSPLIT-calculated value of θ at each of the grid points for which trajectories were computed as of 18 UTC on Mar. 30, 2002 with parcel height set to 250 m AGL at the grid points. Light blue lines connect the grid points having the lowest and highest values on northeast to southwest and northwest to southeast transects.

5. FACTORS AFFECTING TORNADOGENESIS

As noted in Sec. 1, the potential for an outbreak of severe storms and tornadoes was obvious by the time of the 13 UTC SPC Day-1 outlook update. In Sec. 2, the evolution of the event has been documented using the 12 UTC upper air analyses at standard levels and surface analyses and 2-km nexrad mosaic imagery at 3-hour intervals. The potency of the evolving situation led to special rawinsonde launches at 18 UTC from a number of sites from Texas eastward across portions of the southeastern U.S. The most telling results came from Fort Worth (FWD) (Fig. 15). The low-level flow was from the northeast, but then quickly veered to southeast, then south and finally southwest, with increasing wind speed. Storm-relative helicity (s-rh) was computed from the sounding data as follows: 0-1 km: 312 m^2s^{-2}; 0-2 km: 486 m^2s^{-2}; and 0-3 km: 501 m^2s^{-2}. The sounding also detected a significant low-level inversion. It is probable that the inversion was less

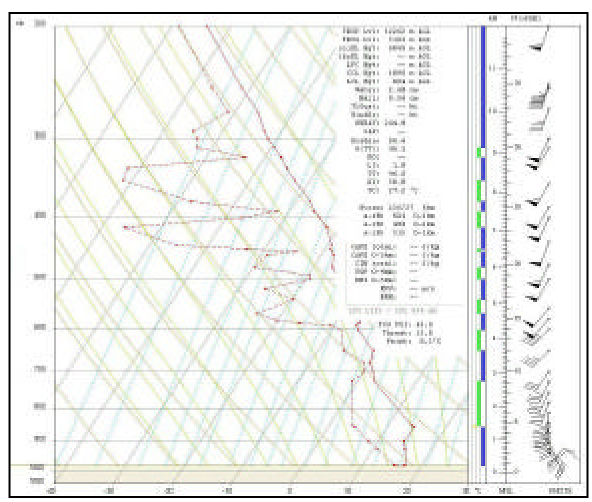

Fig. 15. SkewT-logP plot from special 18 UTC sounding at Fort Worth (FWD) on Mar. 30, 2002.

pronounced southward from Fort Worth toward the quasi-stationary front. The other special soundings (from Corpus Christi, Shreveport and Lake Charles) were examined. These reflected similarity to the Fort Worth plot, but each presented some differences, owing mainly to displacement east or south of the primary ingredients reflected in the Fort Worth plot. The Fort Worth special sounding goes a long way toward explaining that part of the outbreak that occurred southwest of Fort Worth toward San Angelo, but less so the portions of the outbreak east-southeast of Waco into deep east Texas, and in the Houston area.

Wind profiler data was examined in an attempt to explore the latter areas more thoroughly. The NOAA Forecast Systems Laboratory (FSL) maintains a network of 404-mhz wind profilers. One such profiler is at Palestine, TX (PATT2), in relatively close proximity to the long-track tornadoes that developed in the late afternoon and early evening. Data from Mar. 30th was recovered and plotted (Fig. 16) using software available online at the NOAA Profiler website (http://www.profiler.noaa.gov/jsp/index.jsp). The plotted data contains frequent drop-outs at lower levels after 21 UTC. In an attempt to recover additional detail, the data was dumped to a text file and additional detail extracted (see Table 1). It is apparent that the wind field seen on the Fort Worth special sounding also affected areas well southeast of Fort Worth.

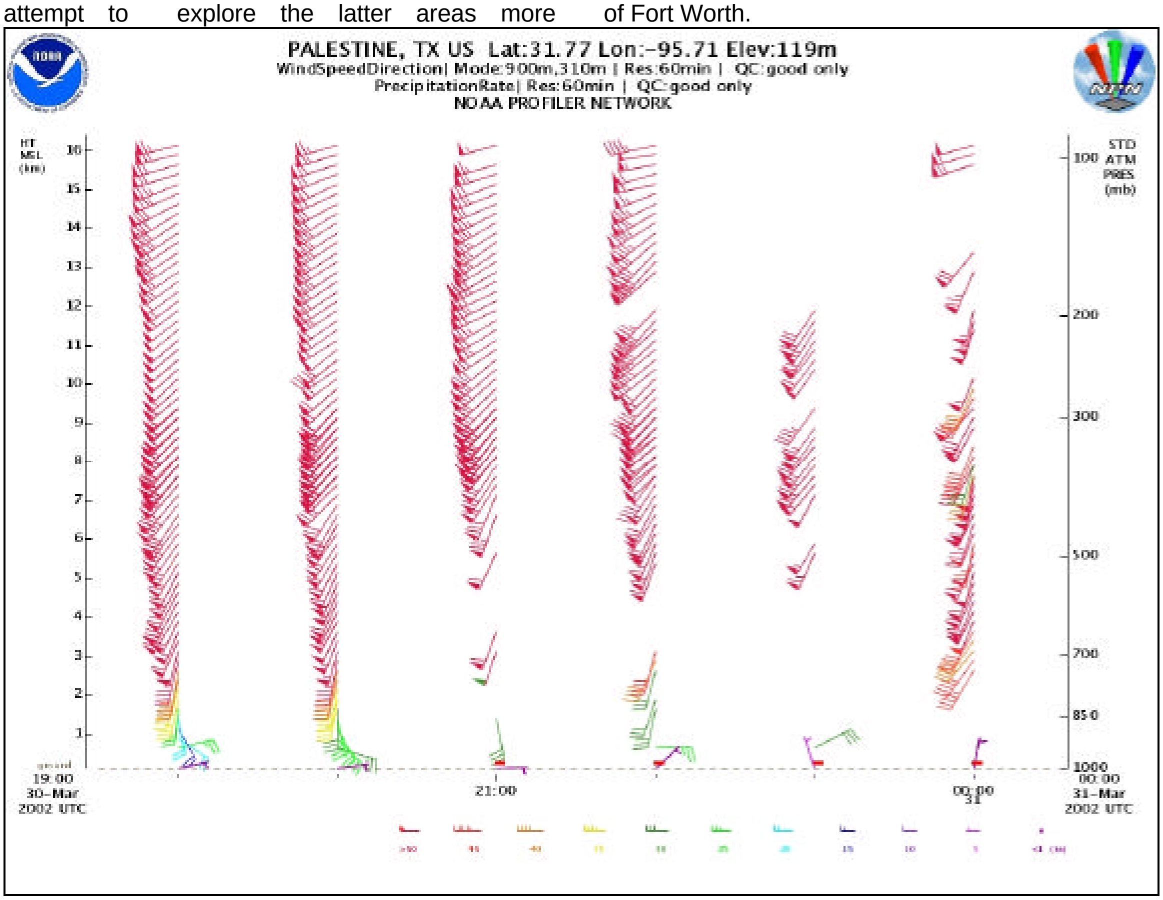

Fig. 16. Plot of data from NOAA Wind Profiler at Palestine, TX (PATT2) for period 19 UTC Mar. 30, 2002 through 00 UTC Mar. 31, 2002.

HGHT MSL (m)	1730 UTC	1830 UTC	1930 UTC	2030 UTC	2130 UTC	2230 UTC	2330 UTC	0030 UTC
619 m	072/16	087/20	078/23	107/29	M	091/27	M	M
869 m	076/05	103/14	123/19	135/26	M	M	M	M
1119 m	170/03	144/11	151/18	151/27	M	M	M	M
1369 m	178/06	181/17	167/21	166/27	168/28	M	M	M
1619 m	201/13	192/26	184/24	180/31	M	191/30	M	M
1869 m	209/22	194/30	191/33	189/36	M	197/30	M	M

Table 1. Data extracted from NOAA Wind Profiler at Palestine, TX (PATT2) for period 1730 UTC to 0030 UTC on Mar. 30, 2002. Data shown is one-hour average from 6-minute data.

In Table 1, note that at the lowest gate (500 m above ground level) there was a sustained easterly flow, which increased from 16 knots at 1730 UTC to 29 knots at 2030 UTC and was still at 29 knots at 2230 UTC. The flow at the second gate, 750 m above ground level, gradually changed from light easterly to strong southeasterly (26 knots) at 2030 UTC. The flow at 1 km above ground level gradually backed slightly and increased from 13 knots to 31 knots between 1730 UTC and 2130 UTC. Thus, the flow in the 0-1 km layer at PATT2 displayed a strongly veering profile.

As seen on the special 18 UTC sounding from Fort Worth, surface-based CAPE could not be calculated because of the relatively deep inversion. The Lake Charles special sounding produced ~1200 J kg^{-1} and the Corpus Christi special sounding produced ~2400 J kg^{-1} (neither plot shown). A technique for deriving point soundings using the Rapid Update Cycle (RUC) model analysis output, modified by one or more nearby surface observations, has been shown to have skill. (Thompson et al. 2003)

When applied to the RUC analysis output at 21 UTC for a point near Abilene and San Angelo, modified for the observed surface observation at Abilene (not shown), surface-based CAPE was found to be 1746 J kg^{-1}. This compares favorably with a modification (not shown) of the Fort Worth 18 UTC sounding for surface conditions between Stephenville and Fort Hood, which yielded surface-based CAPE of ~1900 J kg^{-1}. The RUC-based wind profile suggested that the wind field was decelerating through a deep layer of the troposphere (consistent with the area gradually falling beneath wind minimum associated with the mid- and upper-level low).

Closer to the zone of tornadogenesis east-southeast of Waco, the same technique revealed a very potent combination of moisture, instability and dynamics. The RUC analysis output for a point near College Station at 18 UTC was modified with the surface observation from that station at the same hour (Fig. 17), and surface-based CAPE was indicated to exceed 2300 J kg^{-1}.

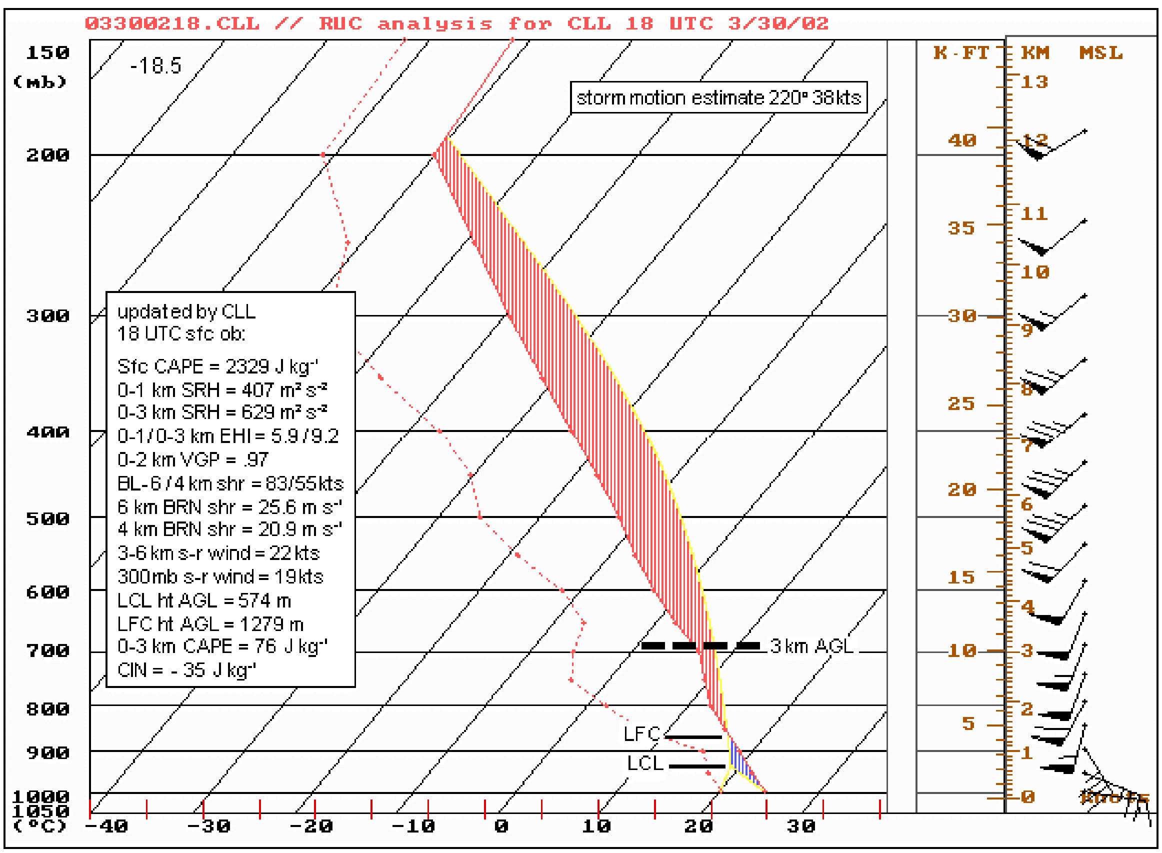

Fig. 17. SkewT-logP diagram created using the RUC analysis output for 18 UTC near KCLL modified with the actual surface observation from CLL. (Created by Jon Davies; used with permission)

Storm-relative helicity (s-rh) in the 0-1 km and 0-3 km layers was quite high (407 m2 s^{-2} and 629 m2 s^{-2}, respectively). The LCL is shown to be 574 m while the LFC is at 1279 m. Of particular significance, the energy-helicity index in the 0-1 km and 0-3 km layers is shown to be 5.9 and 9.2, respectively. Assuming that these parameters are reasonably representative of the 18 UTC conditions near CLL, and re-examining the 18 UTC surface analysis (Fig. 5), one can conclude that the very potent conditions covered a large area of east central and southeast Texas along and south of the quasi-stationary front.

With respect to the third zone of tornadogenesis near and west of Houston, another wind profiler was utilized, along with the 00 UTC rawinsonde data from Corpus Christi and Lake Charles. The surface analyses for 21 UTC (Fig. 6) and 00 UTC (Fig. 7) both indicate a generally southerly flow onto the Texas coast between Corpus Christi and Houston, with the flow at Galveston remaining somewhat more backed (southeasterly). At 00 UTC, surface observations at Victoria (VCT), Palacios (PSX) and Angleton (LBX) all indicated temperatures in the mid 70's and dew points ≥70° F, while Corpus Christi reported a dew point in the upper 60s F.

The 00 UTC sounding from CRP reflected a very potent air mass with surface-based CAPE >4000 J kg^{-1} and mixed-layer (lowest 100 mb) CAPE >2800 J kg^{-1}. At the same time, the Lake Charles (LCH) sounding indicated surface-based CAPE of almost 2400 J kg^{-1} and mixed-layer (lowest 100 mb) CAPE of >1700 J kg^{-1}. Although a slight decrease in CAPE could be expected with the onset of evening, it is reasonable to expect that much of the convective potential of the air mass remained at 02 UTC, as the final significant tornado developed.

The Texas Commission on Environmental Quality maintained a low-level (0-3km) wind profiler at Ellington Field (EFDTX), within 6 miles of the location of the tornado near La Porte. Archived data from the TCEQ profilers is also available at the NOAA Profiler website, and was recovered and plotted for the afternoon and evening hours involved in this event.

Fig. 18 displays the EFDTX profiler data between 2130 UTC and 03 UTC at 30-minute

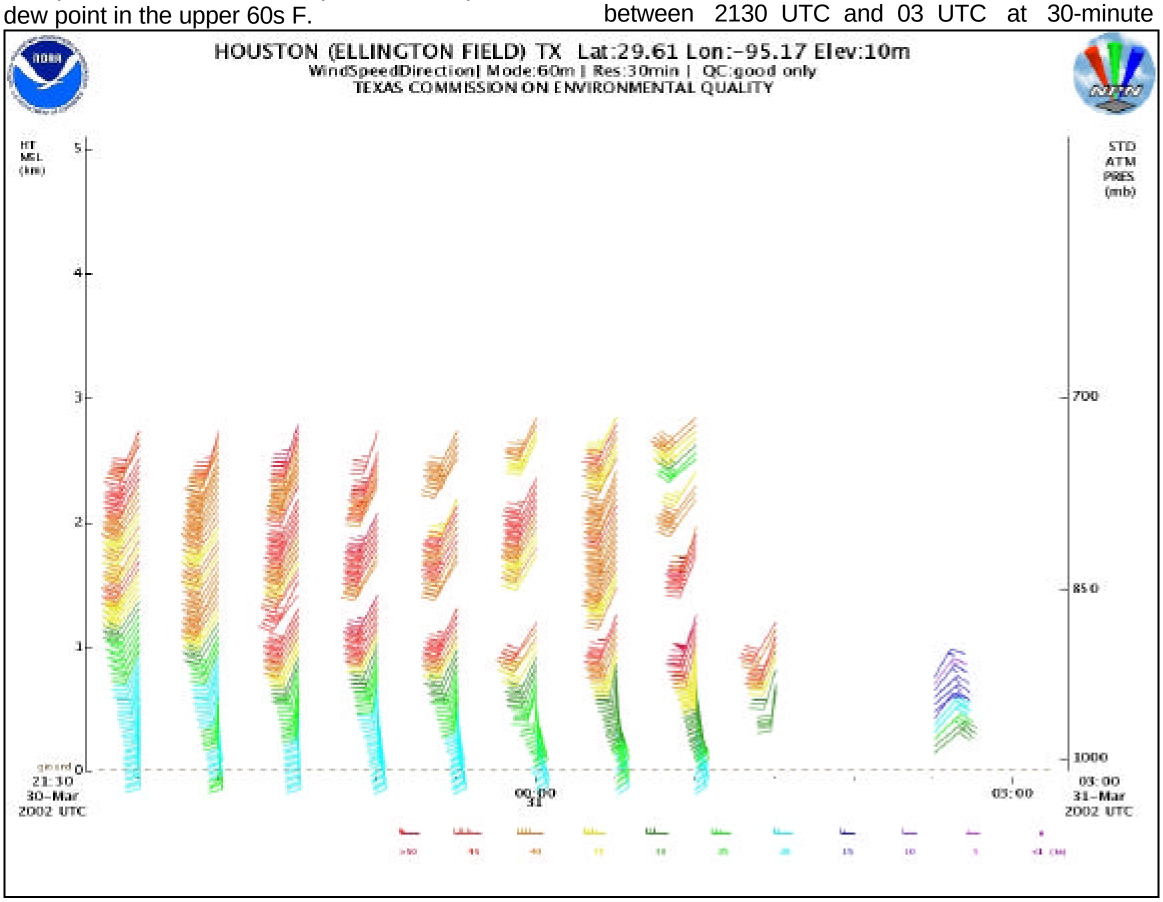

Figure 18. Plot of data from TCEQ Wind Profiler at Ellington Field, TX (EFDTX) for period 2130 UTC Mar. 30, 2002 through 03 UTC Mar. 31, 2002. Loss of data (partial) around 0130 UTC is probably due to the approaching supercell thunderstorm. Unfortunately, the data was completely lost at 02 UTC while the tornado passed within 6 miles of the profiler site.

intervals. Note the extremely strong southerly flow ≥40 knots within 1 km of the ground between 2130 UTC and 0130 UTC.

6. DISCUSSION AND CONCLUSIONS

The foregoing analysis suggests that, although the occurrence of severe thunderstorms and even tornadoes could be foreseen over much of the eastern two-thirds of Texas on Mar. 30th, the separate zones of tornadogenesis apparently evolved in response to different factors that enhanced tornadogenesis in each.

In the zone between San Angelo and Fort Worth tornadogenesis appears to have depended primarily upon the rapid destabilization of the air mass in response to the clearing just ahead of the mid-level low. The slowly-retreating surface boundary, shown as a stationary front northeast of San Angelo at 18 UTC (Fig. 5) and as a warm front southeast of Abilene at 21 UTC (Fig. 6), may have supplied a source of both vertical vorticity and baroclinically-generated horizontal streamwise vorticity. Thus, the tornadoes in this zone may have been a mixture, related to both mesocyclonic and non-mesocyclonic processes. Such mixed events can occur in high-shear events. (Moller 2001)

The occurrence of tornadoes related to mesocyclonic processes along with tornadoes not so related may be explained, at least in part, by reference to the processes described in Fig. 19 (from Maddox et al. 1980), which is a conceptual model of flow near a preexisting thermal boundary.[4] In this case, the preexisting boundary may not have been sufficient, absent the rapid clearing and resultant destabilization, to trigger storms capable of tornadogenesis. With rapid clearing and destabilization along and south of the front, an area between the northward moving warm front and the quasi-stationary dryline underwent a transition from what Maddox et al. classified as a Type C air mass to what they classified as a Type B air mass, with the result being a strong convective response and a narrow zone that became favorable for tornadoes.

Thunderstorm tops were relatively low (~35,000 feet) in this zone compared to the storms in other areas, and storm motion was nearly perpendicular to the boundary, which tended to carry the storms over and well to the north of the boundary rather quickly. The resulting damage tracks were, for the most part, relatively short. This finding is consistent with prior observational research (Markowski et al. 1998; Maddox et al. 1980) as well as more recent model simulations (Atkins et al. 1999).

[4] The conceptual model dealt with generation of vertical vorticity along such a boundary, and did not address whether horizontal vorticity might also be enhanced along the boundary.

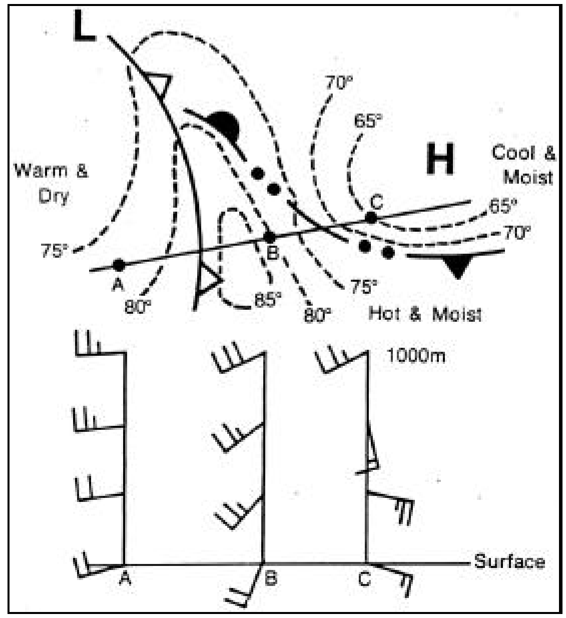

Fig. 19. Conceptual model of flow near a pre-existing thermal boundary. (From Maddox et al., 1980; their Fig. 2.) The air mass within zone A is warm, dry and well-mixed; within zone B, hot, moist and conditionally unstable; within zone C, cool, moist and stable.

In the zone southeast of Waco eastward into deep eastern Texas, the tornadic thunderstorms were clearly supercells and the storms (because of the orientation of the quasi-stationary front and of storm motion) spent more time in the immediate vicinity of the baroclinic zone. Application of the Maddox et al. conceptual model to this zone suggests a significantly larger area (primarily oriented west to east) of favorable Type B to Type C transition across the boundary. Flow on the north side of the front was from the east and, as seen on the Palestine profiler (Table 1), quite strong. The temperature gradient across the front (as seen in both surface observations and in the 250 m θ fields from the NOAA ARL HYSPLIT output) was quite intense, and was continually reinforced during the day. These factors lead to the conclusion that the quasi-stationary front was the key ingredient enhancing tornadogenesis in this zone. The apparent involvement of the preexisting boundary in augmenting tornadogenesis is consistent with previously published research. (Rasmussen et al. 2000; Atkins et al. 1999; Markowski et al. 1998; and Maddox et al. 1980).

With respect to the third zone near and west of Houston, the factor(s) enhancing tornadogenesis are less clear-cut. This zone was well south of the quasi-stationary front and did not become involved with the dry slot ahead of the mid-level low. Close scrutiny of hourly surface observations for the period between 18 and 00 UTC (see Figs. 5-7 for 18, 21 and 00 UTC analyses) shows a significant isallobaric evolution, with rapid surface pressure falls across the area between Austin, College Station, Houston and Victoria. This coincided with a shift of a surface cyclogenesis southeastward (from near Abilene to northeast of Austin) over that period.

The surface analysis at 21 UTC (Fig. 6) shows a surface low along an eastward bulge in the dryline located between Austin and College Station. In response, the surface winds over the Texas coastal plains gradually backed to a southerly or southeasterly direction. This slow backing contributed to the onshore transport of very warm, moist air fron the Gulf of Mexico, a process that continued beyond 00 UTC. This pattern is consistent with that described by Moller (2001), who noted that the isallobaric response often occurs several hours prior to tornadogenesis and often occurs on the moist side of a deepening (often subsynoptic) low in conjunction with eastward bulging drylines.

The 00 UTC sounding from Corpus Christi and the wind profiler data from Ellington Field (Fig. 18) show that by late afternoon, the strong wind field seen at 18 UTC on the special Fort Worth sounding (Fig. 15) had overspread the Texas coastal plains. This created a very potent combination of moist, unstable air, a strengthening surface low to the northwest, and a backing low-level flow, leading to the enhancement of tornadogenesis in this zone.

An unanswered issue regarding the evolution of this system after 02 UTC is its failure to produce significant severe weather events, particularly the failure of tornadogenesis, across Louisiana and Mississippi on the 31st. There was one tornado (F1 damage) over coastal Louisiana southwest of New Orleans shortly before 17 UTC on the 31st, but only widely scattered reports of hail or winds exceeding severe limits. Although not a part of this research, it would appear that the cold pool from the large area of mostly-convective precipitation over eastern Oklahoma, northeastern Texas and Arkansas was reinforced by the numerous strong to severe storms moving north of the quasi-stationary boundary, pushing the boundary southward during the overnight hours and gradually separating the increasingly-limited warm sector from favorable flow aloft.

7. REFERENCES

Atkins, N. T., M. L. Weisman, and L.J. Wicker, 1999: The influence of preexisting boundaries on supercell evolution. *, Mon. Wea. Rev.*, **127**, 2910-2927.

Fujita, T. T., 1981: Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos. Sci.,* **38**, 1511–1533.
Maddox, R. A., L. R. Hoxit, and C. F. Chappell, 1980: A study of tornadic thunderstorm interactions with thermal boundaries. *Mon. Wea. Rev.,* **108,** 322–336.

Markowski, P.M., E. N. Rasmussen, and J. M. Straka, 1998: The occurrrence of tornadoes in supercells interacting with boundaries during VORTEX-95. W*ea. Forecasting*, **13**, 852-859.

Moller, A. R., 2001: Severe local storms forecasting. *Severe Convective Storms, Meteor. Monogr.,* No. 50, Amer. Meteor. Soc., 433–480.

Rasmussen, E. N., S. Richardson, J. M. Straka, P. M. Markowski, and D. O. Blanchard, 2000: The association of significant tornadoes with a baroclinic boundary on 2 June 1995. *Mon. Wea. Rev.*, **128**, 174-191.

Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore, P. M. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Wea. Forecasting*, **18,** 1243-1261**.**