10A.5

Analysis of a Texas Tornado Outbreak Involving Three Modalities of Enhanced Tornadogenesis

Lon Curtis
KWTX-TV
Waco, Texas

1. INTRODUCTION

A cold front moved southward across Oklahoma and into northern Texas on 29 March 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 center moving eastward across southwestern Texas. Increasingly warm, moist, and unstable air pooled south of the front in Texas, setting the stage for an outbreak of 23 tornadoes on 30 March. The tornadoes, including two with damage rated F3 and path lengths of 30 to 50 miles, and one producing damage rated F2, occurred in three distinct clusters or zones (Fig. 1) and post-event analysis suggests that tornadogenesis was enhanced by different factors in each zone. (All F-scale references herein are to Fujita, 1981.) Fortuitously, no deaths were reported.

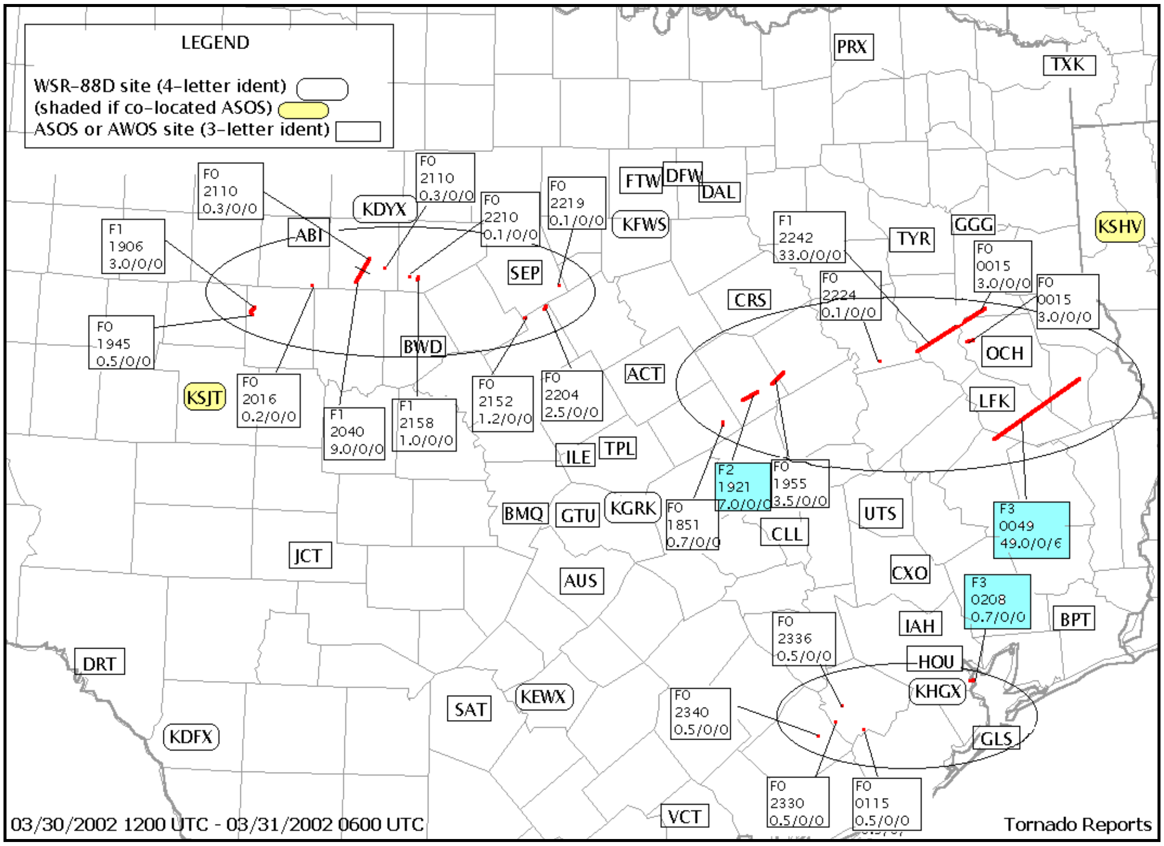

Fig. 1. Tornado locations on 30 Mar 2002, WSR-88D sites, and selected ASOS/AWOS stations.

Objectively analyzed upper air data at 12 UTC on 30 March found the system approaching from west Texas with the 850 mb and 700 mb centers vertically stacked near Midland, while the 500 mb (Fig. 2) and 250 mb centers were still to the west near Guadalupe Pass. Very cold mid-level temperatures (-20° C at El Paso) were associated with the 500 mb low center. 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 south of Brownsville, and a 150 knot jet in the polar jet stream well northeast of the area over the Great Lakes.

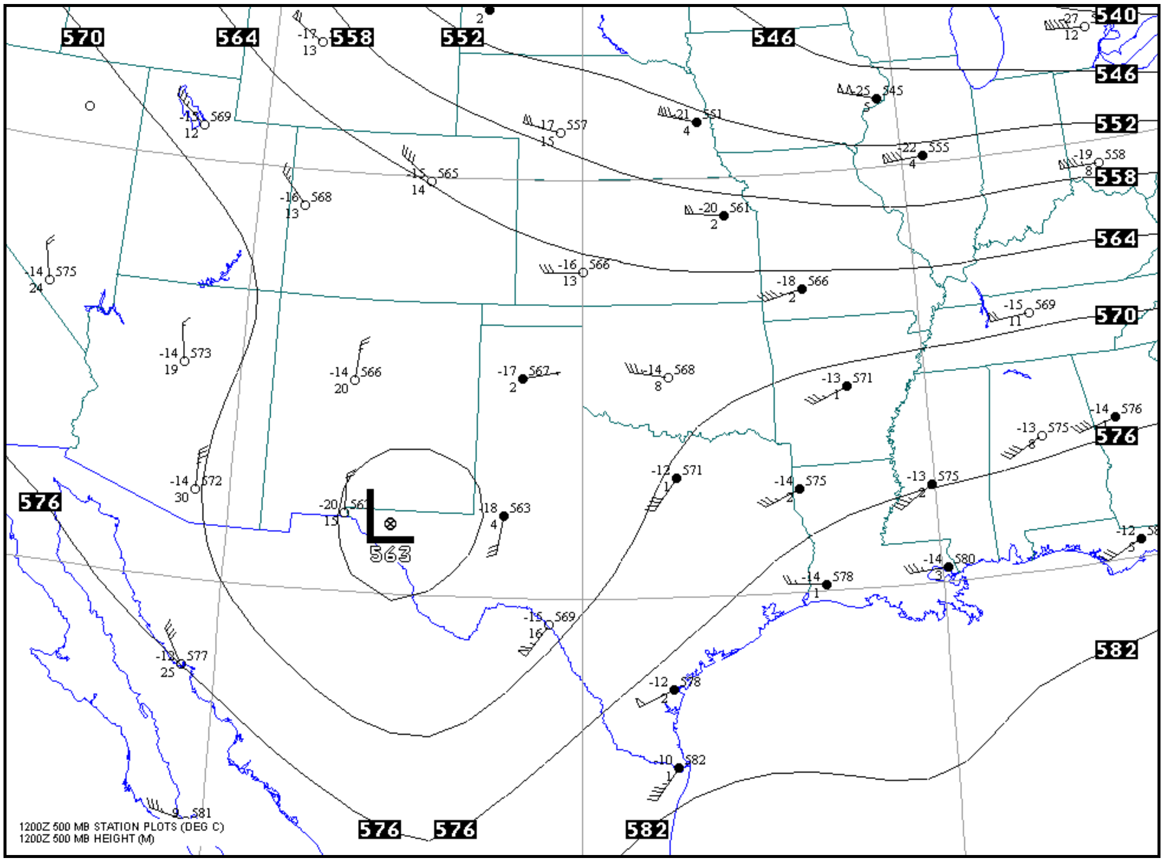

Fig. 2. 500 mb analysis for 30 Mar 2002 at 12 UTC.

Surface analysis at 12 UTC (not shown) found the quasi-stationary front along a line from just north of Shreveport (SHV) to near Waco (ACT) to south 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). Rain-cooled outflow from a large convective mass over northeast Texas, central and eastern Oklahoma and Arkansas was reinforcing the quasi-stationary front over eastern Texas.

The Day-1 Outlook from the Storm Prediction Center (hereafter, SPC) at 13 UTC 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. The outlook described the following scenario: (a) a surface low would develop during the afternoon between San Antonio and Houston near a triple point where the dryline would intersect the stalled east-west boundary; (b) the stalled boundary would become the focus for widespread thunderstorms as the upper low moved eastward across northern Texas into northern Louisiana, inducing a low pressure wave along the stalled front that would track from southeast Texas into northern Mississippi during the overnight hours; and (c) the air mass south of the stalled front was expected to become very unstable with MLCAPE predicted to reach 2000-3000 J kg^{-1} during the late afternoon.

2. EVENT OVERVIEW

Surface analysis at 18 UTC (Fig. 3) found a surface low between San Angelo and Abilene (ABI) with a cold front southwest to near Fort Stockton. A dryline feature extended southward from the low to east of Junction (JCT) and Hondo (HDO). Along the dryline, a secondary (hereafter, subsynoptic) low was developing northwest of Burnet (BMQ). The stalled front was draped across the area east and southeast of the primary low on a line just north of Temple (TPL) eastward to near Nacogdoches (OCH).

Objective analysis of surface data (not shown) indicated strong surface convergence in the warm sector east and southeast of the subsynoptic low, as well as near the primary low between San Angelo and Abilene. Composite nexrad data (not shown) 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 thunderstorms were developing from west of Waco to near Austin, east of the subsynoptic low. Shortly after 18 UTC SPC issued a Tornado Watch (#57) for a large portion of central and eastern Texas effective at 1830 UTC.

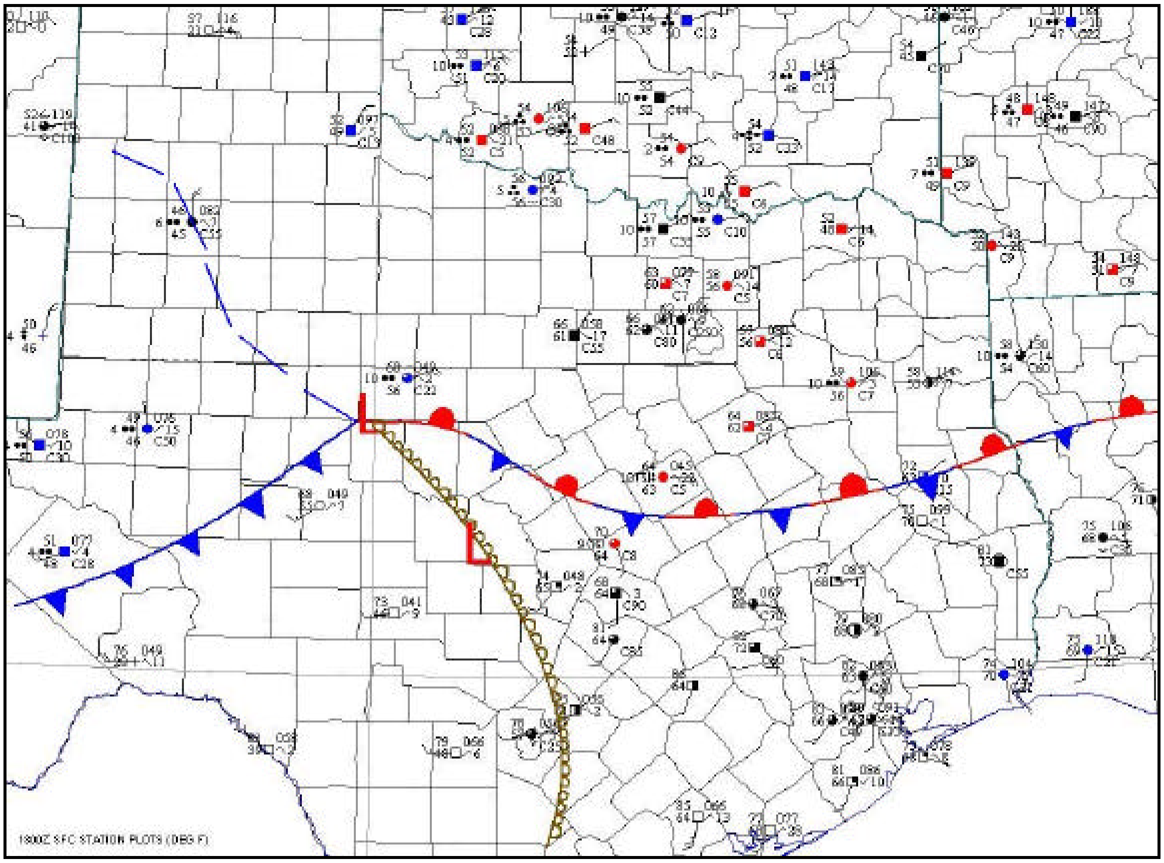

Fig. 3. Surface analysis at 18 UTC on 30 Mar 2002.

About the same time, an intensifying thunderstorm developed supercell characteristics as it moved directly over the KGRK nexrad site and continued to the northeast, spawning the first tornado of the day just southwest of Reagan in Falls County shortly before 1840 UTC. The same storm produced a tornado near Thornton in Limestone County shortly after 1915 UTC, with damage rated F2 and a track length of 7 miles, and subsequently produced a weaker tornado on the Limestone-Freestone county line shortly before 20 UTC.

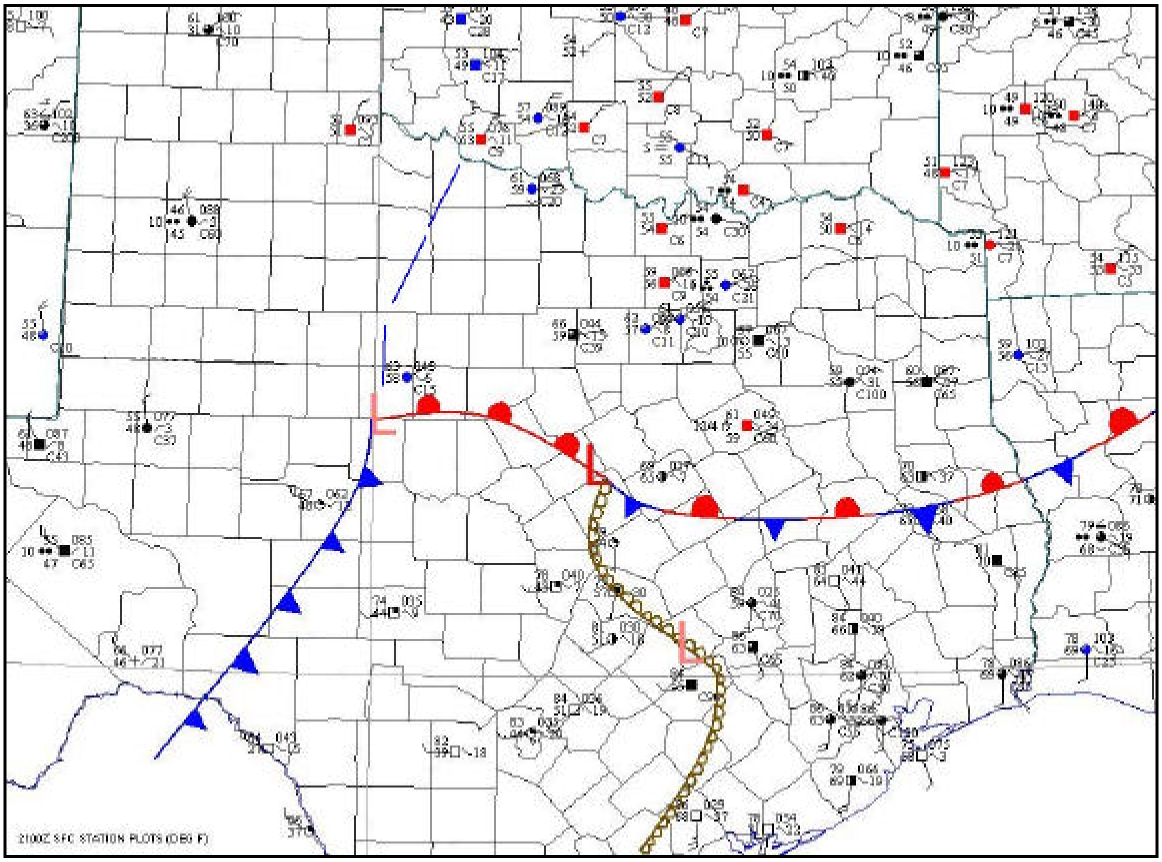

Fig. 4. Surface analysis at 21 UTC on 30 Mar 2002.

Tornado production from that system ceased as it moved across 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 also moved to the northeast and produced at least three tornadoes in Anderson, Cherokee, Rusk and Nacogdoches counties between 22 and 00 UTC.

Contemporaneous with the development of the tornadic storms southeast of Waco, thunderstorms were also developing in the area north through northeast of San Angelo. Shortly before 1845 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. Torndogenesis commenced in the area northeast of San Angelo around 19 UTC, near the stalled front that had been drifting northward in the dry slot. Erosion of the middle and high clouds in the dry slot permitted strong surface insolation and rapid destabilization of the lower troposphere.

By 21 UTC, surface analysis (Fig. 4, above) indicated a rapidly evolving situation. Although a cyclonic circulation was still evident in the wind field near Abilene, the primary low center was located west of Waco, with complex boundaries cluttering the map. In addition to the low west of Waco, there was a suggestion of a developing subsynoptic low southeast of Austin near LaGrange (11R), along the bulging dryline from the low west of Waco to La Grange to west of Victoria (VCT). The quasi-stationary boundary remained along a line from just north of Temple to near Nacogdoches.

The area of storms east and southeast of Abilene continued producing an occasional tornado, mainly near the northward drifting boundary. A Mesoscale Discussion from SPC indicated that severe storms with isolated tornadoes would persist for several more hours. The discussion noted that low clouds had mixed out of the area in the dry slot region north and east of the arcing boundary located southeast of Abilene, where MLCAPES were around 1500 J kg^{-1}.

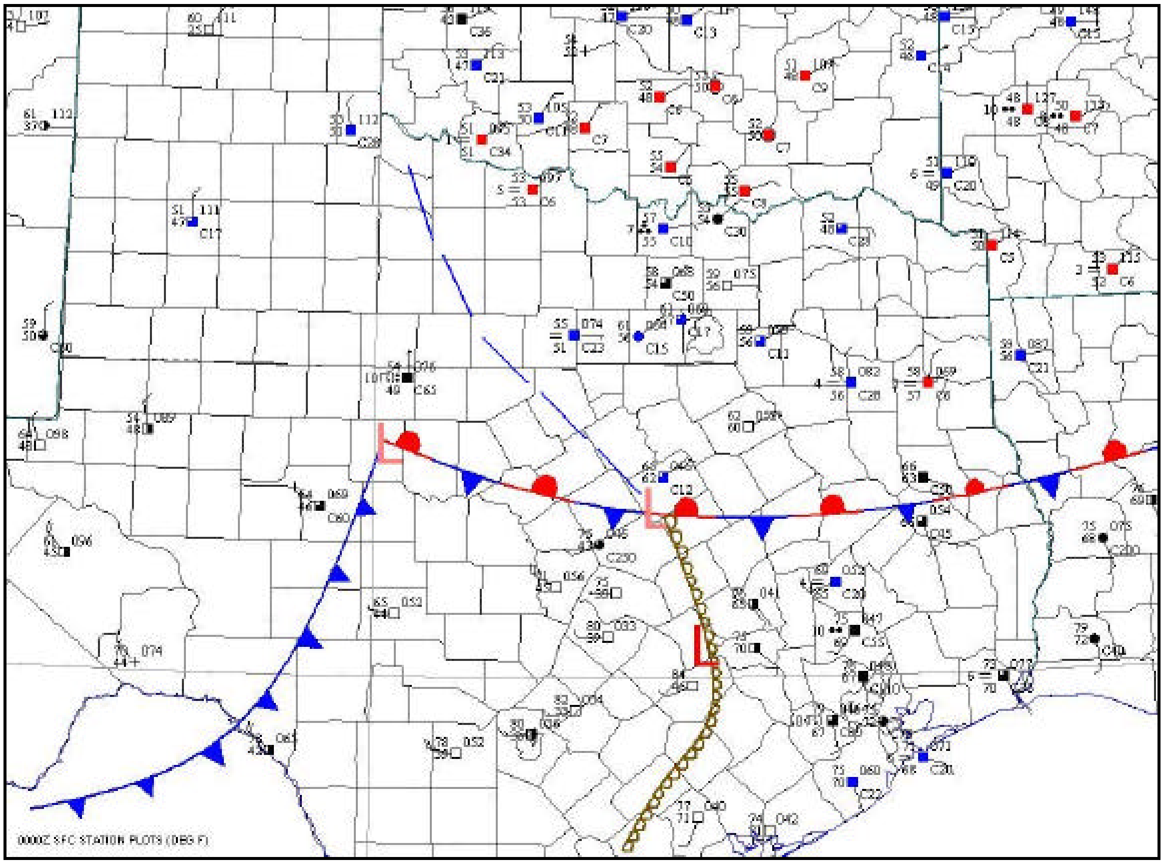

Fig. 5. Surface analysis at 00 UTC on 30 Mar 2002.

Shortly after 23 UTC, SPC issued a new Tornado Watch (#60) for portions of eastern Texas and central and northern Louisiana, replacing the original watch (#57). The watch discussion 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.

Surface analysis at 00 UTC (Fig. 5, above) still indicated the occluding surface low just southwest of Abilene, another occluding low just southwest of Waco, and a developing primary low located 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 produced damage rated F1 as it crossed rural 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 dissipating in San Augustine County. Some 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.

At the same time, intense thunderstorms continued evolving 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 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. The convective mode in this zone was becoming increasingly linear, but shortly after 02 UTC, a supercell storm imbedded in the linear convective system produced a tornado about 3 miles south of La Porte (very close to KHGX), on the northwest shoreline of Galveston Bay. Although the surveyed track was less than a mile in length (path width was ~60 yards), the tornado produced F3 damage. Shortly 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

All storms that produced tornadoes were examined using the Level III data displayed on Digital Atmosphere Work Station. (Digital Atmosphere Work Station, © 2004, Weather Graphics Technologies) Data was assembled (from archives at NCDC) from the following WSR-88D sites: KSJT, KFWS, KGRK, KEWX, KHGX, KSHV, KPOE. No archived data for this event could be located for KDYX.

In the zone from San Angelo to southwest of Fort Worth, the storms moved 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.

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.

In the zone east and southeast of Waco, the storm motion was toward the northeast or east-northeast. A general impression for most of the storms in this zone is that they had radar footprints larger than those to the northwest and maximum tops of at least 45,000 feet (versus ~35,000 feet for the previously discussed storms).

In the third zone of tornadogenesis (located over the coastal plains near and west of Houston), the storm mode was somewhat different from that in the other two zones, as
linear convection was more prevalent. 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. The surface data for 01 UTC indicated that warm, moist air was flowing into the linear system and the imbedded supercell.

4. PARCEL TRAJECTORY ANALYSIS

In an attempt to better define the role 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. 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 READY website, was used for the computations. (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)

Plots of backward trajectory were generated for 18 UTC on 30 Mar for an area bounded by El Dorado, AR; Lake Charles, LA; Dryden, TX; and Jayton, TX. All parcel origins were set to 250 m AGL at grid points with 1 degree (latitude/longitude) spacing. An interesting pattern of trajectories was found in the vicinity of the quasi-stationary front, most clearly seen in parcels along 32°N east of 100°W. Along this zone, the trajectory plots indicated parcel trajectories were primarily from south to north until approaching ~32° N, then turning ~90 °

counter-clockwise and flowing toward the west.

A fair inference from this pattern is that the parcels encountered the quasi-stationary front and began to flow east to west (as opposed to south to north) along the north side of the boundary. This was, of course, a zone of persistently strong baroclinity as the temperature gradient was continuously reinforced by rain-cooled flow from the convective mass over Oklahoma, Arkansas, and northeastern Texas. It is hypothesized that the east to west flow north of the front was developing significant baroclinically-generated horizontal streamwise vorticity that could have enhanced the tornado potential.

5. TORNADOGENESIS FACTORS

As noted in Sec. 1, the potential for an outbreak of severe storms and tornadoes was obvious by the time of the 13 UTC Day-1 outlook. The potency of the situation led to special rawinsonde launches at 18 UTC from a number of sites from Texas eastward across portions of the southeastern U.S. Telling results came from Fort Worth (FWD), where the low-level flow was from the northeast but quickly veered to southeast, then south and finally southwest, with increasing velocity. Storm-relative helicity (SRH) 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 18 UTC special soundings from Corpus Christi, Shreveport and Lake Charles were also examined. These reflected similarity to the Fort Worth plot, but each presented some differences, owing mainly to displacement east or south away from 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 of which is located at Palestine, TX (PATT2), in relatively close proximity to the long-track tornadoes that developed in the late afternoon and early evening. Data from 30 Mar. was recovered and plotted using on-line software available at the NOAA Profiler website. The plotted data contains frequent data drop-outs at lower levels after 21 UTC. The data was dumped to a text file and additional detail extracted (see Table 1, above). From this data, it is apparent that the wind field seen on the Fort Worth special sounding also affected areas well southeast of Fort Worth near Palestine.

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 30 Mar. 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} (plots not shown). However, 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 would be reasonable to expect that much of the convective potential of the air mass remained at 02 UTC, as the final significant tornado developed near Houston.

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. The data (not shown) indicated a very strong onshore flow from the Gulf of Mexico (often exceeding 40 knots) within 1-km of the ground between 2130 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 30 Mar., 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 proximity to the eastward moving 500 hPa cold closed low (hereafter C500L), ahead of which a dry slot developed. The cold air aloft associated with the C500L and rapid clearing of mid- and upper-level cloudiness associated with the dry slot produced rapid destabilization of the airmass in a narrow tongue from south of Waco to between San Angelo and Abilene.

This conclusion is entirely consistent with the preliminary findings of Davies and Guyer (2004), which indicated that tornado events are more likely close to and associated with C500Ls when (a) surface dew points are 50 degrees F or greater within 200 miles east through south of the C500L center, and (b) a surface boundary intersection focus point is located near or east of the surface low associated with the C500L, in the warm sector within 200 miles east through south of the C500L.

The slowly-retreating surface boundary may have supplied a source of vertical vorticity as well as 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. 6 (from Maddox et al. 1980), which is a conceptual model of flow near a preexisting thermal boundary. 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.

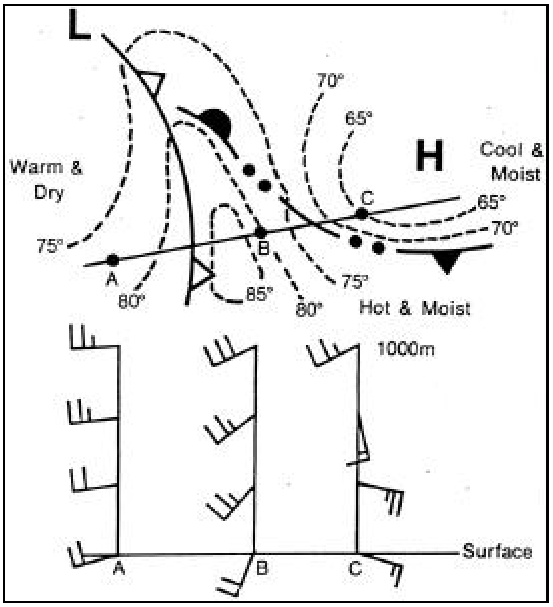

Fig. 6. Conceptual model of flow near a pre-existing thermal boundary. (from Maddox et al., 1980; their Fig. 2).

It is important to note that 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.

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).

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. 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. 4-6 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 primary surface cyclogenesis southeastward (from near Abilene to east-northeast of Austin) over that period.

The surface analysis at 21 UTC (Fig. 5) 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 contributed to the onshore transport of very warm, moist air from 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 indicated that by late afternoon, the strong wind field seen at 18 UTC on the special Fort Worth sounding 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.

REFERENCES

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

Davies, J.M. and J.L. Guyer, 2004: A preliminary climatology of tornado events with closed cold core 500mb lows in the central and eastern United States. Preprint Preprints, *22nd Conf. on Severe Local Storms*, Hyannis, MA, Amer. Meteor. Soc., (pages not numbered, CD-ROM only).

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.