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MESOSCALE ANALYSIS OF THE MARCH 27, 1994, SEVERE WEATHER OUTBREAK

Aaron Studwell
J. Nielsen-Gammon
Texas A&M University
College Station, Texas

Scientific Services Division
Southern Region
Fort Worth, TX

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James Baker
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Assistant Administrator

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1. Introduction

On March 27-28, 1994, an outbreak of severe weather struck the southeastern United States. The outbreak started with thunderstorms and high winds in south central Texas, moved east along the Gulf Coast, and dissipated in North Carolina. This system left 40 people dead and hundreds injured. In addition, there were 34 reported tornadoes, 12 reports of hail, and wind gusts over 45 ms^{-1}. This analysis of the outbreak will examine many aspects of the system, including the varying structures of storms within a single event. The goals of this report are to:

- Associate the occurrence of severe weather with mesoscale structures of the evolving system.
- Examine the consistency of severity indices with severe weather patterns.
- Examine the accuracy of watches and warnings issued by National Weather Service offices.

Spatial and temporal distributions of the severe weather are shown in Section 2. Section 3 will cover the mesoscale environment with analysis and comparison of meteorological parameters. The propagation of the storm cells with relation to the fronts and outflow boundaries will be examined in Section 4. Section 5 compares the severity indices from soundings in the region with the local weather reports. Finally, Section 6 will examine the watches and warnings issued in association with the storm system. All dates and times are given as date/time in UTC.

2. Distribution of Severe Weather

There were many reports of hail, tornadoes, and wind damage during the severe weather outbreak. Most of the hail reports were from central Texas; but hail was also reported near the Arkansas/Louisiana border, in northeast Mississippi, northern Alabama, and along the North Carolina/South Carolina border (Fig. 1a). The majority of the wind damage occurred in the same area in which tornadoes were reported (Figs. 1b,c). The wind damage and tornadoes fell along a single line from central Mississippi into central North Carolina. Additional wind damage was also reported in south central Texas and northern Louisiana.

3. Mesoscale Environment

Figures 2a-i depict major features associated with synoptic and mesoscale features of this developing system. Following is a brief synopsis.

At 27/0300, a cold front extended across Texas, Arkansas, and the western extremes of Tennessee and Kentucky. Thunderstorms associated with the front developed east of Del Rio, Texas, and extended from Greenville, Texas, to Little Rock, Arkansas, and into Tennessee.

Over the next 24 hours, the front pushed through the Deep South, and a severe weather outbreak occurred.

Between 27/0300 and 27/0600, the Del Rio storm grew rapidly. Radar measured a maximum height of 17,700 m (58,000 ft) at 27/0535. The thunderstorm produced an outflow boundary which caused additional storms to form ahead of the front.

A squall line developed at approximately 27/0900 along an outflow boundary which extended from central Tennessee southwestward into Mississippi. A warm and moist low level jet from the Gulf of Mexico, along with an upper level trough to the west, provided an optimal environment for the development of severe thunderstorms. Consequently, throughout the following hours, numerous squall lines developed along outflow boundaries from previous storms.

The 27/0900 squall line moved eastward toward the Appalachians. By approximately 27/1300, this squall line dissipated in the mountains. A second squall line developed about 27/1500 in central Mississippi and Alabama and moved across the upper half of Alabama during the next several hours. Several thunderstorms associated with this line produced tornadoes.

After the second squall line dissipated, a number of thunderstorms developed along the cold front at 28/0000. At this time, the cold front extended from Morgan City, Louisiana, northward through Mississippi, central Alabama and into the Appalachians. A number of severe storms moved into Georgia with the cold front at 28/0135.

During the 24-hr period shown in Fig. 2, consecutive storms struck northern Mississippi and Alabama. Most of the storms propagated at velocities between 15 and 20 ms^{-1} toward the northeast. After the frontal passage, scattered thunderstorms continued in the region; and stratiform rain was widespread in the area 800 km to the rear of the cold front.

4. Propagation of Storm Cells

In this section we will evaluate the movement and development of storms and severe weather associated with this outbreak in relation to the position of fronts and outflow boundaries. To accomplish this task, the positions of the surface fronts and severe weather occurrences were plotted, and their movement was tracked. Radar summaries were also used to track individual cells within the system.

The development of the storm system was examined in four time periods:

- 27/0300 to 27/0900
- 27/0900 to 27/1500
- 27/1500 to 28/0000
- 28/0000 to 28/0600

During the first period (0300 to 0900 on the 27th), severe weather was limited to thunderstorms and two hail storms in south central Texas. A cold front was analyzed in Texas and Arkansas. The storms were located along the leading front; and as a result, storm movement was primarily along the front itself. This period had the fewest number of severe weather reports of any of the four periods.

The second period (0900 to 1500 on the 27th) was also relatively inactive. The occurrence of storms during this period was comparable to that of the previous six-hour period; that is, there were thunderstorms but no reports of tornadoes or hail. Also, as in the previous period, the storms were located along the front itself, since the outflow boundary was only weakly developed. The propagation of storms remained along the front.

During the third period (1500 on the 27th to 0000 on the 28th), the greatest number of severe weather reports of any of the periods was noted, with a total of 27 tornadoes and 10 hail events during the nine-hour period. Storms broke out initially along the front; but as the system intensified, the associated outflow boundaries also intensified. This resulted in enhanced lifting, and consequently more severe weather was reported along these boundaries. During the most intense three-hour period (27/1930 - 27/2230), a total of 16 tornadoes and five hail events were reported, all of which were located along the outflow boundaries. Thunderstorms initially moved along the front; but as the outflow boundaries intensified, storms developed along and moved with them, to the east of the front.

In the final period (0000 to 0600 on the 28th), the convection began to weaken, and the number of severe reports was similar to that of the first two periods. During the period, the thunderstorms were located primarily ahead of the cold front and propagated with the front itself. Although no hail events were reported, seven tornadoes were recorded during this period.

In summary, during the early part of the outbreak the severe weather was primarily associated with the leading cold front. A significant factor contributing to the development of severe weather was the increase in the thermal gradient along the front. The increase enhanced already existing conditions for the lifting of warm, moist air along the frontal boundary, which led to more intense and frequent outbreaks of severe weather. As the system developed and intensified, the cells began moving more along the outflow boundaries until the dissipating stage of development, when their movement was primarily along or ahead of the cold front.

5. Analysis of Soundings and Stability Indices

An investigation of the Skew-T/Log-P diagrams sheds light on conditions noted by forecasters during the hours before the outbreak. Additionally, an examination of various stability indices is helpful in determining if the areas containing the most severe weather showed critical index values prior to the onset of severe weather.

a. Explanation of Diagrams and Indices

For the post-analysis, Skew-T/Log-P diagrams and hodographs were first processed with the GEMPAK software. Three stability indices were chosen for examination: Convective Available Potential Energy (CAPE), Bulk Richardson Number (BRN), and storm-relative helicity. These parameters are often used as general predictors of certain weather conditions when their values fall within various limits established by earlier studies. For example, CAPE values greater than 1000 J/kg indicate the potential for severe thunderstorms. Similarly, Bulk Richardson numbers less than or equal to 40, in correlation with large CAPE values, indicate the potential for the formation of supercell thunderstorms. Helicity values of greater than 400 m^2s^{-2} indicate the likelihood of tornadogenesis in the region.

b. Analysis

As stated earlier, the period during which most of the severe weather events were noted extended from about 27/1500 to 28/0000. Soundings were taken at the upper air observation sites at 27/1200, 27/1800, and 28/0000. When GEMPAK processed these data, problems in obtaining verifiable stability indices were encountered on the 27/1200 soundings because of low level inversions found on those early morning profiles. To verify whether the soundings were useful as predictors of the severe weather, a second software package was enlisted to modify the 27/1200 soundings. The SHARP Workstation, developed by the National Weather Service (Hart and Korotky,), was used to adjust low level data to values approximating conditions observed at the time of the most severe weather. Starting with these modified parameters, parcels were then lifted to yield both adjusted CAPE and Bulk Richardson numbers. Such adjustments were possible since only low level warming and moisture advection occurred in the hours immediately following the sounding; no significant changes were shown to take place at the middle and upper levels. This process was employed with the soundings from 27/1200 at Centreville, Alabama, and Jackson, Mississippi, and with the special 27/1800 soundings from those sites.

The SHARP software package also computed other storm parameters, such as storm motion, mean wind, and storm-relative helicity. The computer analysis of data verified the usefulness of these soundings and stability indices.

c. Verification of Sounding Parameters

The stability indices were shown to be strong indicators of the geographical extent of the varying types of weather observed in this outbreak. The area affected by tornadoes extended roughly from east central Mississippi through west central North Carolina; within this region, upper air observations showed helicity values greater than 400 m^2s^{-2}. In north Georgia, northwest South Carolina, and west central North Carolina where the number of tornadoes was greatest, helicity values in excess of 700 m^2s^{-2} were observed. All areas affected by the strong and severe thunderstorms showed high values of CAPE (or adjusted CAPE). Conversely, in areas of low CAPE and helicity, there was no convective activity. In central Alabama and coastal South Carolina, the CAPE was less than 1000 J/kg, and the helicity was less than 450 m^2s^{-2}.

The Jackson, Mississippi, soundings at 27/1200 and 27/1800 correlated with the occurrence of severe weather for a single site. At 27/1200, the CAPE was 774 J/kg and the helicity was 327 m^2s^{-2}. Between 27/0900 and 27/1600, there were no thunderstorms reported in the vicinity of Jackson. The 27/1800 sounding showed the CAPE had increased to 2020 J/kg, and the helicity increased to 486 m^2s^{-2}. Thunderstorms began at about 27/1615 and continued through 27/1930.

Further information concerning specific values of CAPE, Bulk Richardson numbers, and storm relative helicity can be found in Appendix A.

6. Watches and Warnings

a. Watch Analysis

The NWS National Severe Storms Forecast Center in Kansas City issued one severe thunderstorm watch and eight tornado watches during this outbreak between 27/0600 and 28/0600. The locations of the watch areas are shown in Fig. 3, and further information is given in Appendix B. As mentioned earlier, there were 101 reports of severe thunderstorms (hail and high winds) and tornadoes during this period. Eighty-four of these reports occurred within the watch areas and during their respective valid times.

Directly north of WT042 there were three reports of severe weather (two tornadoes and one report of high winds) in extreme northwestern Georgia and western North Carolina before the watch issuance. This severe weather was reported to have started at 27/1325, while WT042 was not issued until 27/1700. (When the reports were available to NSSFC forecasters is not known.) To the north and northwest of WT043, there were ten reports of severe weather (two reports of hail and eight reports of high winds) in northern Louisiana and northeastern Texas. This severe weather was reported to have occurred after 27/1440, while WT043 was not issued until 27/1734. Directly to the north of WT044 in western North Carolina, there were three reports of severe weather between 27/1926 and 28/0100, the time encompassed by WT044. These occurred prior to the issuance of WT047, which covered western North Carolina.

b. Warning Analysis

During this outbreak, tornado warnings were issued by local NWS offices with lead-times (the time between warning issuance and occurrence of severe weather) of generally 10 to 20 minutes, although there were some notable exceptions. Some warnings were not issued until after the tornado had touched down and caused damage. For example, two tornadoes reported by the sheriff's office of Walker County, Georgia, at 27/1855 resulted in a warning issued by the Chattanooga WSO at 27/1905. Several other tornadoes were reported on the ground in the actual tornado warning statement as offices were issuing warnings for that county. A number of factors may result in delayed warnings, most notably failure of spotter reports to reach the responsible NWS office in a timely manner.

In this analysis, it should be noted that in several locations, such as the Oconee County area in South Carolina, the Greenville-Spartanburg-Cherokee County area in South Carolina, the Davidson-Randolph County area in North Carolina, and the St. Clair-Calhoun-Cherokee County area in Alabama, several tornadoes (apparently) at different times and in different parts of the counties were reported. This made the task of determining lead times very difficult and points out that even negative lead times (warnings issued after initial touchdown of a tornado) are not without value.
For example, it may be assumed that if a county is warned, then everyone in the county should be prepared for a tornado. As a result, in this case several locations had lead times of over a half hour. A tornado in White County, Georgia, was given a lead time of 40 minutes by the Athens office. The county was actually under two warnings at the time of the report. A tornado in Floyd County, Georgia, was given a lead time of 48 minutes by the Atlanta office. This tornado was reported one minute before the warning expired. Several offices were able to give good lead times because they warned the county ahead of the approaching tornadic thunderstorm.

The strongest tornadoes of this outbreak were in the Oconee County, South Carolina, and the St. Clair-Calhoun-Cherokee County, Alabama, areas. The Oconee County tornado was briefly rated as an F3, and the St. Clair-Calhoun-Cherokee tornado was rated an F4. However, these strong storms were not the only ones to hit those areas. Calhoun County, Alabama, was under six different tornado warnings from the Birmingham office during the day. Oconee County also had at least two tornadoes pass through during the afternoon.

The Birmingham, Alabama, and Greenville-Spartanburg, South Carolina, offices issued excellent warnings during this event. Birmingham issued 27 warnings during the period when at least five tornadoes were confirmed and generally provided lead times of 15 to 30 minutes. Unfortunately, one tornado which resulted in 20 deaths at a church in Cherokee County, Alabama, was given a lead time of only eight minutes. The Greenville-Spartanburg office issued nine warnings which were associated with at least seven confirmed tornadoes. The office provided lead times of 15 to 30 minutes, although the second tornado which struck Oconee County was given a lead time of only five minutes.

After analyzing warnings issued by other offices whose areas of responsibility included parts of the large area affected during this event, it was concluded that all did a very professional job in response to the outbreak. In all, 89 tornado warnings were issued, and 34 tornadoes were reported. Several funnel clouds were also observed during the outbreak, including some reported to the office in Shreveport, Louisiana.

7. Summary

This study analyzed various aspects of the distribution, generation, and propagation of severe weather during one outbreak. The examination of mesoscale structures showed that the development of outflow boundaries assisted in the propagation of existing cells and caused the generation of subsequent cells. Maps were generated that displayed the spatial distribution of reported severe weather. From that analysis, watches and warnings which were issued during the event were compared with reports of severe weather.

Some reports were received from outside the area or time of a few of the watches suggesting that the watches might have been larger. A more detailed analysis by NSSFC would be necessary to determine whether that is the case. This analysis showed the usefulness of several indices frequently used by forecasters to assess the potential for severe weather. In regard to warnings, it was determined that local NWS offices did a generally excellent job of issuing timely warnings for the many tornadoes that occurred.

APPENDIX A

Stability Indices and Storm Parameters

ID	TIME	CAPE	A-CAPE	BRN	A-BRN	SRH	MVT	WIND
AHN	27/12	0	3142	0	14	740	271/40	227/45
AYS	27/12	764	2239	9	26	432	267/27	221/32
CHS	27/12	377	1828	3	13	569	268/28	216/34
CKL	27/12	855	N/A	9	N/A	435	265/33	227/35
GSO	27/12	0	39	0	0	909	254/41	208/47
JAN	27/12	774	N/A	4	N/A	327	256/32	220/34
CKL	27/18	2103	N/A	11	N/A	510	253/41	218/44
JAN	27/18	2020	N/A	15	N/A	486	250/40	218/42
AHN	28/00	1054	N/A	6	N/A	662	257/41	215/43
CHS	28/00	490	N/A	10	N/A	196	257/31	224/35
GSO	28/00	0	648	0	N/A	795	254/37	213/36

Abbreviations:

ID	Station identifier
TIME	Date/Time (UTC)
CAPE	Convective available potential energy
A-CAPE	Adjusted convective available potential energy
BRN	Bulk Richardson number
A-BRN	Adjusted Bulk Richardson number
SRH	Storm relative helicity
MVT	Storm motion, given in Direction (deg)/Speed (kts)
WIND	Mean wind, given in Direction (deg)/Speed (kts) from 0-3 km
N/A	Value or computation does not apply, is unnecessary, or is not computable given other quantities

APPENDIX B

Location and Time of Watch Areas

WS040 Lines 65 miles north and south (N & S) of the axis from 20 miles WSW of San Antonio, TX, to 65 miles SE of College Station, TX, from 27/0635 to 27/1029.

WT041 Lines 70 miles N & S of the axis from 70 miles WNW of Meridian, MS, to 35 miles E of Gadsden, AL, from 27/1513 to 27/2130.

WT042 Lines 55 miles N & S of the axis from 25 miles SW of Rome, GA, to 20 miles NE of Athens, GA, from 27/1700 to 28/0000.

WT043 Lines 70 miles N & S of the axis from 20 miles W of Fort Polk, LA, to 30 miles NNE of Jackson, MS, from 27/1734 to 28/0000.

WT044 Lines 55 miles N & S of the axis from 30 miles WSW of Anderson, SC, to South Pines, NC, from 27/1926 to 28/0100.

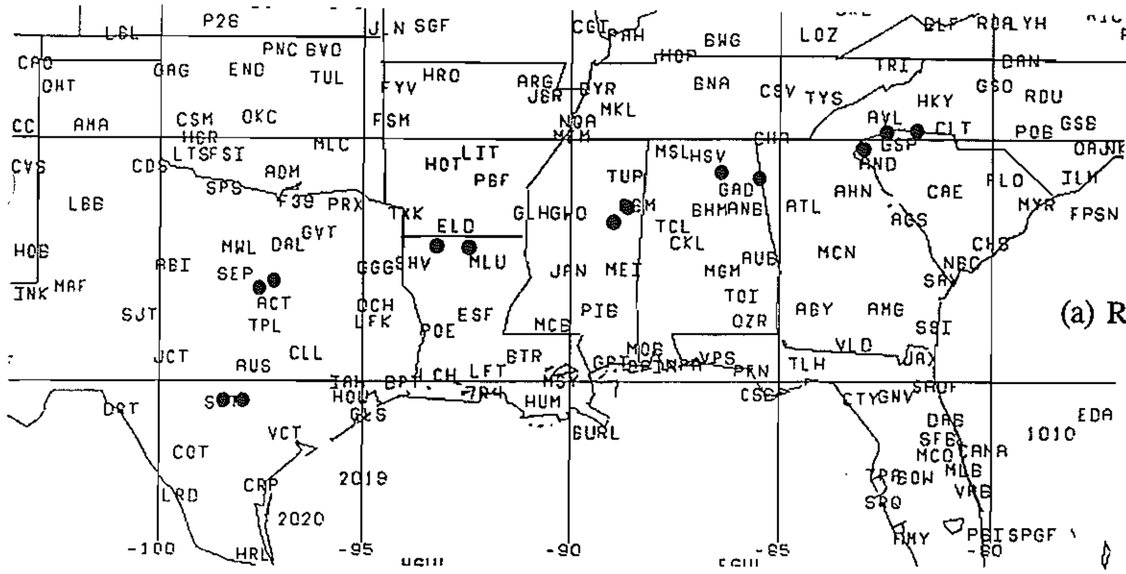
WT045 Lines 70 miles N & S of the axis from 55 miles NW of Laurel, MS, to 35 miles E of Gadsden, AL, from 27/2047 to 28/0400.

WT046 Lines 65 miles N & S of the axis from 35 miles SSW of Rome, GA, to 30 miles NNE of Athens, GA, from 27/2217 to 28/0400.

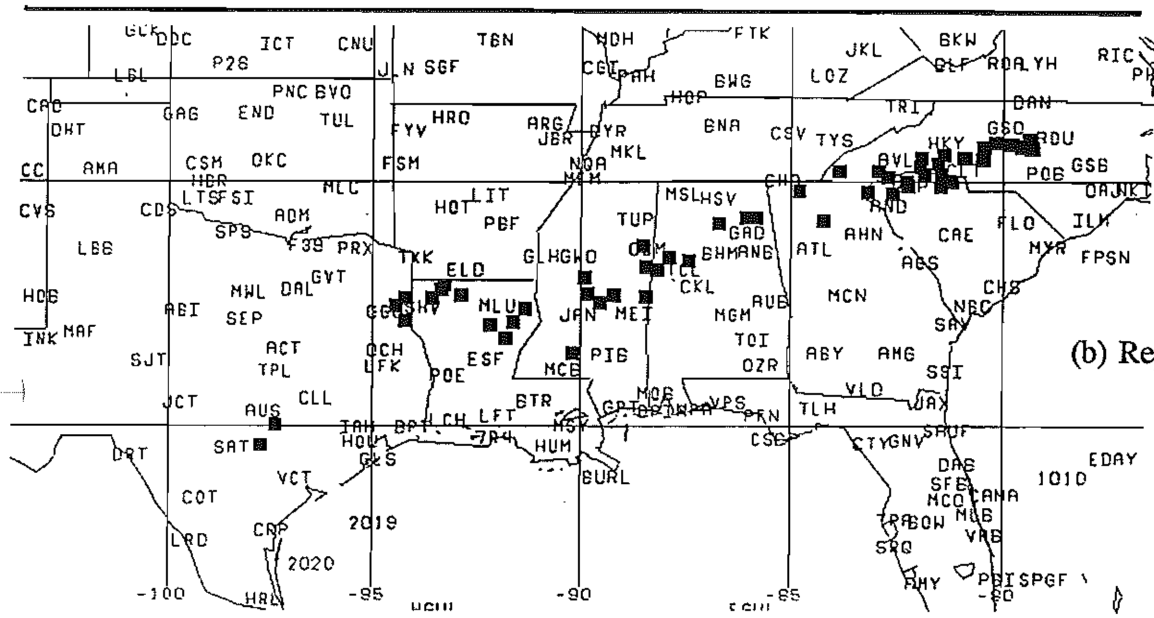
WT047 Lines 60 miles N & S of the axis from 35 miles NW of Anderson, SC, to 10 miles SSE of Rocky Mount, NC, from 28/0031 to 28/0700.

WT048 Lines 40 miles either side of the axis from 55 miles SSW of Atlanta, GA, to 45 miles NNE of Athens, GA, from 28/0316 to 28/0700.

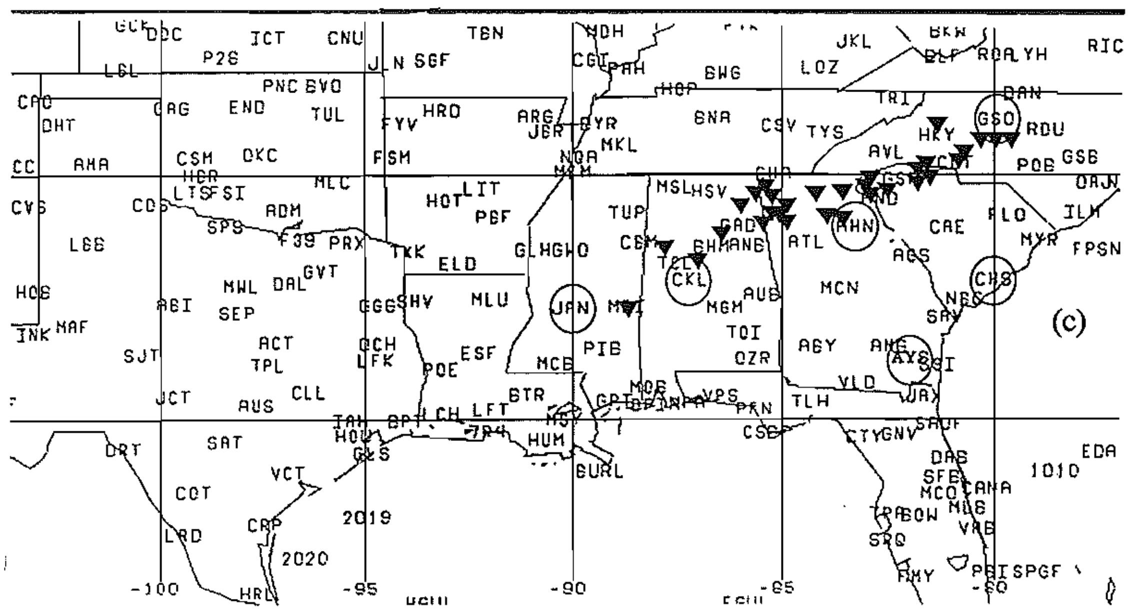
Figure 1



(a) Reported hail events



(b) Reported high wind events



(c) Reported tornadoes. (Upper air sites circled.)

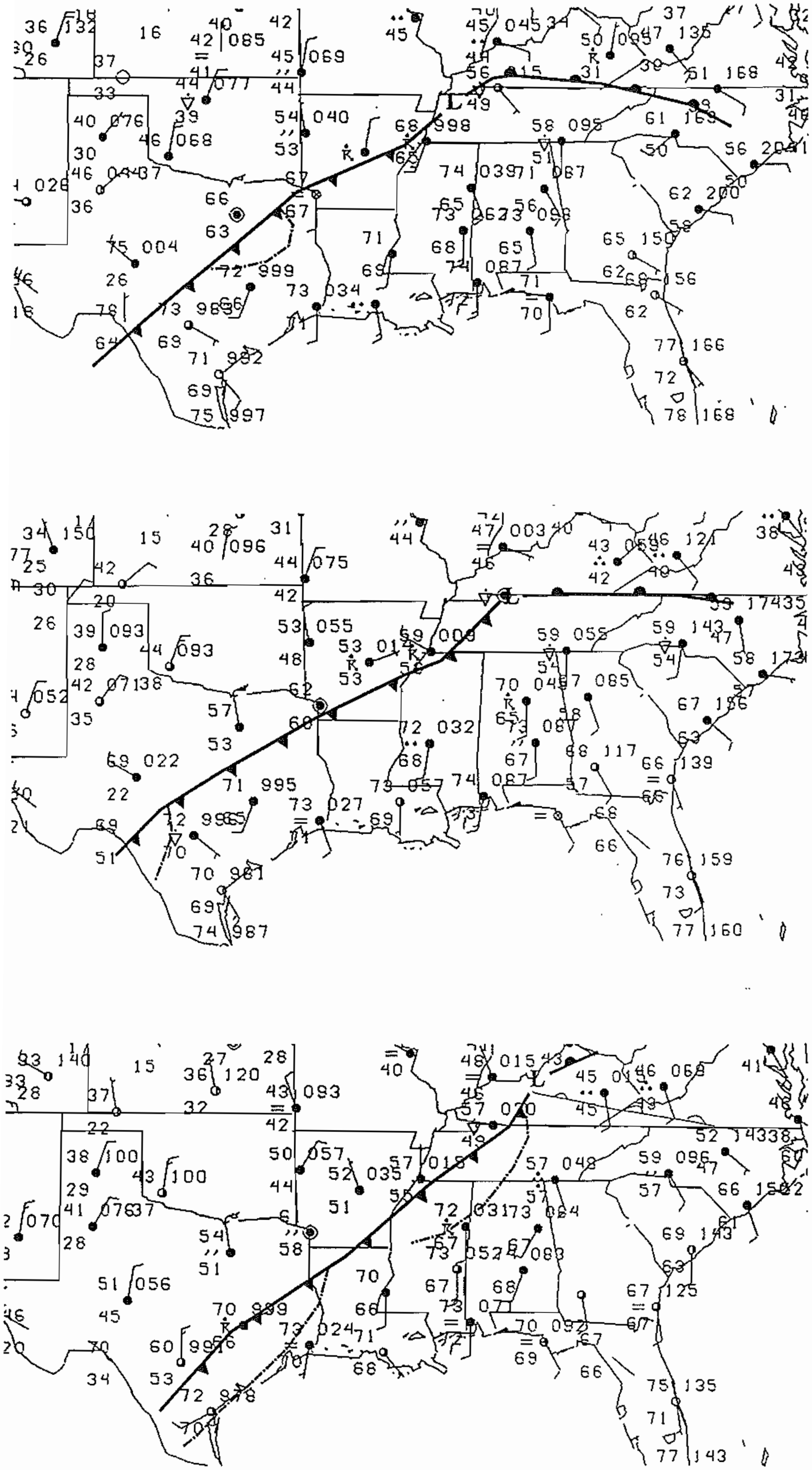
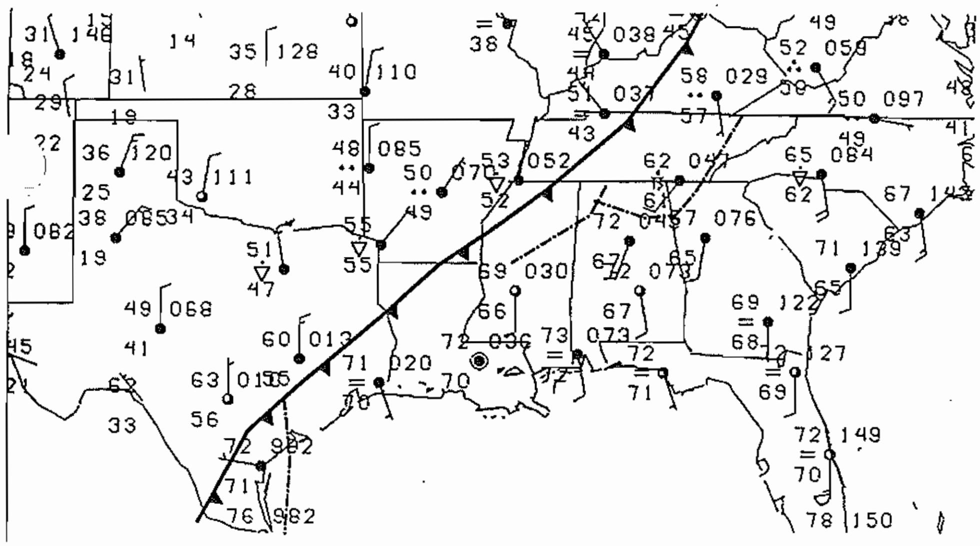


Fig. 2. Surface Analysis.

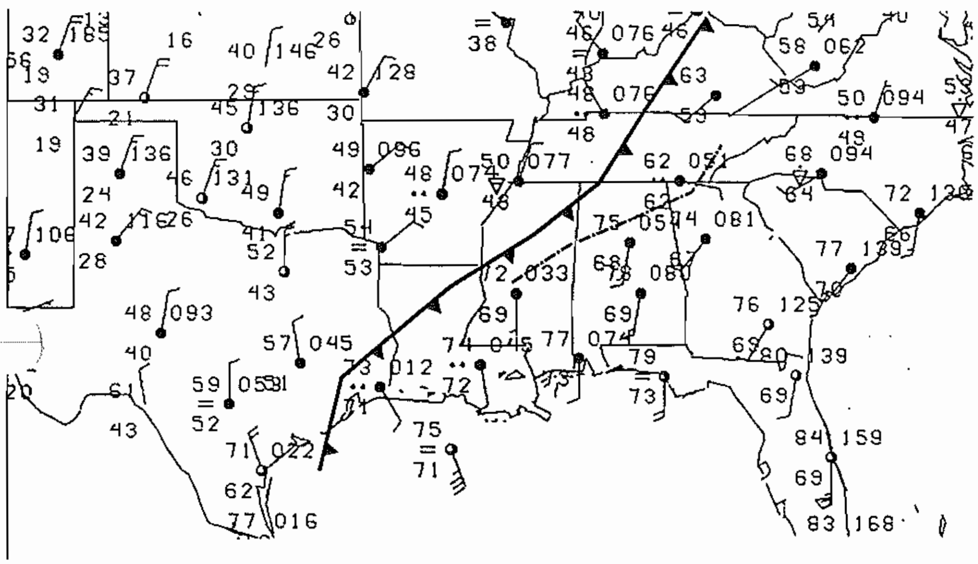
(a) March 27, 1994 0300 UTC

(b) March 27, 1994 0600 UTC

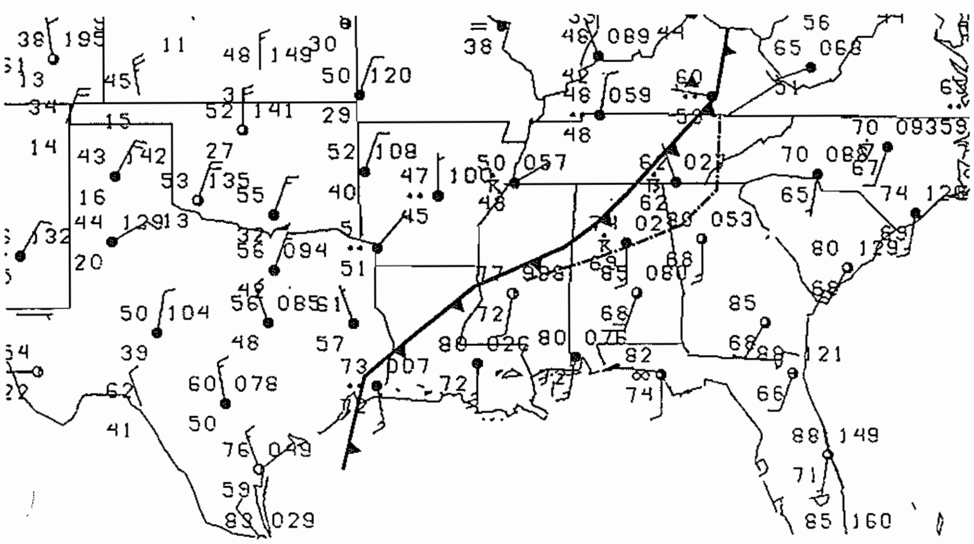
(c) March 27, 1994 0900 UTC



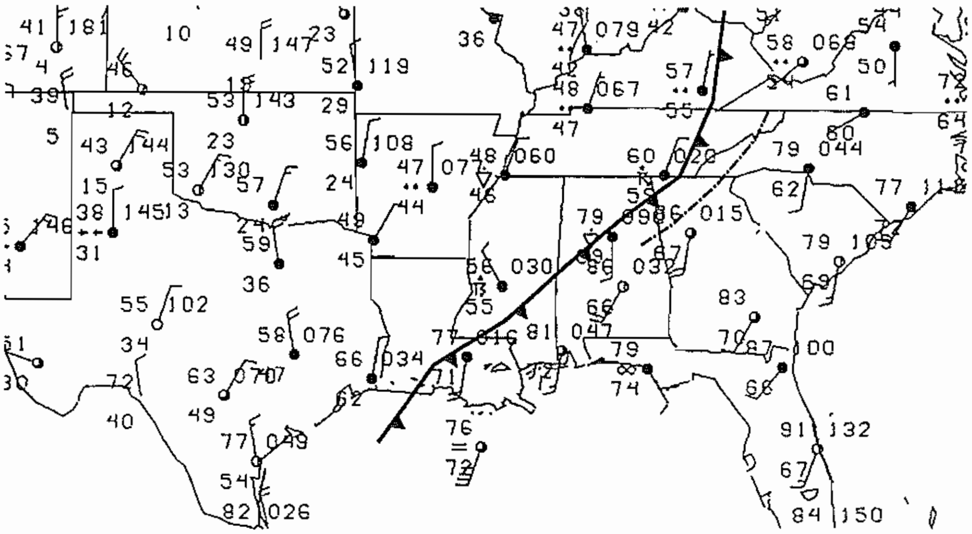
(d) March 27, 1994
1200 UTC



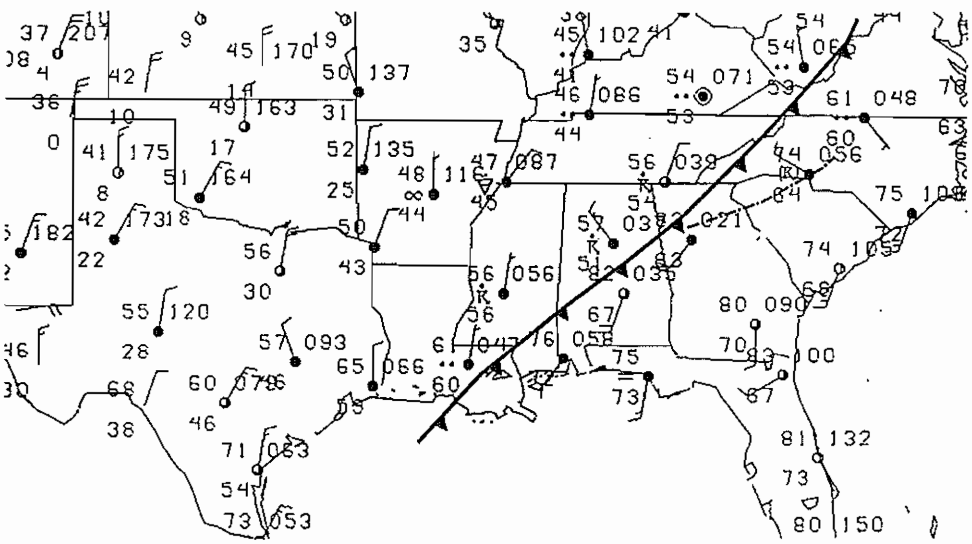
(e) March 27, 1994
1500 UTC



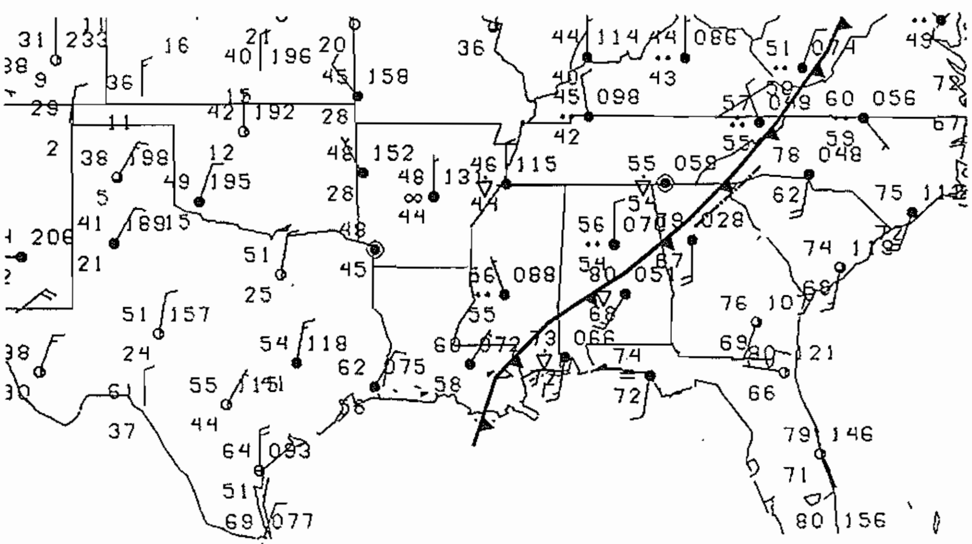
(f) March 27, 1994
1800 UTC



(g) March 27, 1994
2100 UTC



(h) March 28, 1994
0000 UTC



(i) March 28, 1994
0300 UTC

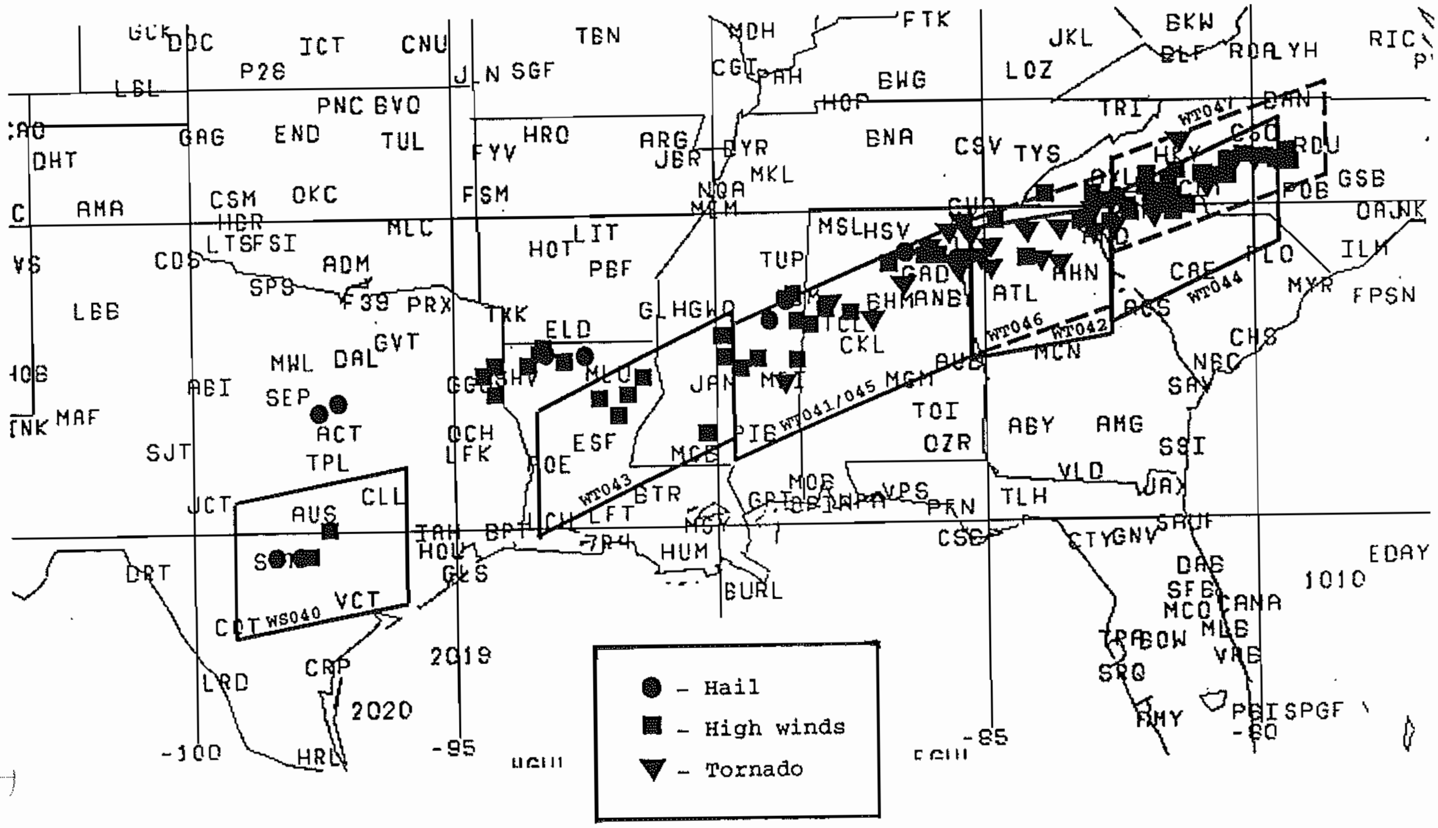


Fig. 3. Location of severe weather between 27/0300 and 28/0300. The severe thunderstorm watch and tornado watch areas issued by the NSSFC are also shown for this time period. WT046 and WT047 are shown in dashed lines to easier distinguish from previous watch areas. WT041 and WT045 overlap (to the scale of this map) and are shown as one area. WT048 is not shown.