ELEVATED COLD-SECTOR SEVERE THUNDERSTORMS: A PRELIMINARY STUDY

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Abstract

A preliminary study of atmospheric conditions in the vicinity of severe thunderstorms that occurred in the cold sector, north of east-west frontal boundaries, is presented. Upper-air soundings, surface data and PCGRIDDS data were collected and analyzed from a total of eleven cases from April 1992 through April 1994. The selection criteria necessitated that a report occur at least fifty statute miles north of a well-defined frontal boundary. A brief climatology showed that the vast majority of reports noted large hail (diameter: 1.00–1.75 in.) and that the first report of severe thunderstorms occurred on an average of 150 miles north of the frontal boundary. Data from 22 proximity soundings from these cases revealed a strong baroclinic environment with strong vertical wind shear and warm air advection from just above the surface through 500 mb. This advection was reasoned to provide a constant source for destabilization from lifting above the frontal inversion.

Convective instability was noted in all cases above the boundary layer with stability indices revealing the most unstable parcel located near the 850-mb layer. Despite quite cool and stable surface conditions, CAPE, best lifted index and total-totals index values suggested at least a marginal degree of instability was required for cold-sector, severe thunderstorm development. After examining the proximity soundings, PCGRIDDS data were then analyzed to determine which forecast fields from the ETA model best delineated cold-sector, severe thunderstorm development. Reports of severe weather occurred very near the ETA model forecast, 850-mb, warm air advection maximum. In addition, a majority of reports occurred along the axis of strongest 850-mb theta-e advection. Constructed cross-sections normal to isotherms or thickness contours showed where areas of elevated or slightly sloped theta-e surfaces were located above the frontal surface. These areas of potential convective instability combined with upward vertical velocity fields correlated well with the location of subsequent severe thunderstorm reports.

1. Introduction

Forecasting severe thunderstorms is challenging year round even in classic "synoptically evident" patterns (Johns and Doswell 1992). Forecasting can be particularly difficult in situations where thunderstorms develop well north of a surface boundary in an environment characterized by relatively cool, stable conditions at the surface. These cold sector, or "elevated thunderstorms," as Colman (1990) has termed them, are typically not as destructive as thunderstorms that form in the warm sector. However, these elevated storms can still produce a significant amount of severe weather and are more numerous than one might expect.

Colman (1990) found that nearly all cool season (Nov–Feb) thunderstorms east of the Rockies, with the exception of those over Florida, were of the elevated type. The environment that produced these thunderstorms displayed significantly different thermodynamic characteristics from environments whose thunderstorms were rooted in the boundary layer. In addition, he found a bimodal variation in the seasonal distribution of elevated thunderstorms with a primary maximum in April and a secondary maximum in September. The location of the primary maximum of occurrence in April was over the lower Mississippi Valley. This maximum shifted into eastern Kansas by May (Fig. 1).

One of Colman's criteria for case selection was that a reported thunderstorm (from surface observation) had to lie on the cold side of an analyzed frontal boundary that showed a clear contrast in temperature, dew point temperature and wind direction. This restriction was also adopted for this study of cold-sector severe thunderstorms. In addition, inclusion in this study necessitated the occurrence of at least five severe thunderstorm reports (tornado, wind gusts ≥ 50 kt, hail ≥ .75 in., or thunderstorm wind damage) at a location at least 50 statute miles north of the boundary.

Eleven severe thunderstorm cases from April 1992 through April 1994 satisfied the collection criteria. These cases were collected and investigated for this study with the primary source of data being the NWS/National Severe Storms Forecast Center's (NSSFC) severe local storms (SELS) rough log and the SVRPLOT (Hart 1993) program. Proximity soundings, surface observations and objective analysis were utilized in order to examine the individual cases. A total of twenty-two proximity soundings from both 1200 and 0000 UTC sampled the thermodynamic and kinematic structure of the atmosphere in the vicinity of cold-sector severe thunderstorms. To ensure that each proximity sounding was representative of the elevated, cold-sector storm environment, the sounding needed to occur within three hours and 100 statute miles of a severe thunderstorm report. Moreover, all proximity soundings had to be taken in the cold sector, north of the main frontal boundary.

Subjective, upper-air analyses of conditions at 1200 and 0000 UTC were also used to assess the position of observed meteorological parameters. Observed sounding data were displayed in graphical format for individual and aggregate illustration. In addition, the NWS PC-based GRidded Information Display and Diagnosis System (PCGRIDDS) data from the NWS/National Meteorological Center's (NMC) ETA model were examined to determine which, if any, parameters from the model showed good correlation with areas of severe thunderstorm development for a 12-hour forecast period.

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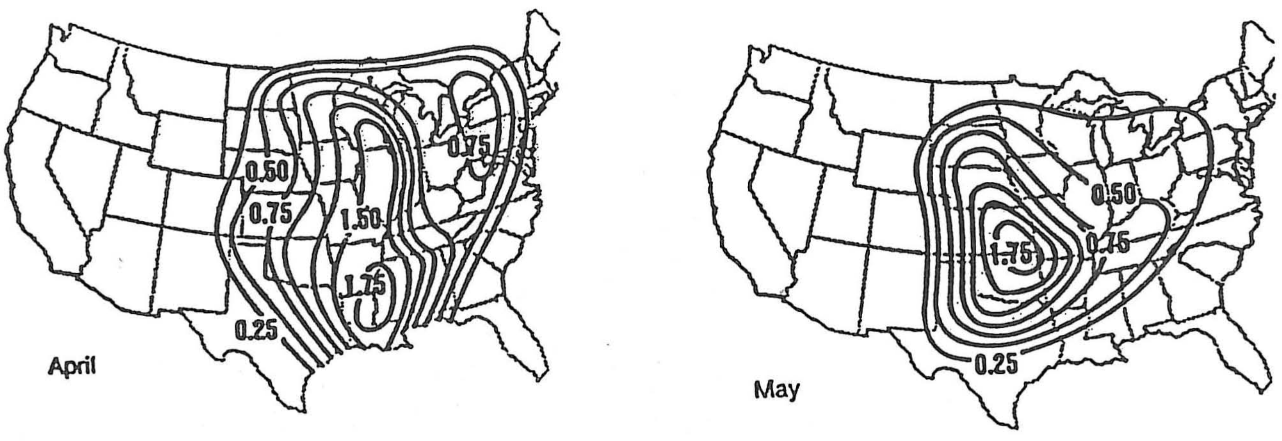


Fig. 1. The number of elevated thunderstorms (reports per station) for April and May (from Colman 1990).

2. Results From Sounding Data

A total of 321 severe reports occurred during the eleven cases. Of that number, the majority (92%) were hail reports. Seven percent were wind related reports with tornadoes comprising the remaining one percent. Figure 2 shows the size distribution for hail reports. The graph indicates that over half of all reports were large hail (diameter: ≥ 1.00 in.).

The severe reports occurred to the north of either a warm front (six times) or a stationary frontal boundary (five times). The orientation of the front was generally east to west. The average north-south distance from the location of the initial severe report to the frontal boundary was 143 miles, with the greatest distance being 380 miles from the front.

Examination of the 22 proximity soundings revealed a considerable amount of directional and speed shear in the lower and middle layers of the atmosphere. Figure 3 is a scatter diagram comparing the wind direction at 850 mb and 500 mb. The average amount of directional shear was 45 degrees. Assuming geostrophic balance, warm advection can, therefore, be inferred in those cases where the wind veered between layers.

In most cases, soundings possessed at least 20 kt of positive speed shear between 850 and 500 mb (Fig. 4). This illustrates the importance of a strongly baroclinic environment in cold-sector severe convection.

In addition, winds veered in all but one sounding from the surface to 850 mb (Fig. 5). The average directional shear between surface and 850-mb levels was more extreme (140 deg), with the surface direction generally easterly, and the 850-mb flow southerly to southwesterly.

An examination of the orientation of the 850 and 500-mb wind flow at 1200 and 0000 UTC revealed that in most of the cases, the analyzed 500-mb jet was well to the north of the severe weather area, with the direction being generally westerly. The 850-mb jet, on the other hand, ranged from a southerly to southwesterly direction with the maximum originating in the warm sector and extending at least 100 to 200 miles north of the surface frontal boundary. In situations where the severe reports occurred well before or after sounding time (three hours or more), ETA model forecasts were used to interpolate jet

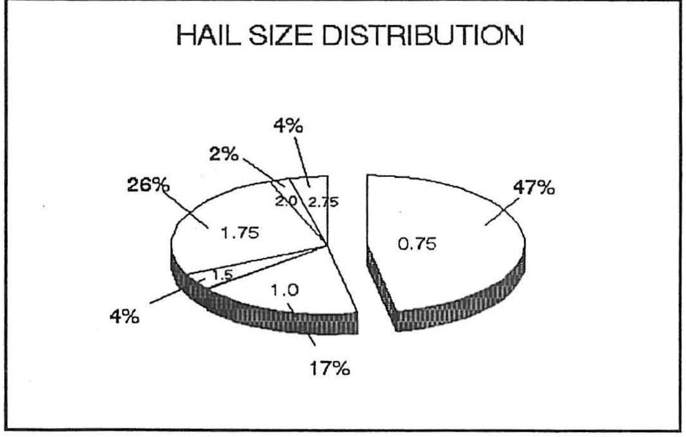


Fig. 2. Distribution of hail sizes (in.) from cold-sector thunderstorms studied.

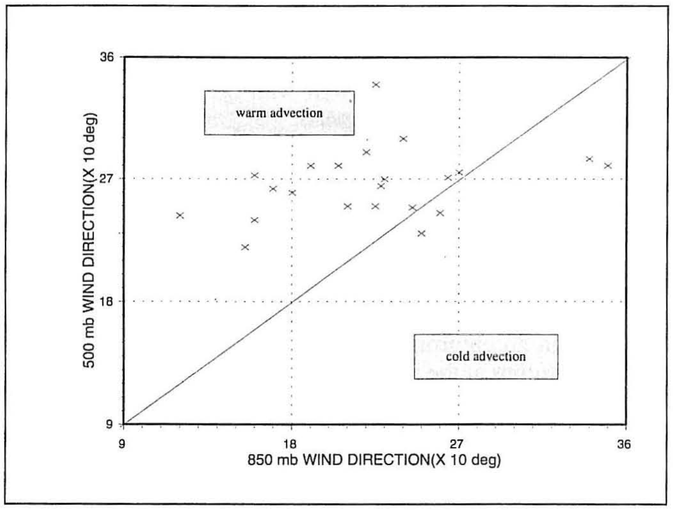


Fig. 3. Wind directions at 850 mb vs 500 mb from 22 soundings analyzed.

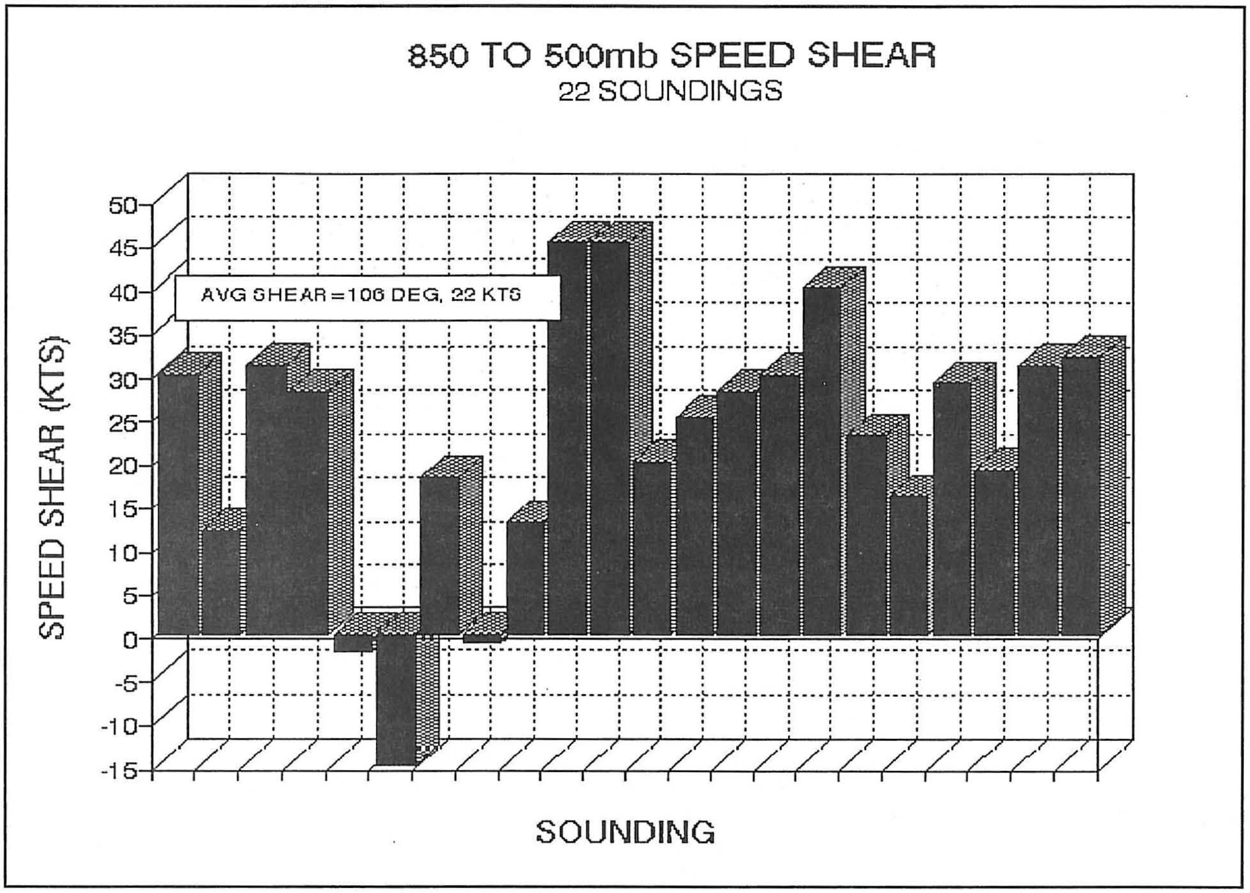


Fig. 4. Wind speed shear (kt). Value is scalar difference of 500-mb wind speed minus 850-mb wind speed from 22 soundings analyzed.

positions. The majority of reports occurred in the northeastern quadrant of the 850-mb jet streak. The average 500-mb temperature for the 22 soundings was −16.3°C. Surface and 850-mb temperatures and dew points, and their respective means are shown in Figs. 6 and 7. The graphs indicate cool and moist conditions existed in most cases from the surface to the 850-mb layer.

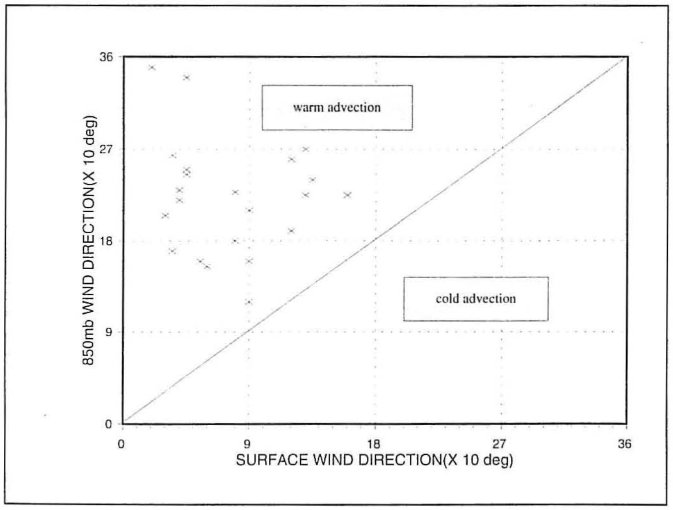


Fig. 5. Wind directions at surface vs 850 mb from 22 soundings analyzed.

A proximity sounding from Topeka, Kansas (TOP) from 1200 UTC 9 APR 1992 (Fig. 8) is representative of the environment associated with severe convection north of the front. Note that although parcels originating at the surface will be quite stable, parcels lifted from near 850 mb become quite buoyant before reaching their equilibrium level at 200 mb. In fact, the SHARP program indicates a CAPE (Convective Available Potential Energy) of 1326 J Kg^{-1}.

Stability indices have long been used in severe local storms forecasting for measuring the degree of instability in a given upper air sounding. A lifted index (LI) was calculated for all 22 soundings in the sample lifting the most unstable parcel in the lowest 300 mb and subtracting the parcel temperature from the ambient 500-mb temperature. The results in Fig. 9 show an average LI of −3.1°C. This is slightly more unstable than results obtained from Colman (1990) for general thunderstorm cases when the parcel was lifted from near 850 mb. The two stable cases in Fig. 9 where LI values were positive were associated with soundings taken three hours before severe thunderstorms occurred. Thus, the environmental air mass probably was modified and became more unstable in the vicinity of the storm.

The Showalter index (SI), which measures latent instability in soundings by lifting parcels from 850 mb, was also calculated for every proximity sounding (graph not shown). Results were very similar to the LI (avg SI = −1.6°C), but occasionally when the frontal inversion extended beyond the 850-mb layer, SI underestimated the latent instability.

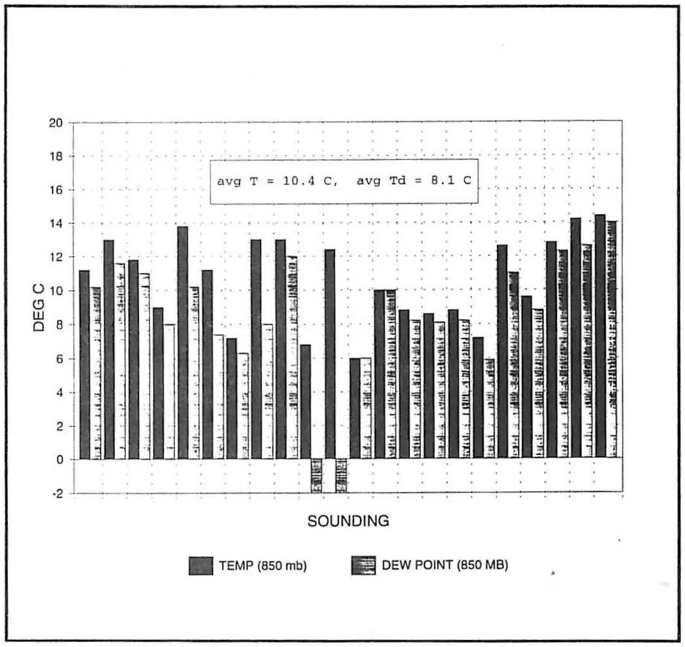


Fig. 6. Temperatures (°C) and dew points (°C) at 850 mb.

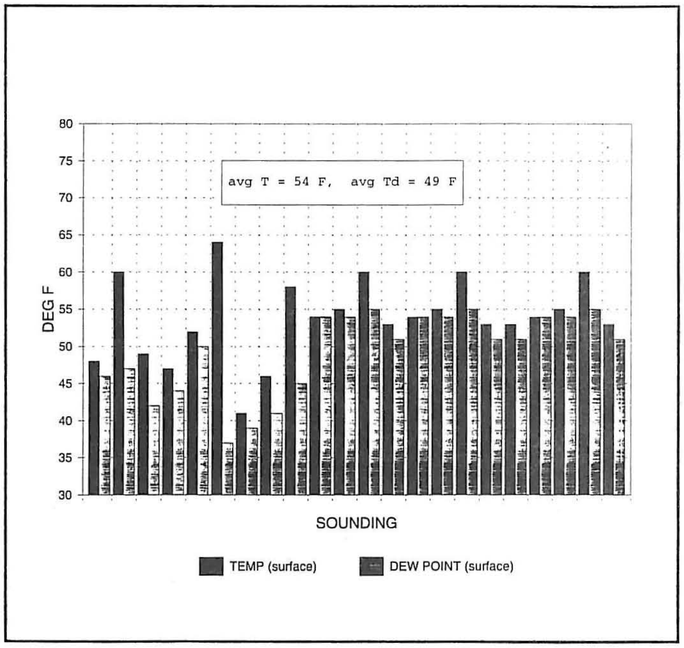
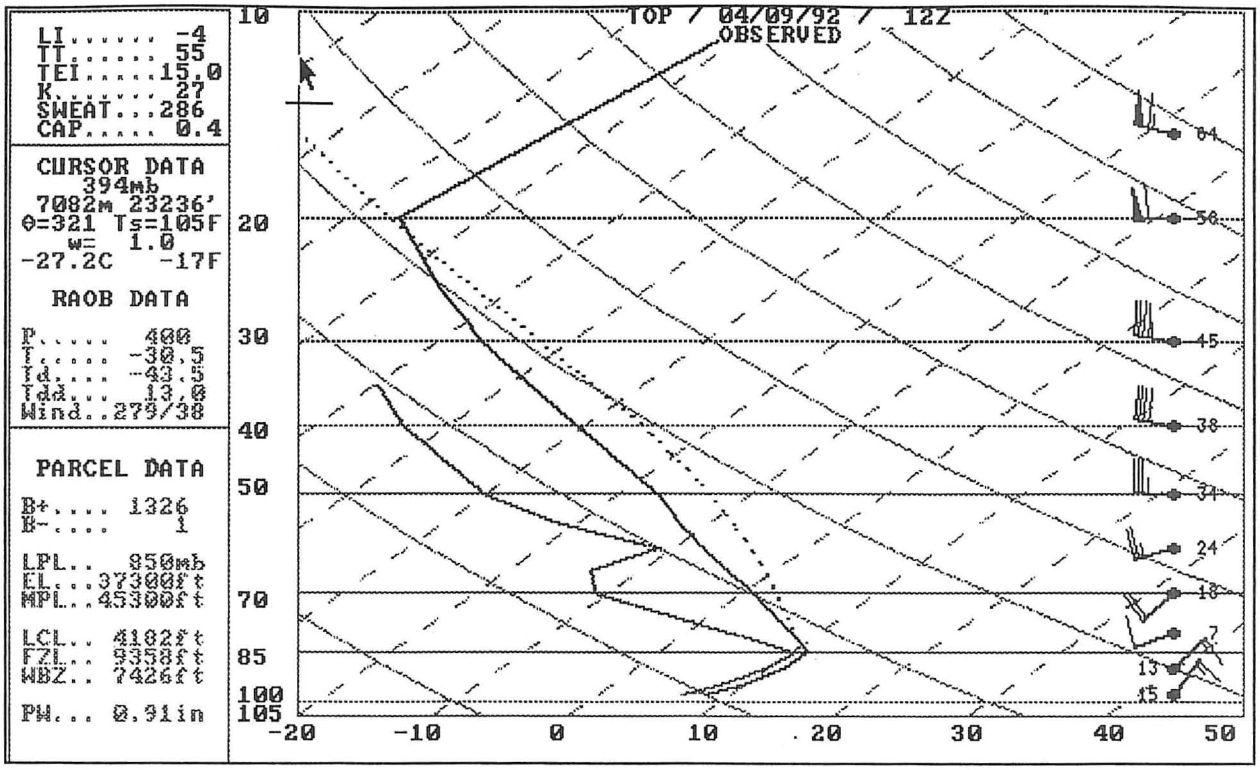


Fig. 7. Temperatures (°F) and dew points (°F) at surface.

Thus, the instability near cold-sector severe thunderstorms always exhibited at least a marginal degree of instability when the most unstable parcel in the lowest 300 mb of the sounding was lifted to 500 mb. Surface-based LI values, on the other hand, were quite stable and were very unrepresentative of the convective potential of the environmental air in the vicinity of the sounding. The convection evidently resulted from air parcels originating above the frontal inversion.

CAPE was calculated for each sounding using the SHARP (Hart and Korotky 1992) program (graph not shown). CAPE



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LI....... -4
TT....... 55
TEI.....15.0
K........27
SWEAT...286
CAP...... 0.4

CURSOR DATA
   394mb
 7082m 23236'
θ=321 Ts=105F
    w= 1.0
-27.2C    -17F

RAOB DATA

P.....    400
T.....  -30.5
Td....  -43.5
Tdd...   13.0
Wind..279/38

PARCEL DATA

B+....  1326
B-....     1

LPL..   950mb
EL...37300ft
MPL..45300ft

LCL..  4102ft
FZL..  9358ft
WBZ..  7426ft

PW... 0.91in
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Fig. 8. Sounding from Topeka, Kansas (TOP) at 1200 UTC 9 April 1992.

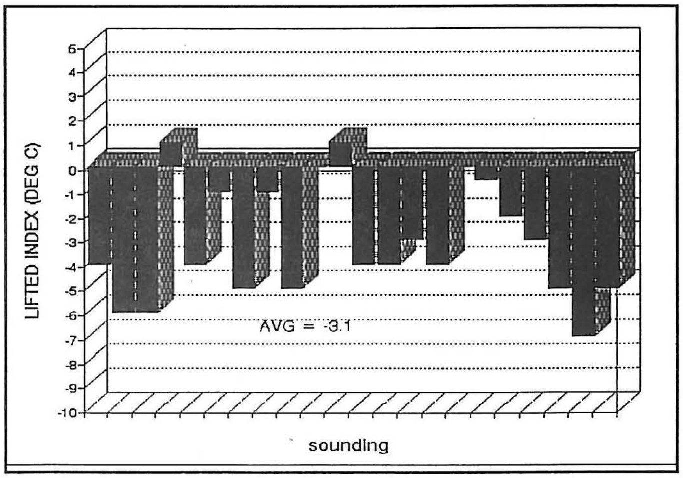

Fig. 9. Lifted Index (LI) values for 22 soundings analyzed.

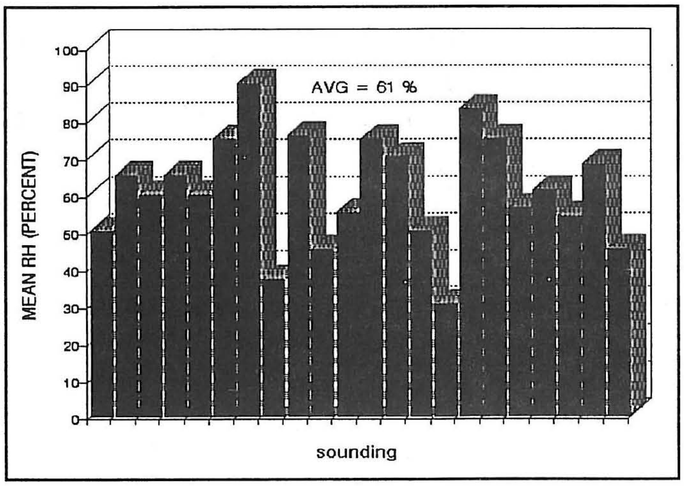

Fig. 10. Mean relative humidity (%) in the 700–500 mb layer.

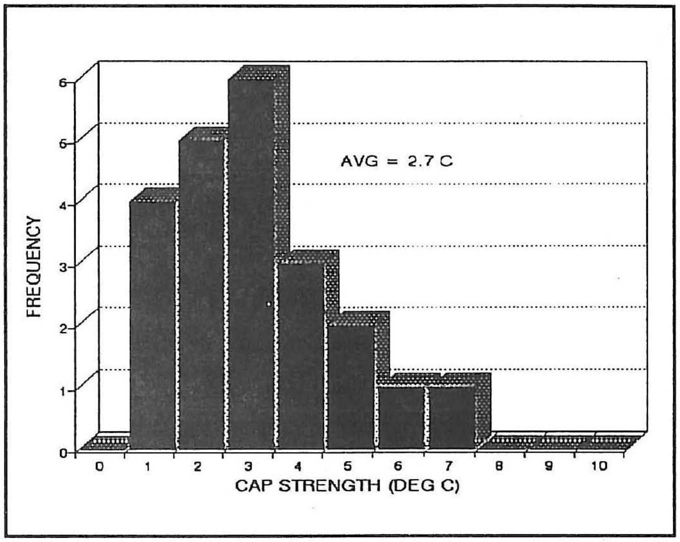

Fig. 11. Cap strength (°C) for 22 soundings analyzed.

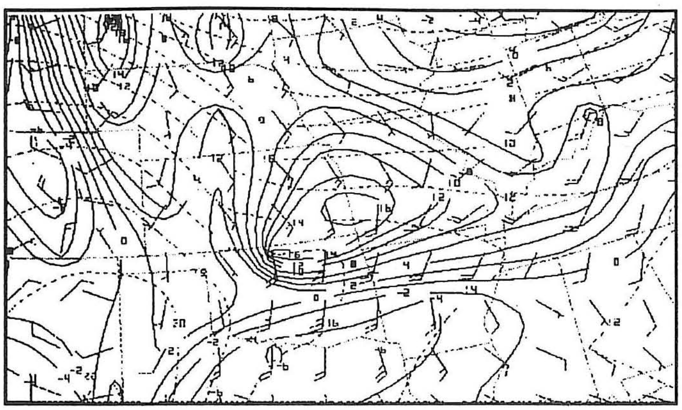

Fig. 12. ETA model 12-h forecast of 850-mb winds (kt), temperatures (°C; dashed lines) and temperature advection (solid lines) valid for 0000 UTC 10 April 1992.

was defined as in SHARP as the integrated area between parcel ascent curve and the environmental temperature curve, from the level of free convection (LFC) to the equilibrium level (EL). The most unstable parcel originating out of the lowest 150 mb was used in these calculations. Values ranged from around 100 to nearly 2000 J Kg^{-1} with the average proximity sounding CAPE being approximately 700 J Kg^{-1}

Another stability index used in SELS is the Total Totals Index (TT), an index based on the 850–500 mb lapse rate combined with moisture at 850 mb. The average TT for the 22 cold sector soundings was 52, a value which is classified as a moderate threshold for severe thunderstorm activity.

The existence of mid-tropospheric dry air is a factor in severe thunderstorm development (Miller 1972; Doswell 1982). Mean relative humidity (RH) was calculated in the soundings for the 700 to 500-mb layer (Fig. 10). The average RH over 22 soundings was 61 percent, indicating that some degree of deeper moisture should be present in the pre-storm environment for cold-sector elevated severe thunderstorms.

Figure 11 shows the ''cap'' for surface parcels lifted to 850 mb. The ''cap'' in this sense is defined as the temperature deficit of the surface air passing through 850 mb. The distribution of the cap is quite noticeable with the peak around two to three deg C, which reiterates the importance of a strong frontal inversion for the development and maintenance of elevated severe convection.

3. Results From PCGRIDDS Data

Various fields from the ETA model were analyzed via PCGRIDDS data to see which parameters best forecast the severe thunderstorm area. Of all the fields analyzed, 850-mb warm air advection and theta-e advection displayed the best correlations between forecast gridded fields and the area where subsequent severe reports occurred. Figure 12 shows the 12-hour forecast from 1200 UTC 9 April 1992 from the ETA model showing 850-mb temperatures, winds and resulting temperature advection fields. As can be seen from the severe reports for the day (Fig. 13), the warm advection maximum correlated quite well to the location of storm reports north of the front. In fact, almost 70% of all reports in the 22 soundings were contained in a 10 degree or greater warm advection contour interval (avg. max contour = 23). Vertical cross sections of equivalent potential temperature (theta-e) have been shown to be useful in diagnosing areas of elevated convective instability (Moore 1992). A north-south cross-section from PCGRIDDS constructed from near the Texas coast to central Minnesota is shown in Fig. 14. The cross-section, which was also for the 12-hour forecast valid 0000 UTC 10 April 1992, indicated the area of highest theta-e above the frontal inversion (at 850 mb) near 39°N 95°W. This region is also where theta-e contours are most vertical and decrease with height aloft. Thus, this area is locally convectively unstable and lifting can release the instability. The strongest upward motion as indicated by the vertical velocity fields (noted by the dashed lines) correlated quite well to this area of elevated high theta-e values. This area of upward motion was likely linked to the warm advection zone (Fig.12).

4. Conclusions

Convection associated with severe thunderstorms that develop in the cold sector, north of east-west frontal boundaries, appears to be rooted in a layer above a rather shallow, but quite significant, frontal inversion. An investigation of the soundings taken in the vicinity of these storms, which were typically hail-producers, indicated that the most unstable parcels in these soundings were frequently located near the 850-mb level. Wind fields from the soundings showed strong warm air advection profiles above the boundary layer up to 500 mb. Despite quite cool and stable surface conditions, stability indices revealed that soundings taken in the vicinity of cold-sector severe thunderstorms possessed a marginal degree of instability when the

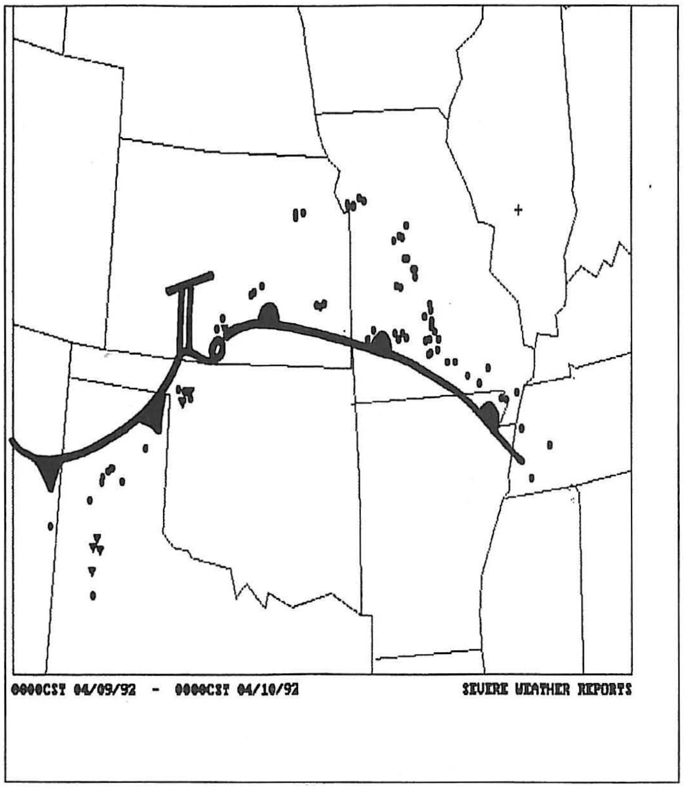

Fig. 13. Severe weather reports for 9 April 1992 (▼ = tornado; • = hail; + = wind). Only those reports north of the analyzed warm front (1800 UTC) were included in the study.

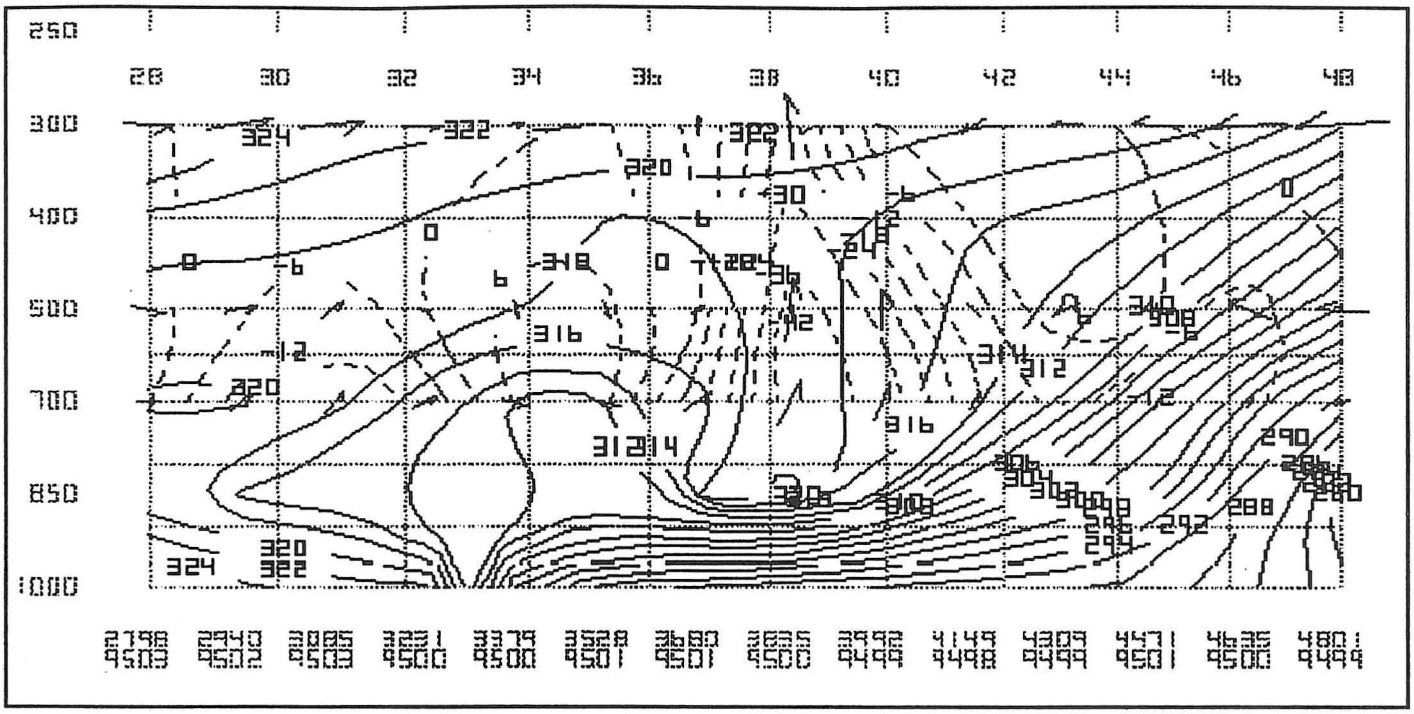

Fig. 14. Cross section from near the Texas coast to central Minnesota valid 0000 UTC 10 April 1992 showing equivalent potential temperature (°K; solid lines), vertical velocity with negative values indicating ascent (μ s^{-1}; dashed lines) and vertical circulation (m s^{-1}; arrows). Latitude (°N) and longitude (°W) values (× 10^{-2}) at bottom of chart.

most unstable parcel was lifted above the capping inversion. Forecast parameters such as 850-mb warm air advection and theta-e advection most accurately delineated the areas where subsequent severe thunderstorms were reported. These advection fields showed where regions of strongest upward motion and destabilization were occurring above the boundary layer which led to the development of severe thunderstorms.

PCGRIDDS constructed cross-sections showed where areas of elevated or slightly sloped theta-e surfaces were located relative to the frontal inversion. Overlaid parameters such as upward vertical velocity correlated well to these areas and to areas of subsequent severe thunderstorm reports.

With only a limited number of cases in this study, the results of this investigation may not be totally conclusive. The inclusion of more cases will undoubtedly increase the understanding and improve our ability to forecast cold-sector severe thunderstorms.

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Brad Grant recently became a meteorologist instructor at the NEXRAD Operational Support Facility (OSF) in Norman, Oklahoma. He spent the last four years at the National Severe Storms Forecast Center (NSSFC) in Kansas City, Missouri. During that tenure, he worked three years in the Severe Local Storms (SELS) unit as a convective outlook forecaster, and one year in the now defunct Satellite Interpretation Unit (SIM). Before that, Brad served two years at the National Weather Service Forecast Office (WSFO) in Memphis, Tennessee, and two years as a staff meteorologist with WTVT/Gulf Coast Weather Service in Tampa, Florida. He has a B.A. in Physics from Drury College (1984) and a M.S. in Atmospheric Science from the University of Missouri (1986).

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