7A.8 TORNADOES FROM ELEVATED CONVECTION

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1. INTRODUCTION

On May 21-22, 2004, eighty-four tornadoes swept across Iowa, Nebraska, and Kansas. One of the eighty-four tornadoes was rated as having an intensity of greater than F2, the F4 Hallam, Nebraska, tornado on May, 22, 2004. Adams (2005) discussed the synoptic and mesoscale environments creating favorable conditions for the intense Hallam tornado. She also mentions six other tornadoes and the supercell differences allowing for seven of the thirty-nine tornadoes that developed across Nebraska on this day. Of the 21 tornadoes on May 21, 2004, eight were spawned from elevated thunderstorms (using the definition from Colman, 1990). The public generally associated tornadoes with hot, humid weather, so tornadoes from elevated convection, when the surface conditions are relatively cool, can be especially unexpected.

Elevated convection, a term first introduced by Colman (1990), is the idea that the fuel for convection is a layer of unstable air brought to some elevation above a frontal inversion. Three requirements must be satisfied for convection to be considered from an "elevated source":

1) The observation must lie on the cold side of an analyzed front that shows a clear contrast in temperature, dewpoint temperature, and wind.
2) The station's wind, temperature, and dewpoint temperature must be qualitatively similar to the immediately surrounding values.
3) The surface air on the warm side of the analyzed front must have a higher equivalent potential temperature (Θ_e) than the air on the cold side of the front.

Colman also looked at the frequency of thunderstorms resulting from elevated convection, and found the highest number of storms were in April or September. Elevated thunderstorms in April were likely the result of cold air aloft, advances of cold Canadian air supporting a baroclinic environment, and a surface layer that is easily "heated and moistened" before being lifted over the frontal surface. Since Colman's introduction of the term, "elevated convection" has become a widely accepted idea that is used throughout the literature.

With this background**,** eight of the tornadoes that occurred on May 21, 2004, were unusual because they were the result of elevated convection. To understand this phenomenon, section two considers meteorological methodology, section three discusses the result of the data analysis, section four discusses mesoscale modeling of this case, and section five provides a summary and brief discussion of the results.

2. METHODOLOGY

The twenty-one tornadoes on May 21, 2004 occurred in Iowa and Nebraska in the afternoon and evening hours, while the remaining sixty-three tornadoes of this outbreak occurred in the late afternoon and evening hours of May 22. Digital Facsimile (DIFAX) maps were obtained for May 20-23, 2004 to obtain background on large-scale motions in the Iowa and Nebraska regions during this time. Rapid Update Cycle (RUC) data were obtained for May 20-23, 2004 from the NCDC. The RUC data was loaded into the General Meteorological Package (GEMPAK) for analysis. The RUC data was used to obtain information about convective available potential energy (CAPE), convective inhibition (CIN), helicity, surface lifted index (SLI), lifted index from the 850 hPa level (LI-85), and the equivalent potential temperature (Θ_e).

Both metar observations from the National Climatic Data Center and the RUC data were used to determine the distance of the tornadoes from the front, as well as the surface temperature, dewpoint temperature, and wind direction in the area around the tornado. If the tornado appeared to occur on the cold side of the front, the conditions on the warm front were also recorded. Estimates of convective energy from the different indices were used to identify the source of the convection associated with the tornado.

Finally, the The Fifth Generation National Center for Atmospheric Research/Pennsylvania State University Mesoscale Model (MM5) was used to gain insight on the mesoscale details of the frontal boundary where the elevated convection occurred.

3. DATA ANALYSIS

3.1 *Synoptic Analysis*

At 00 UTC on May 21, 2004, a stationary front reached from Nevada up into Wyoming through Colorado and into the extreme southeast corner of Nebraska, where the front became a cold front reaching from Iowa into Quebec. A

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strong temperature and dewpoint temperature gradient existed on the north side of the front. The horizontal temperature gradient was 12ºC over 400 km and the dewpoint gradient was 9ºC over 350km. The cold air to the north of the front was characterized by dewpoint temperatures lower than 16°C and light winds from the east and southeast. A band of precipitation was located on the north side of the front, with precipitation values generally less than .3 inches for the twenty-four hour period reaching from 12 UTC on May 20 to 12 UTC on May 21. Local maxima of rain occurred in the northern Iowa and Chicago areas. The warm air to the south of the front was characterized by dewpoint temperatures ranging from 20°C to 23°C and light winds from the south-southwest. By 12 UTC, the stationary front moved across eastern Nebraska and central Iowa. By 18 UTC, the front had become a warm front, pushing the warm, moist air into northwestern Iowa and central Nebraska with the winds having shifted to the southwest. Surface temperatures had warmed considerably through the day, reaching 25°C to 30°C with dewpoints still ranging from 20°C to 23°C (Fig. 1). A high pressure system was dominating to the north of the front centered in eastern Ontario and western Quebec. A weak low pressure system in the western Great Plains continued its track east throughout the day. By 18 UTC it was centered in eastern Colorado and western Nebraska. Between 18 UTC and 21 UTC, several outflow boundaries developed around northeastern Iowa, northern Illinois, and southern Wisconsin, which were accompanied by heavy rainfall throughout the region.

The upper level maps clearly showed two distinct air masses meeting along the stationary front at 00 UTC on May 21. The 850hPa map showed the air mass to the south having winds from the south-southwest while the winds to the north of the front are from the east. In central Minnesota, dewpoint temperatures at the 850hPa level are -10ºC to -2ºC. Along the front in Iowa, the dewpoint temperature reached 14ºC to 16ºC, however, the moisture content rapidly decreased to the south of the front into the Missouri region, falling to 2ºC (Fig. 2). During the day, the distinct moisture band aloft pushed farther north than the surface front, bringing very moist air aloft to central Minnesota, Wisconsin, and Michigan by 18 UTC (Fig. 3). The rapid movement at the 850hPa level indicates that the warm, moist air was advecting at heights more quickly than at the surface. The higher dewpoint temperatures were seen at the 500hPa level as well, where local maxima of higher dewpoints existed between eastern Nebraska up into South Dakota and Minnesota and down into eastern Missouri.

3.2 *Tornado Outbreak*

At 1928 UTC, the first tornado of the day occurred near Holland, Iowa (42.4N, 92.8W). The surface temperature was 23°C, with a dewpoint at 18°C, and winds from the southeast at 10 knots. The air to the south had surface temperatures greater than 25°C, dewpoints from 20ºC, and winds at 10 knots from the south-southwest (Fig. 4). These conditions indicate that the cold air to the north of the warm front is located in this region. A skew-T/log-p diagram of the environment indicates that the frontal surface exists around the 950hPa layer, shown by near constant temperatures and dewpoint temperatures and veering winds (Fig. 5). At the time of the tornado, the warm front was located 45km to the south of Holland, indicated by a shift in wind direction and temperature, and equivalent potential temperatures on a cross section (see Fig. 6). Figure 3c clearly shows the warming of Θ_e with height, indicating the overriding air has more convective potential than the surface air. The LI was -9℃ and the LI-85 was -8℃ indicating that a stable surface layer existed. The environmental temperature at 500hPa was -12.7℃. CAPE of the surface parcel was low at 366 J/kg while the surface had a high amount of CIN, at -103 J/kg, indicating that a large amount of energy was required to lift the surface parcel. The 900hPa level air had significantly higher CAPE, at 2,100 J/kg, which indicated a moderate amount of instability, while the CIN, at -9 J/kg indicated relative ease at initiating convection. The environmental conditions around the Holland tornado, an F0 on the Fujita scale, show it was spawned from elevated convection.

The next three tornadoes of May 21, 2004, occurred between 1946 UTC and 2015 UTC, near Grundy Center and Dike, Iowa (42.4N, 92.7W). The surface temperature was between 20ºC and 22.5°C at all three locations, with the dewpoint at 19°C. The winds were from the southeast at 5 to 10 knots (see Fig. 7). The warm front, indicated by wind direction, temperature gradient, and equivalent potential temperatures on a longitudinal cross section, was located 31km south of the tornadoes during this time. Temperatures in the warm air were greater than 25°C with dewpoint temperatures ranging from 20°C to 22°C. A skew-T/log-p diagram of the environments around these tornadoes shows a stable layer at 950hPa that had constant dewpoint temperature to the 890hPa level (see Fig. 8). Figure 9 again shows that the overriding air has more convective potential than the surface air because Θ_e is shown increasing with height. The LI was -8℃ and the LI-85 was-6.5℃. The environmental temperature at the 50hPa level was -12.8℃. The surface parcel had low values for CAPE and CIN, at 837 J/kg and -79 J/kg respectively. The 900hPa level's CAPE was 1,680 J/kg indicating a moderate amount of instability, and the CIN was -8, indicating that relatively little energy was required to initiate convection at this level. Grundy Center experienced its third tornado of the day, the sixth overall in Iowa, at 1922 UTC with identical conditions as the second through fourth tornadoes. The environmental conditions surrounding the four tornadoes show that the fuel spawning the tornadoes was from elevated convection.

The fifth tornado on May 21, 2004, occurred near Waterloo, Iowa (42.4N, 92.3W), at 2021 UTC. The surface temperature was a little cooler for this tornado than the previous four tornadoes, between 21°C and 23ºC, with a dewpoint of 18°C. The winds were from the

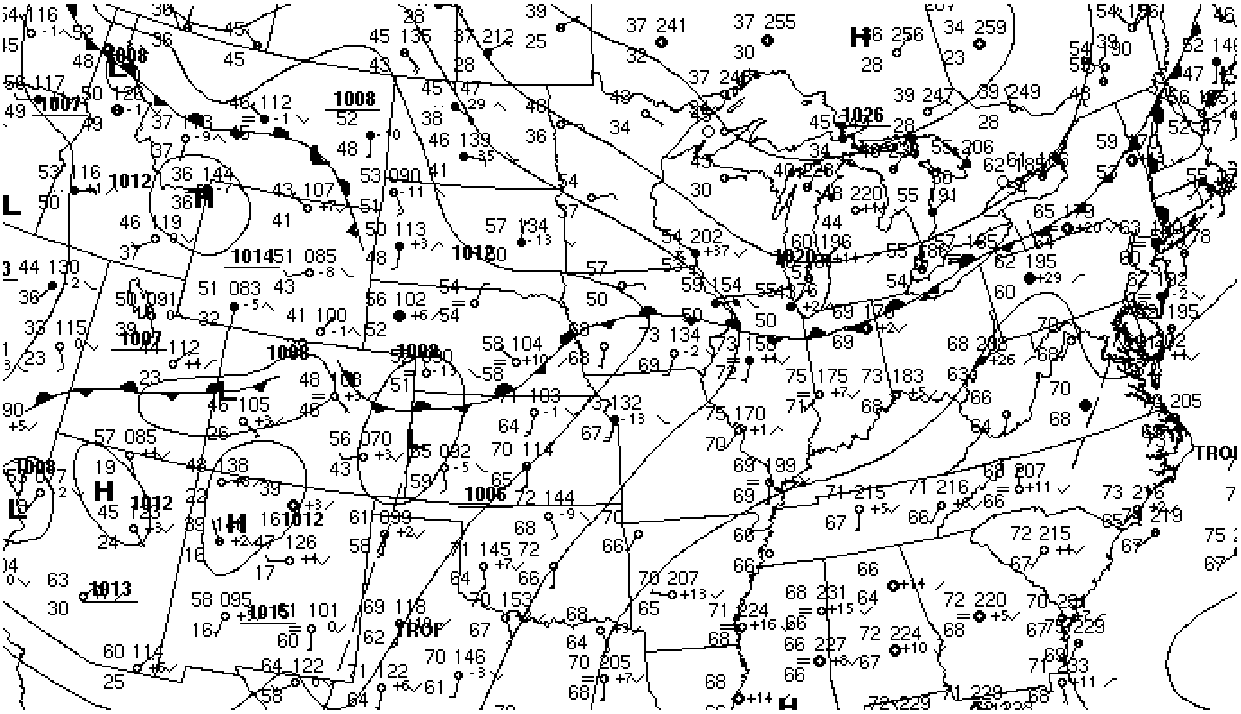

Figure 1. Portion of May 21, 2004, 1200 UTC NWS Observational Analysis

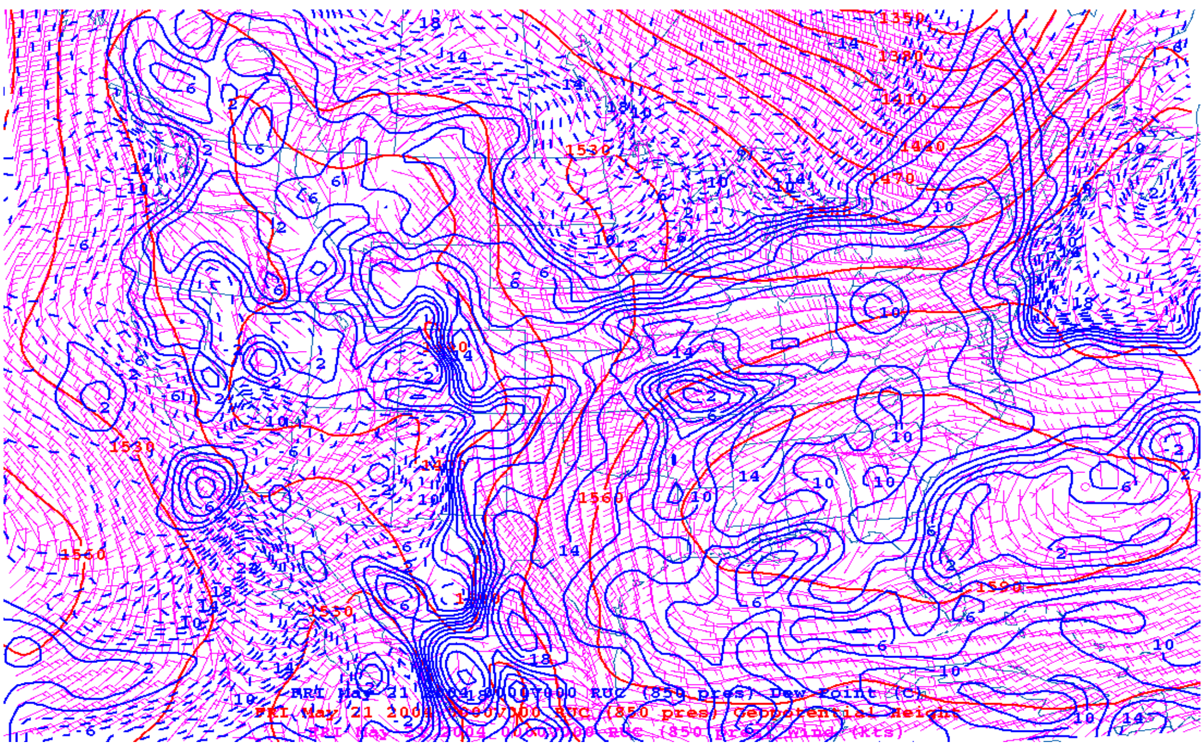

Figure 2. 850hPa surface RUC analysis valid at 00 UTC. The pink barbs show wind velocity, the red lines show height in meters and the blue lines show dewpoint temperature.

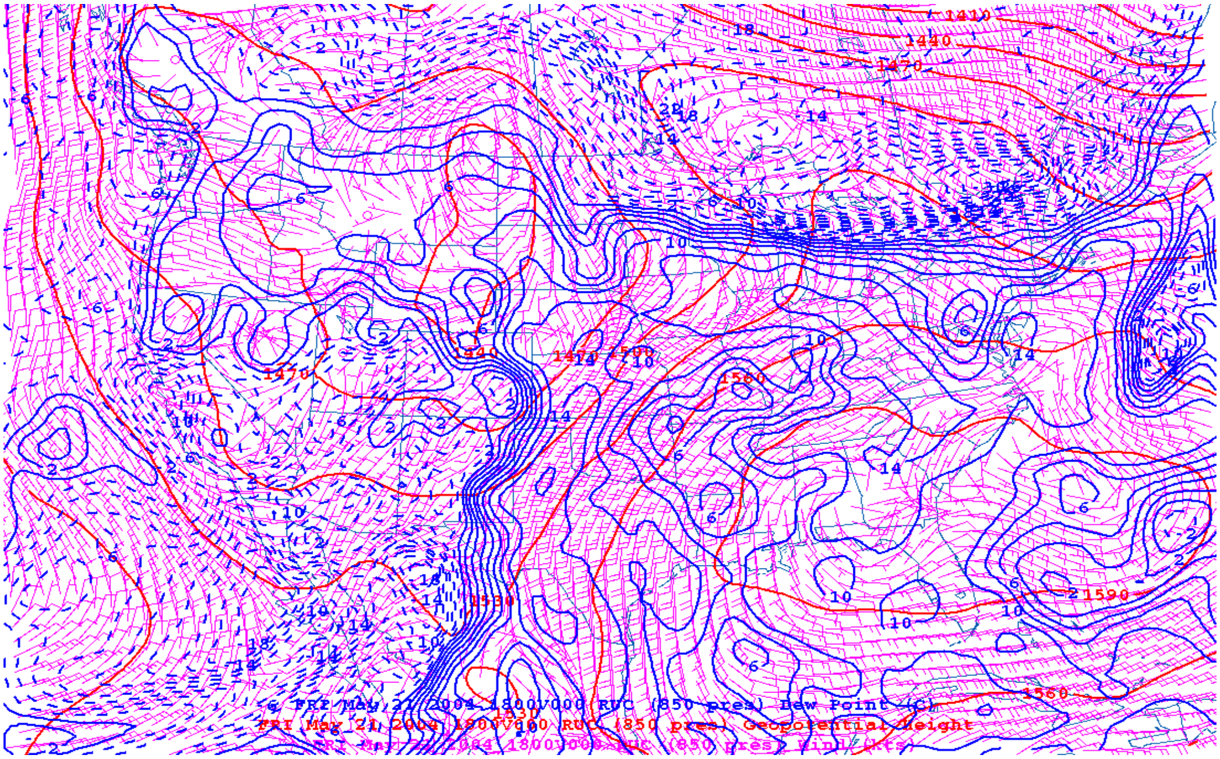

Figure 3. 850hPa surface RUC analysis valid at 18 UTC. The pink barbs show wind velocity, the red lines show height in meters, and the blue lines show dewpoint temperature. Note that the tight dewpoint gradient that existed in Fig. 2 has moved further north into central Minnesota.

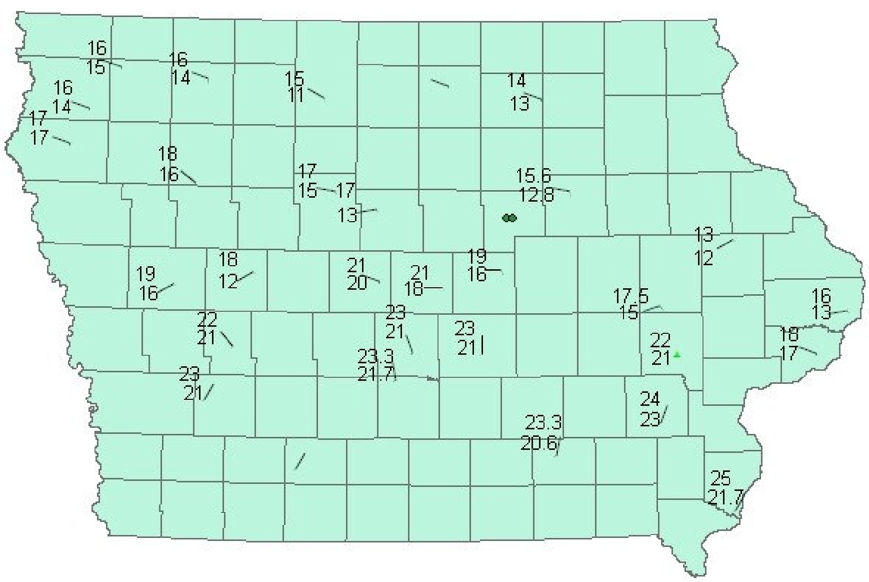

Figure 4. Surface observations at 1900 UTC. Tornado location is shown by the green diamonds. Temperatures and dewpoints are in ^{o}C, and winds are shown in conventional format in knots. The first tornado of the day occurred near Holland, IA. Note the temperature gradient and wind shift south of the tornado.

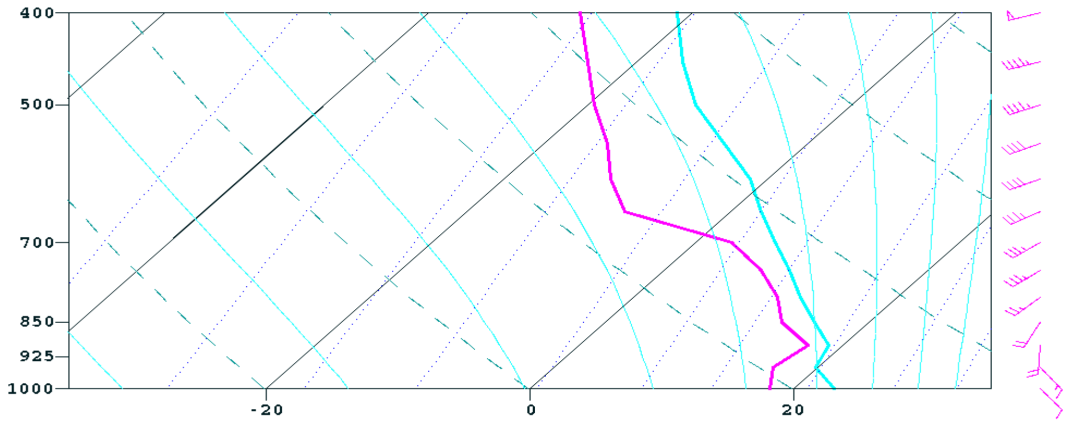

Figure 5. The skew-T/log-p from RUC analyses of the area near Holland, IA, which clearly shows the stable boundary layer. The blue line represents the temperatures (°C) and the pink line represents the dewpoint temperatures (°C) through the atmosphere above Holland. Note the wind shift in the lower atmosphere.

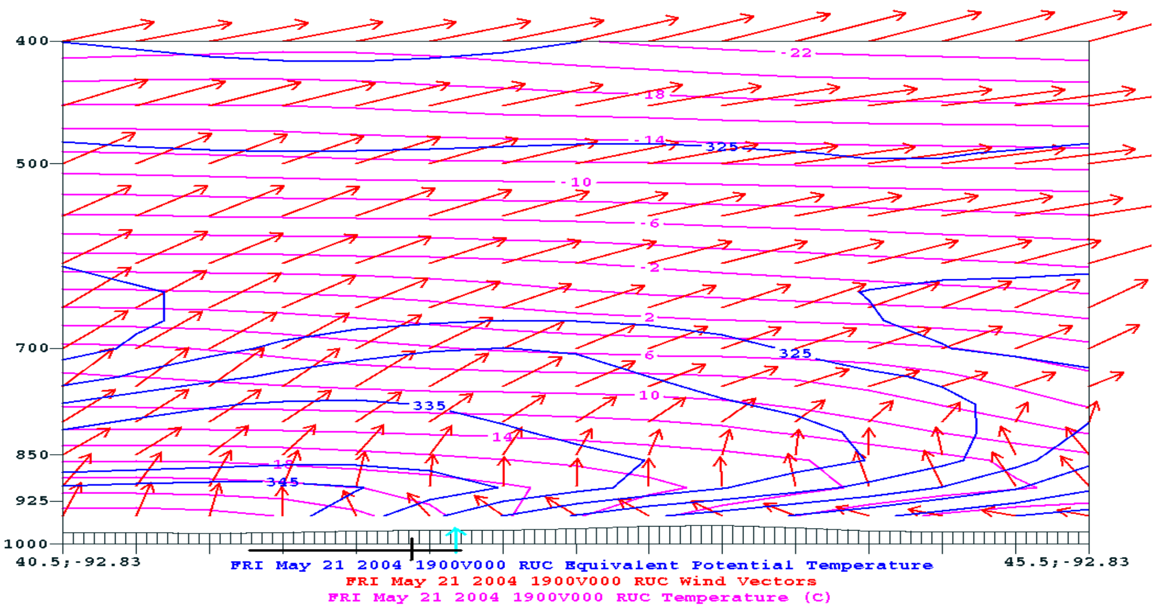

Figure 6. Meridional cross section through Holland, IA. The blue arrow indicates the location of the tornado. Equivalent potential temperature (K) is shown by the dark blue lines, and temperatures (°C), shown by the pink lines. The black line indicates the location of the front, given the surface observation data. Horizontal winds are shown by the red vectors.

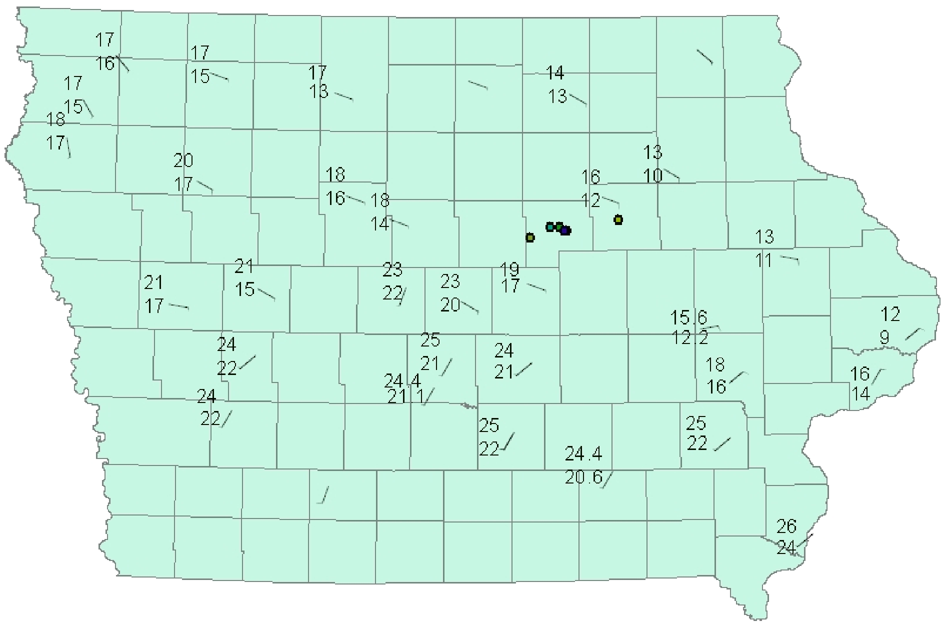

Figure 7. As in Fig. 4, except for 20 UTC. A total of four tornadoes occurred around Grundy Center, IA, within 36 minutes in this environment. Note the wind change and the sharp dewpoint temperature gradient, indicating the location of the front.

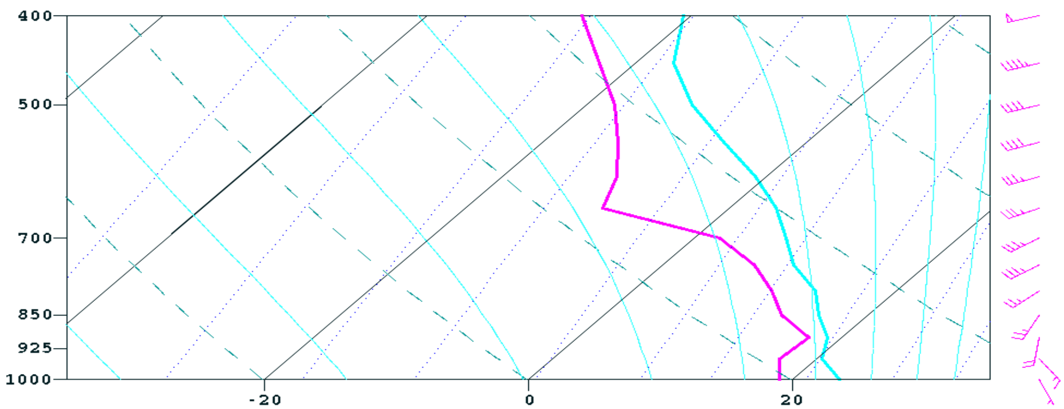

Figure 8. As in Fig. 5, for the area around Grundy Center at 20 UTC.

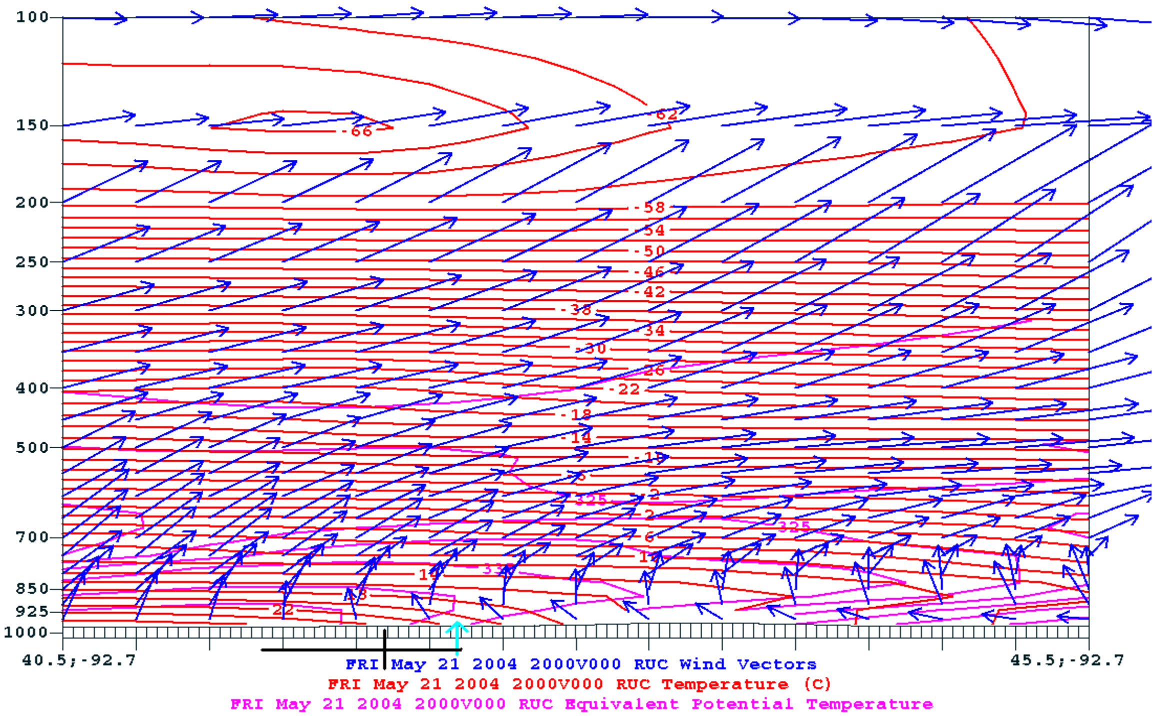

Figure 9. As in Fig. 6, forGrundy Center, IA, at 20 UTC.

southeast at 10 knots. As with the four previous tornadoes of the day, the warm front was located 75km south of the tornado. Figure 10 is the skew-T/log-p diagram showing the frontal surface located at the 950hPa surface, illustrated by the near constant dewpoint temperatures and wind shift at the 950hPa level, indicating that the warm air mass is located aloft. Figure 11, a cross section of the environment, shows Θ_e increasing with height, indicating that the air aloft has more convective potential than the air at the surface and the shift in wind direction at the front. The LI was -8°C and the LI-85 was -6.5°C. The environmental temperature at 500hPa was -12.8°C.

The eleventh tornado of the day occurred at 2144 UTC near Vinton, Iowa (42.20N, 92.083W). Figure 12 clearly shows that the warm front was further south and the cold air mass behind it has begun dominating the surface conditions near Vinton. While the surface and dewpoint temperatures have only cooled slightly, to 22ºC and 19ºC respectively, there was a pronounced stable layer at the surface. Figure 13 shows the meridional cross section through Vinton, which indicates that the tight Θ_e gradient had moved to Vinton, and the winds have shifted more to the southeast, and strengthened more with height. The LI was -8°C and the LI-85 was -6°C. The environmental temperature at 500hPa was -12.1°C. The surface level air had very low CAPE, at 591 J/kg, with CIN at -251 J/kg, a value generally considered too high to be overcome. The 900hPa level air had CAPE of 2,046 J/kg with CIN at -25 J/kg. The eleventh tornado of the day was fueled from elevated convection.

The seventeenth tornado of the day, the last in Iowa, occurred near Clarion (42.8N, 93.8W) at 0030 UTC. Figure 14 shows the surface observations at the time of this tornado, indicating that the front is 60km to the south of the tornado. The environment around Clarion at the time of the tornado indicated that this tornado was spawned from convection aloft, rather than convection from the surface. Clarion had a surface temperature of 23ºC and the dewpoint was 19ºC at the time of this tornado. The temperatures to the south of the warm front ranged from 25ºC to 28ºC, dewpoint temperatures were higher than 20ºC and winds were from the southwest at 10-15knots. The vertical profile, Figure 10b, shows the temperatures decreasing with height until the 950hPa layer, where a stable layer existed. The stable layer indicated the location of the frontal surface through the near constant dewpoint temperatures and the veering winds. Figure 16, the meridional cross-section, shows the tight Θ_e gradient to the north and wind shift continuing to occur near Clarion. The LI was -8°C and the LI-85 was -5.5°C. The environmental temperature was -11.2°C. The surface air around Clarion was very stable, with CIN at -223 J/kg and CAPE only at 580 J/kg, whereas the 900hPa level air was moderately unstable with CIN easily overcome at -8 J/kg and CAPE at 1,809 J/kg.

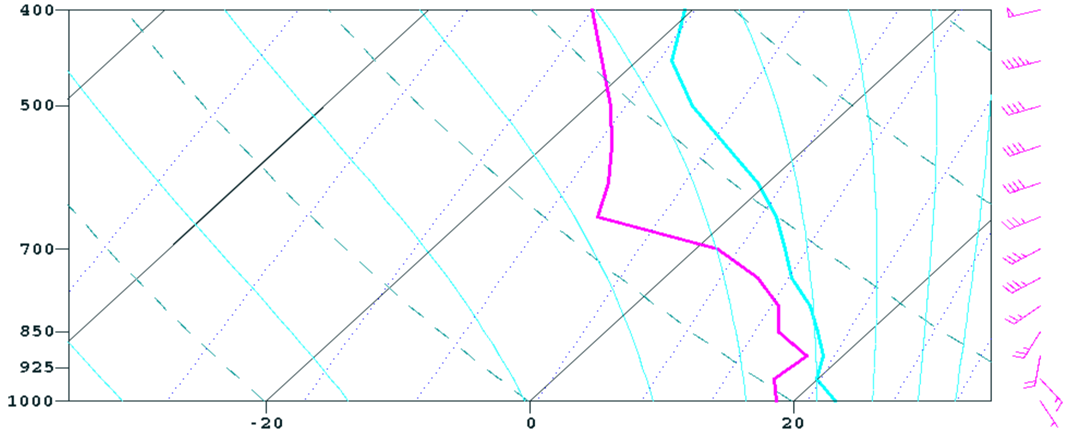

Figure 10. As in Fig. 5, for the environment near Waterloo, IA during the time of the tornado near 21 UTC on May 21, 2004.

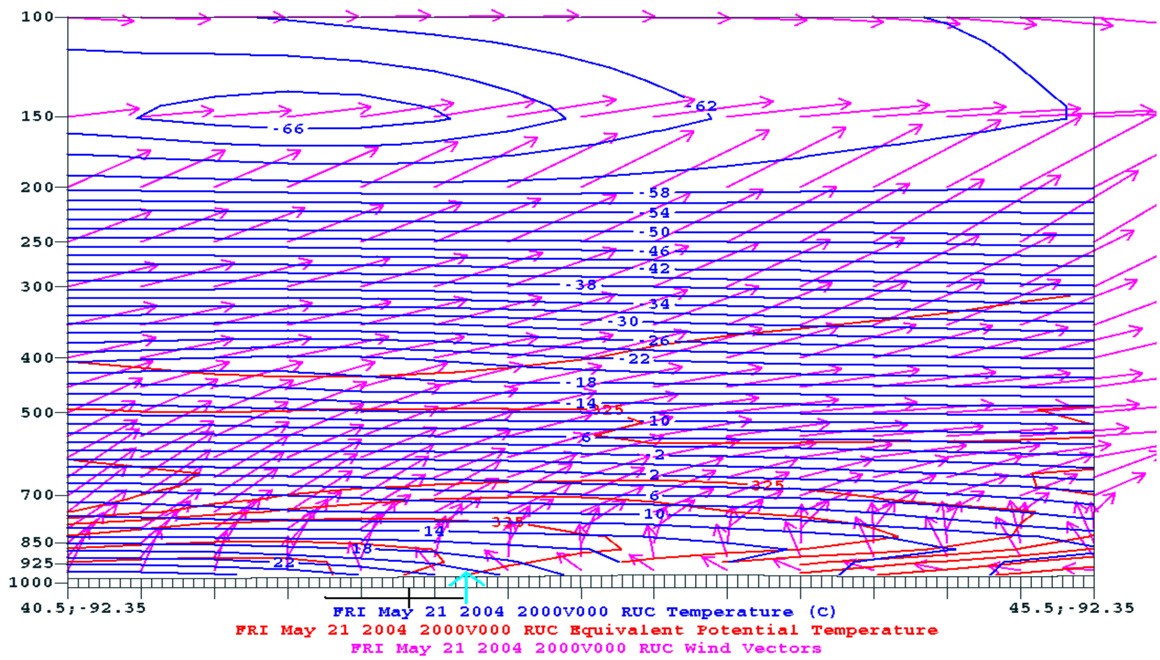

Figure 11. As in Fig. 6, for the cross section through Waterloo, IA at 20 UTC.

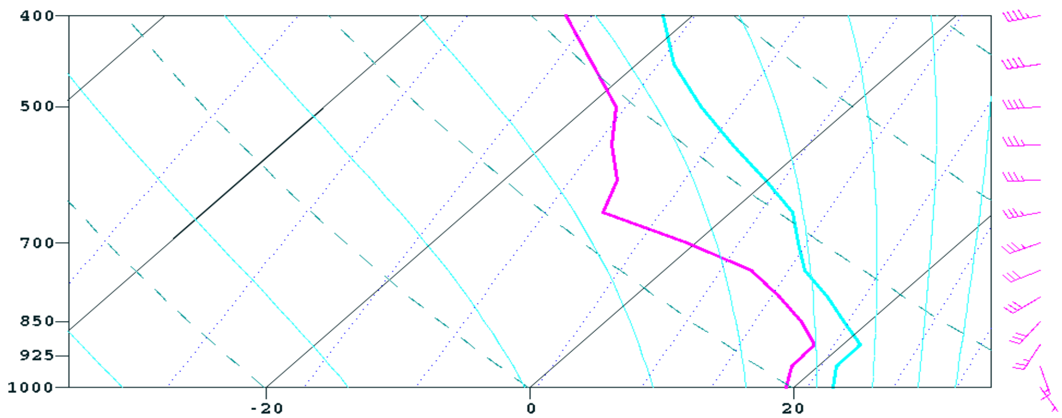

Figure 12. As in Fig. 5 for the area near Vinton, IA, at 22 UTC, near the time of the eleventh tornado of the day.

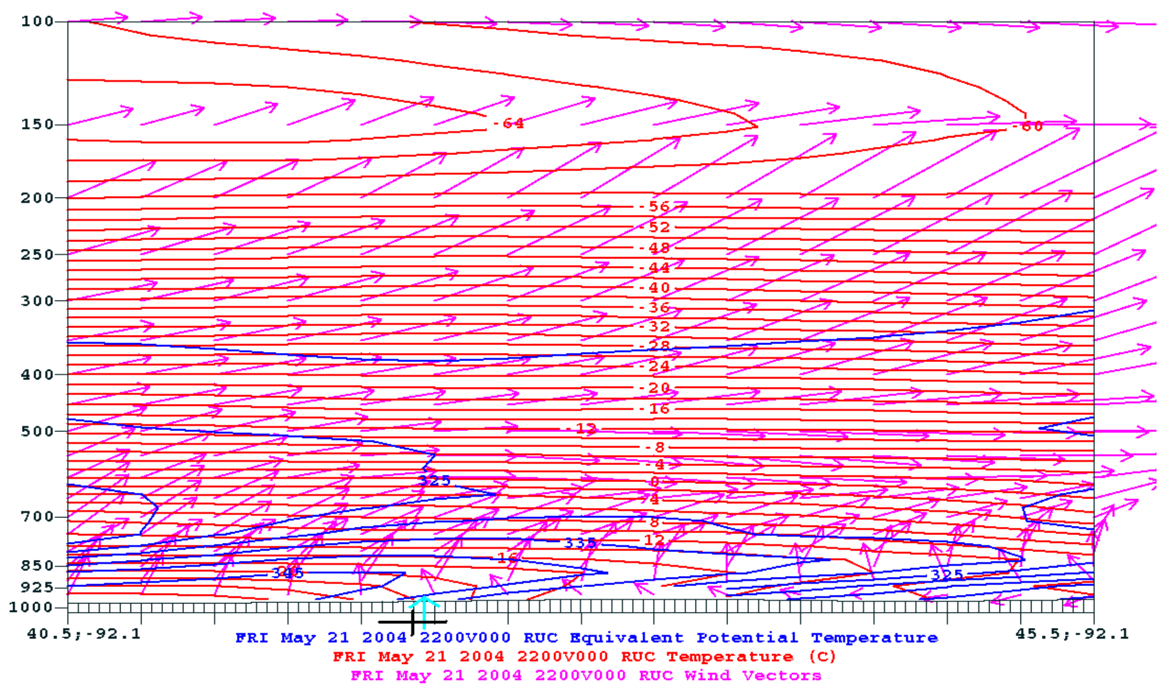

Figure 13. As in Fig. 6 for the cross section through Vinton, IA, at 22 UTC.

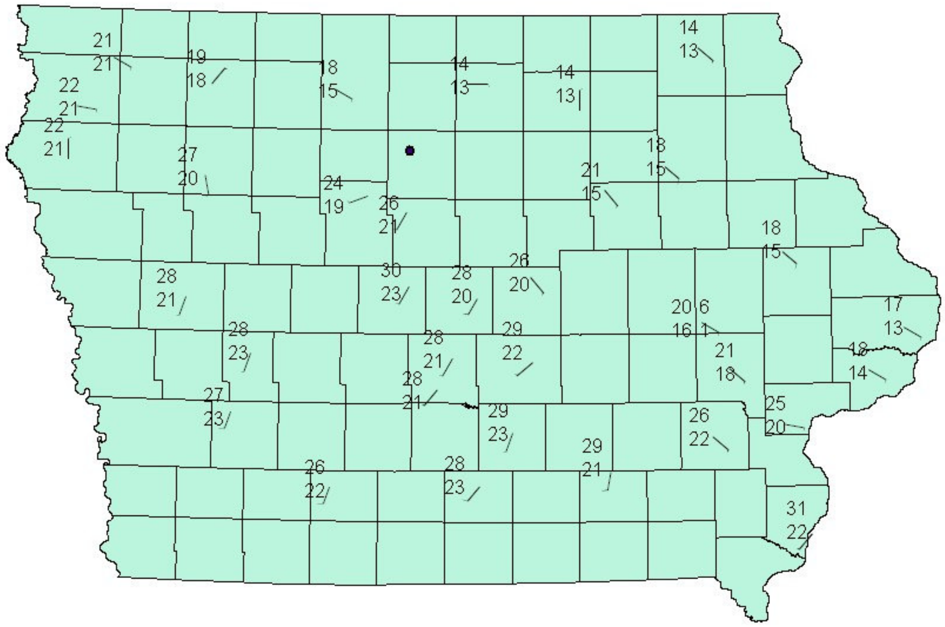

Figure 14. As in Fig. 4, except for 00 UTC, May 22, 2004. The seventeenth tornado of the day occurred at 0030 UTC.

5. MESOSCALE MODELING

(MM5) was run using three nested domains. The three domains had grid spacings of 36 km, 12 km, and 4 km, respectively. The model run was initialized at 00 UTC on May 21, 2004, and ran for 24 hours of simulated time. Initial and boundary conditions were provided by the National Centers for Environmental Prediction Global Forecast System (GFS) analysis, which was available every six hours. The MRF boundary layer scheme (Hong and Pan, 1996) was used in all three domains, and the Grell cumulus scheme (Grell, 1993) was used in the 36 km and 12 km domains, while no cumulus scheme was used in the 4 km domain and simple ice physics (Dudhia, 1989) was employed in all three domains. The model was run with 34 sigma levels in the vertical, twelve of which were below 1.5 km.

The model output was produced at one hour intervals, and processed into GrADS format using a Unix script, (Grid Analysis and Display System – see http://grads.iges.org/grads for more details) .

The operational regional model in May 2004 was the 40 km Eta model. Soundings and cross sections from either the 00 UTC run or the 12 UTC run from May 21, 2004, show that the model moved the frontal boundary too far to the north during the afternoon. The model did develop the inversion structure, but the upper part of the atmosphere was more stable to the north, and the instability that was present was not simulated.

Figure 15 shows a cross section running perpendicular to the front at 18 UTC on May 21, 2004 from the RUC analyses. The corresponding 18 hour forecast from the 00 UTC run of the Eta is in Fig. 16. The inversion present north of the frontal boundary in Fig. 15 is further to the north in the Eta model forecast. The 12 UTC Eta model run was no different. A representative sounding for the region of elevated instability is shown in Fig. 17. The sounding is taken from the RUC analyses, at 43 N latitude, 93 W longitude, which is just north of the frontal boundary. The frontal inversion shows up very clearly. The sounding from the 00 UTC Eta model run for a similar location, that is, just north of the frontal boundary, is shown in Fig. 18 (44 N, 93 W). The inversion is present, but parcels from the base of the inversion, the most unstable level, do not generate much Convective Available Potential Energy (CAPE). Figure 19 shows a plan view of CAPE and surface winds for the portion of the frontal boundary in Iowa from the RUC analysis at 15 UTC, just before the convection begins. The lobe of unstable air north of the boundary is present. Figure 20 shows CAPE at 18 UTC, and there is still some instability present north of the front. Figure 21 shows CAPE at 18 UTC from the 00 UTC Eta model run, and it is evident that the instability north of the boundary is not present. So despite the fact that the RUC analyses have the same horizontal resolution as the Eta model runs, the Eta model forecasts

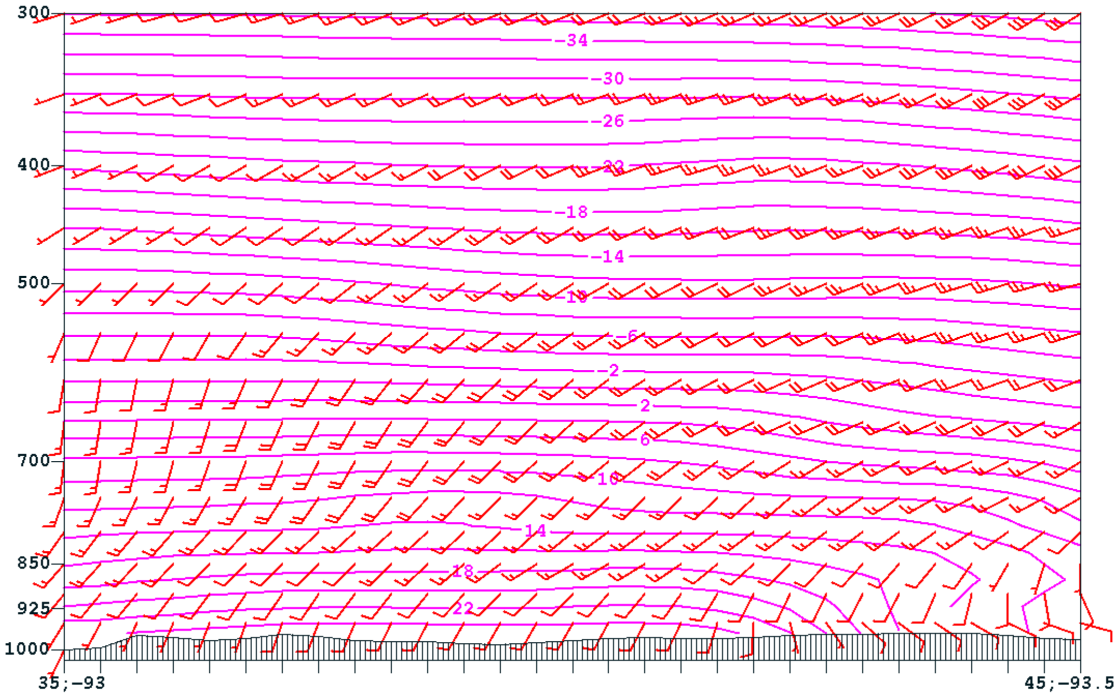

Figure 15. Cross section perpendicular to the front running through the tornadic region at 18 UTC, May 21, 2004. Horizontal winds are shown with red barbs, temperatures (ºC) are contoured in purple.

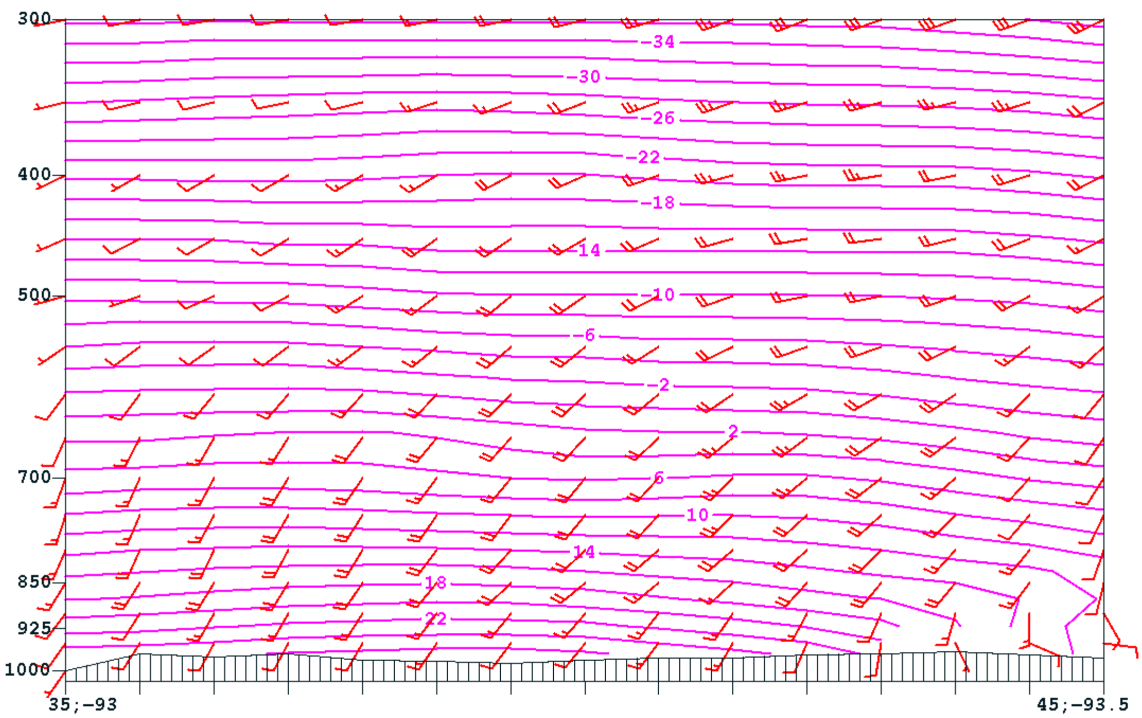

Figure 16. As in Fig. 15, but for 18 hour forecast from 00 UTC Eta model run, valid at 18 UTC.

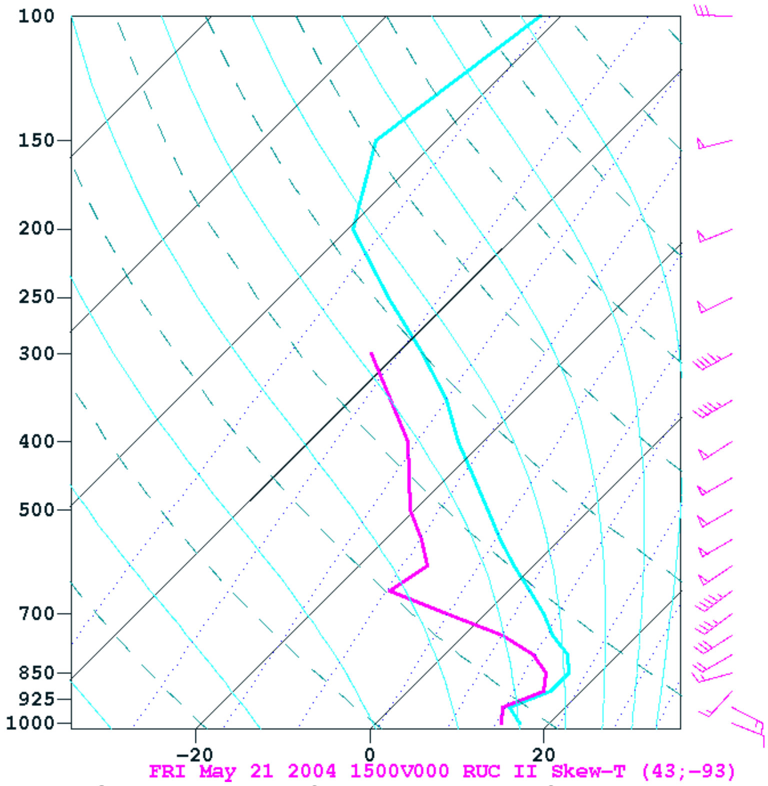

Figure 17. Sounding from RUC analyses for 15 UTC, May 21, 2004, near region where elevated tornadic convection started. Cyan line is for temperatures and purple line is for dewpoints.

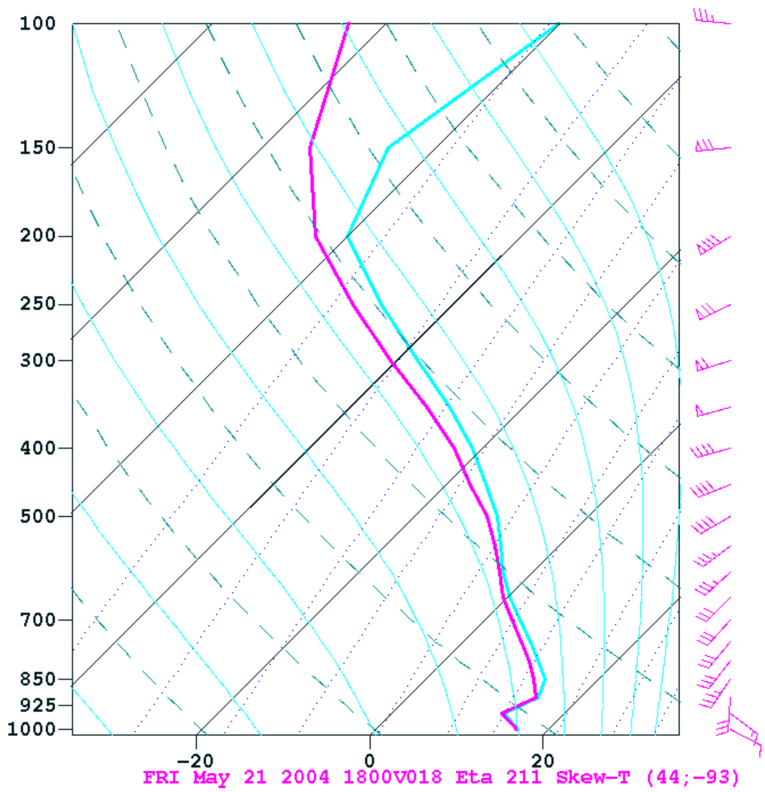

Figure 18. As in Fig. 17, except for 18 hour forecast from Eta model run.

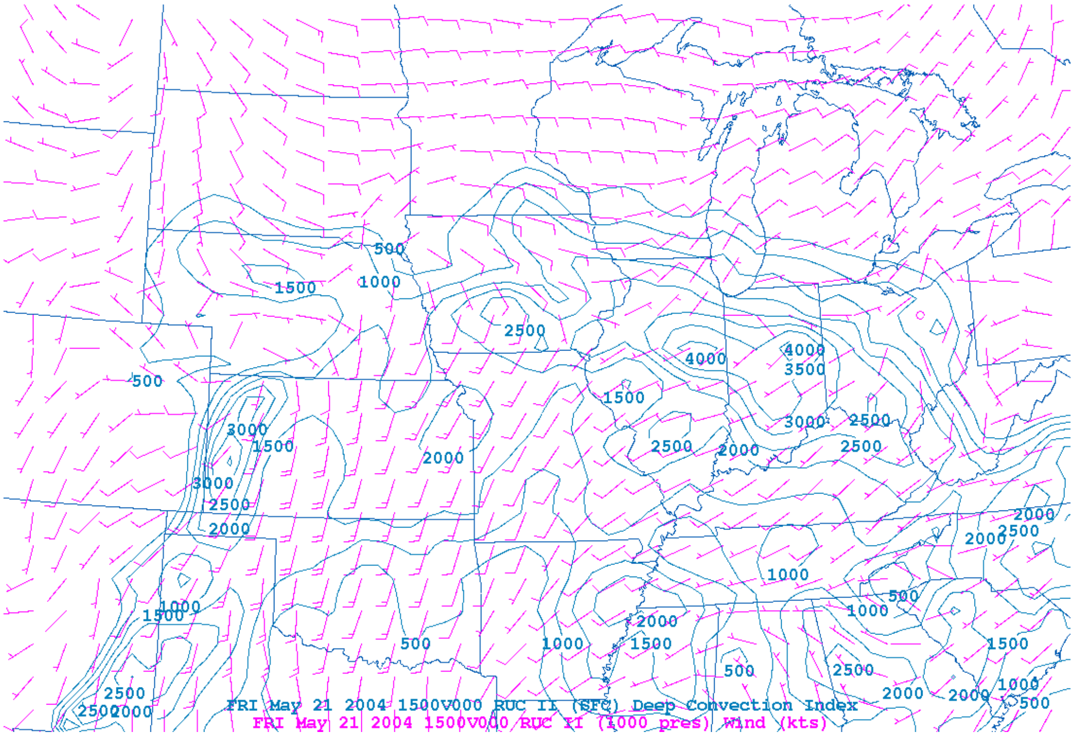

Figure 19. CAPE (J/kg) and surface winds from RUC analyses valid at 15 UTC, May 21, 2004.

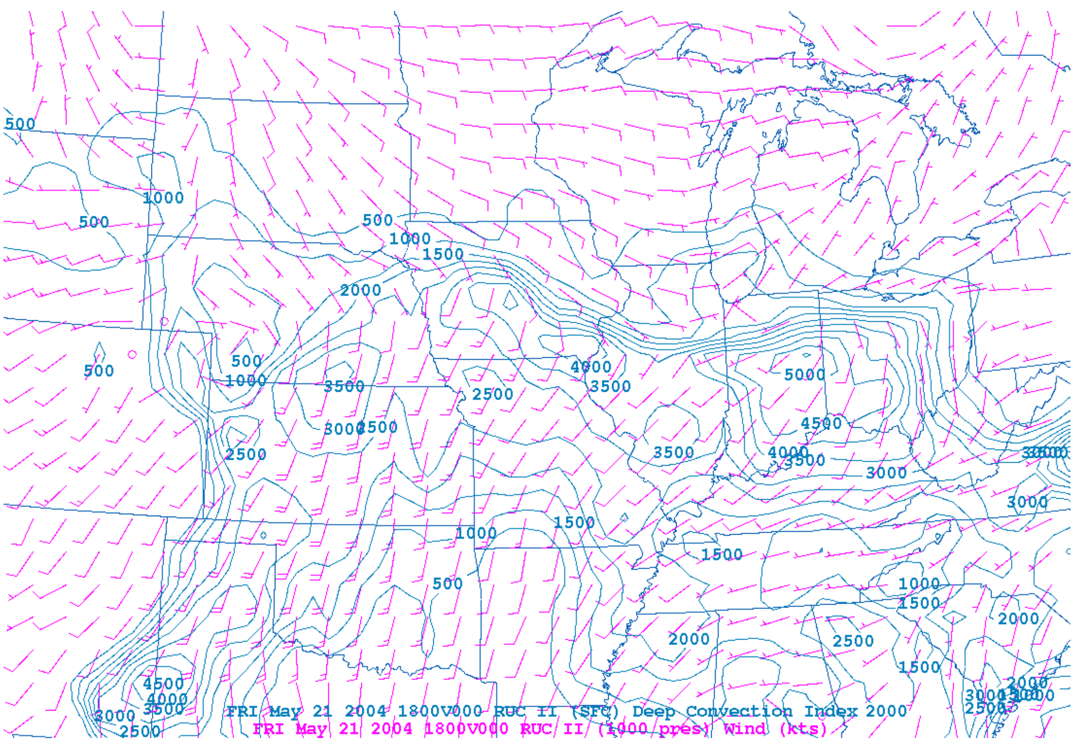

Figure 20. As in Fig. 19, for 18 UTC.

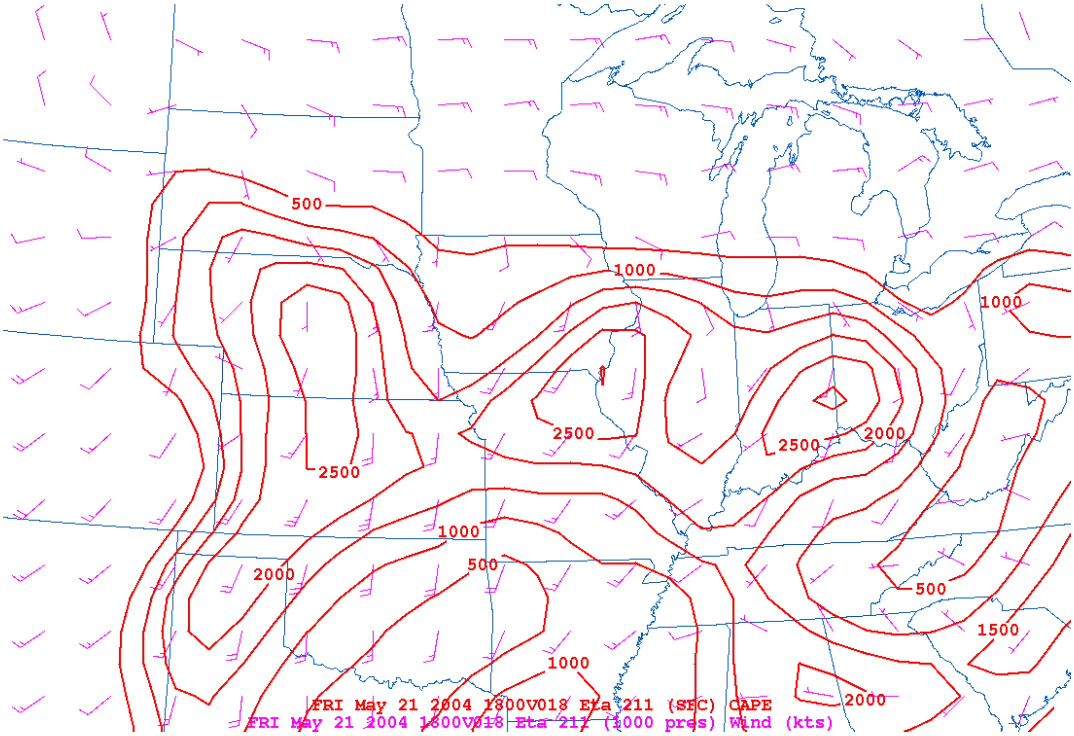

Figure 21. As in Fig. 19, for the Eta model output valid at 18 UTC.

were unable to correctly simulate the development of the elevated instability.

All three domains from the MM5 model run show the elevated unstable layer structure, until the convection erupts around 15 UTC. The Level II radar data from Davenport, IA (DVN) shows that the cell which spawned the Holland, Grundy and Waterloo tornadoes first showed up on radar as a number of small echoes around 16 UTC (see Fig. 22). The Clarion tornado was associated with a separate cell which grew rapidly between 21 and 22 UTC, further to the west. The 36 km grid from the MM5 model run does show an elevated unstable layer (see Fig. 23), A sounding at 43 N, 93 W is shown in Fig. 24, showing that the elevated parcel not only produces more CAPE than the surface parcel, but that there is almost no CIN either. Figure 25 shows the same cross section for the 12 km domain, although over a smaller range of latitude, since the 12 km domain doesn't extend far enough to the south to show data beyond 41 N. The inversion is sharper, and the sounding at 43 N, 93 N has even more CAPE for the elevated parcel (see Fig. 26). The 4 km domain cross section is quite similar to the 12 km (not shown).

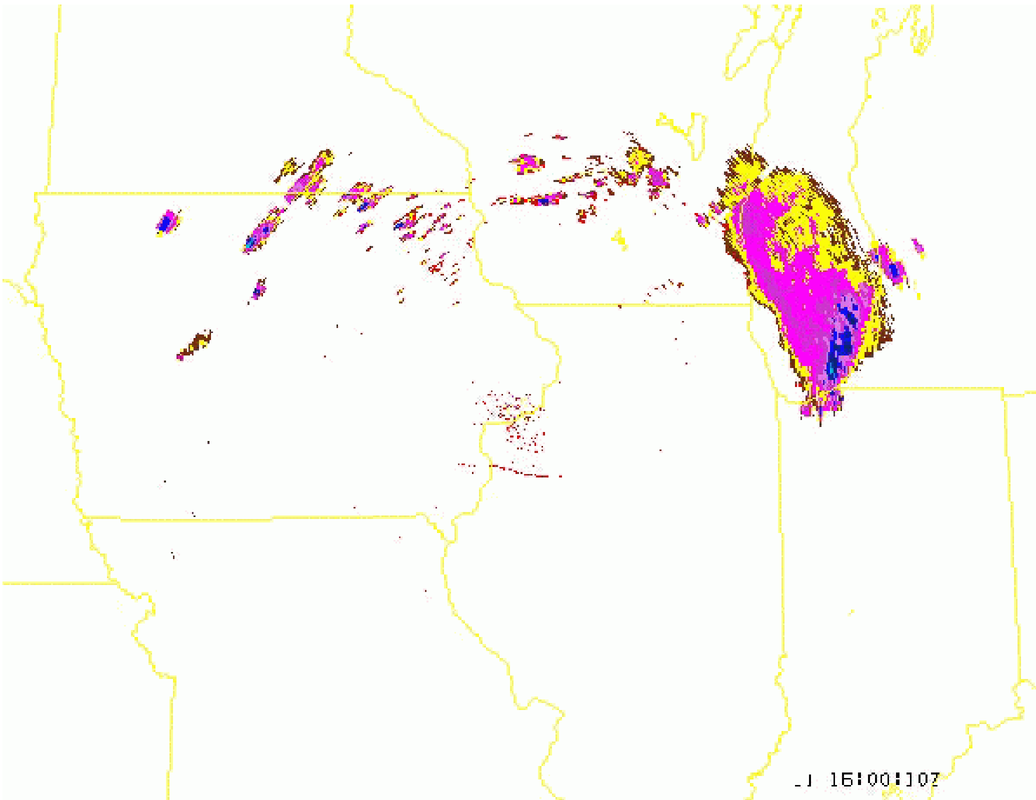

Figure 22. Reflectivity at 0.5 °C elevation angle from Davenport Iowa NWS radar, valid at 16 UTC, May 21, 2004.

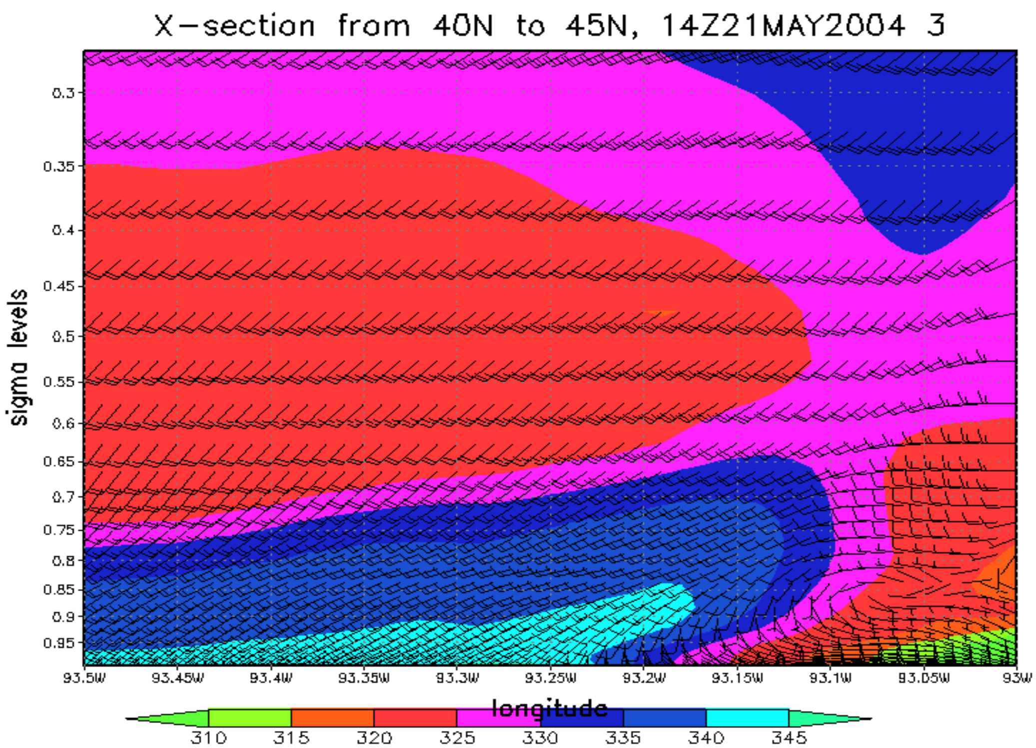

Figure 23. Cross section perpendicular to the front through the tornadic region at 14 UTC, May 21, 2004. Horizontal winds (m/s) are black barbs, and equivalent potential temperature is contoured in 5 K intervals.

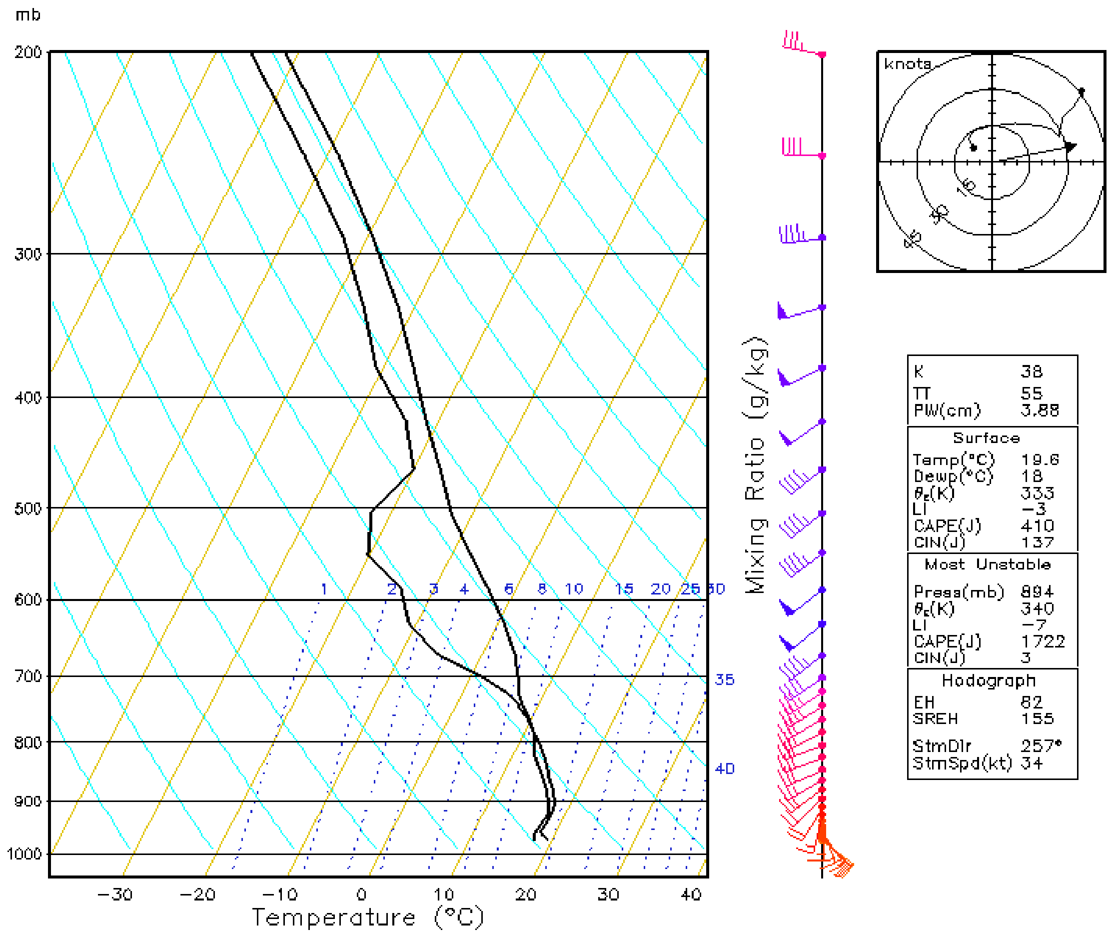

Figure 24. Sounding from MM5 model run, 36 km grid, valid at 14 UTC, May 21, 2004, in the tornadic region.

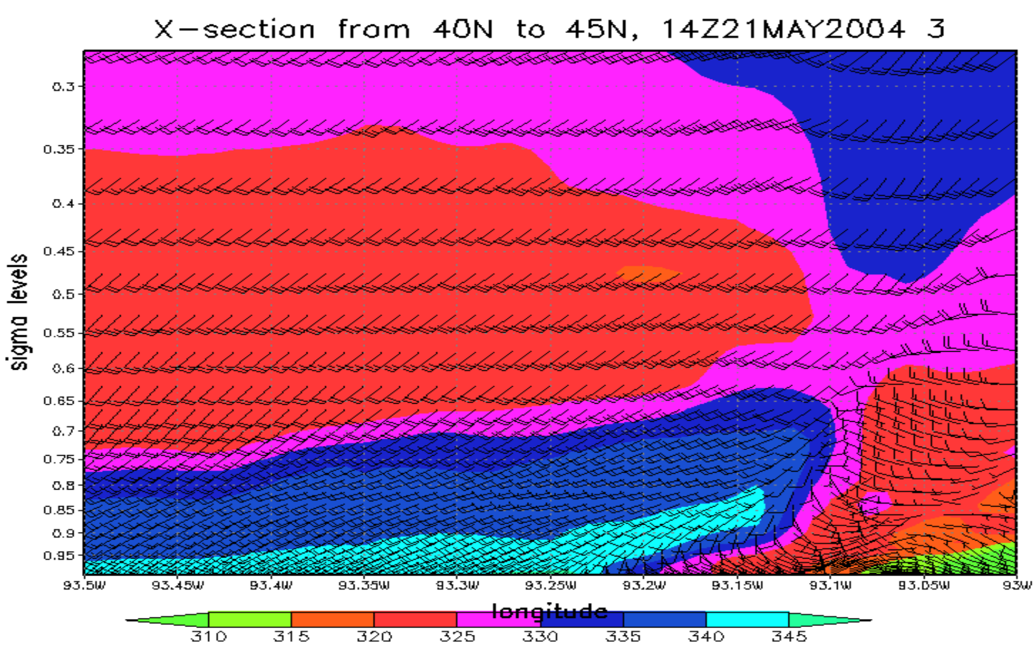

Figure 25. As in Fig. 23, but from 12 km domain.

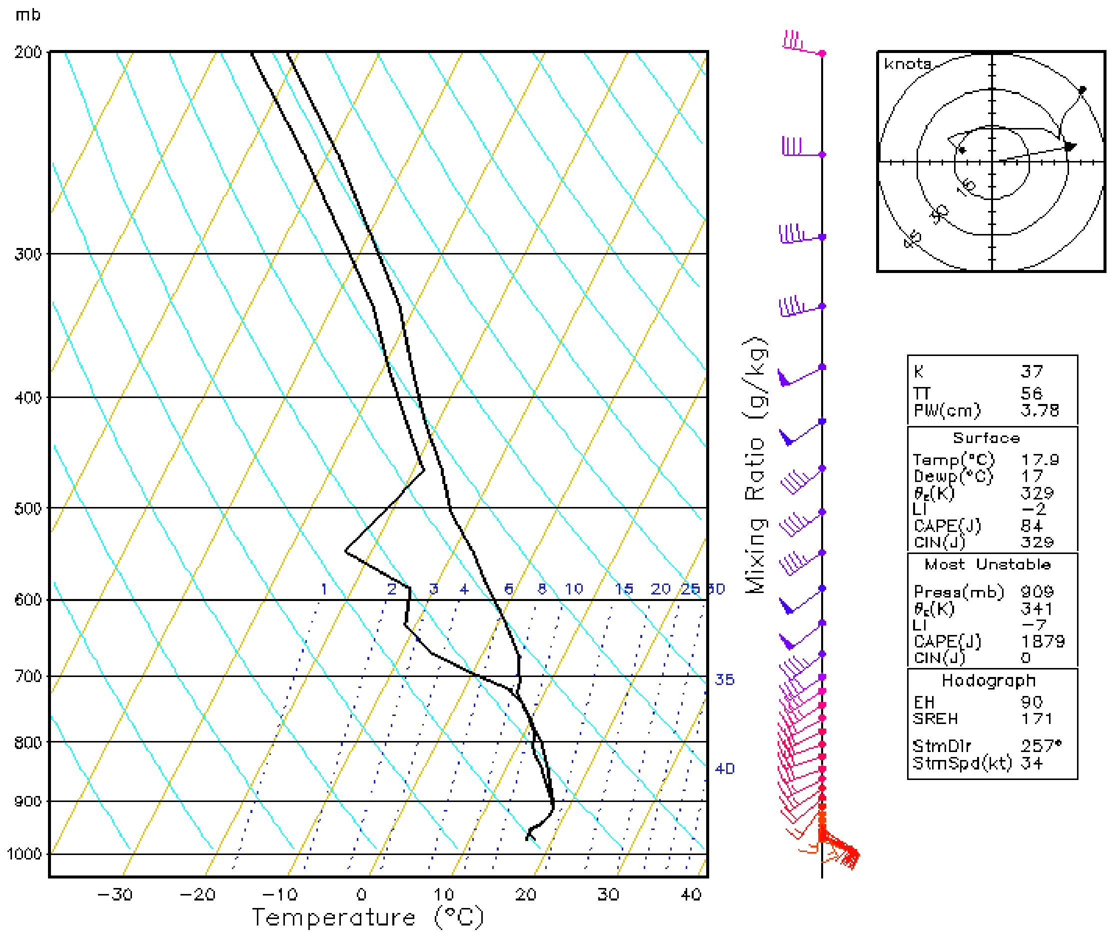

Figure 26. As in Fig. 24, but from 12 km domain.

6. Summary and Conclusions

The convergence of two air masses across Iowa and Nebraska on May 21, 2004, resulted in twenty-one tornadoes between 2:28PM CDT and 10:13PM CDT. At height, the advection of warm, moist air from the south above the colder, drier air to the north resulted in a distinct frontal surface from the 950hPa level to the 850hPa level. Investigations based on analysis of several convective indices to identify the surface source of the instability resulted in finding that eight of the twenty-one tornadoes on this day were the result of elevated convection. All eight of the tornadoes fueled from an elevated source were in Iowa: the first six tornadoes of the day in Holland, Grundy Center, Dike, and Waterloo, the eleventh tornado of the day, near Vinton, and the seventeenth tornado of the day, near Clarion. The two different air masses were distinct in temperatures, dewpoint temperatures, and wind directions; Θ_e was higher in the warm air mass and aloft than at the surface, and the environments around the tornadoes were similar in the immediate vicinity. All eight environments also had smaller surface LIs than LI-85s, and the elevated parcels all had higher CAPE and lower CIN than surface parcels, indicating that the surface was more stable than the air aloft. The magnitude of the CIN at the surface was high enough in each case to suppress any surface based convection.

When a tornado occurs on the cold side of a front, coupled with the large differences in temperature, dewpoint temperatures, and wind directions in the air masses, the convection forced aloft can be strong enough for the formation of tornadoes. The frequency of the tornado formation as a result of elevated convection is unknown, but this study indicates that this is phenomenon is possible. Therefore, additional studies need to be performed to obtain a better understanding of this phenomenon. Using Colman's (1990) work, which indicates that the majority of thunderstorms between December and February are the result of elevated convection, the next step can be the study of the tornadoes that occur during this time to determine whether these tornadoes are located in the environments of elevated convection as well. Six of the eight tornadoes fueled from an elevated source occurred within one hour of each other. Additional research should also investigate whether this clustering of tornadoes is a common occurrence when tornadoes are fueled from an elevated source or whether this clustering is merely a coincidence.

The general belief that elevated convection would not result in tornado formation has been shown to be incorrect. However, the mechanism behind how a tornado could form in an environment with elevated convection is still not known. Studies into the mechanisms allowing for the funnel development in a stable environment could lead to a better understanding of tornado development within cold air masses.

7. REFERENCES

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