7B.2 A Preliminary Analysis of Mesoscale Environments Associated with Significant Nocturnal Tornadoes in the Plains

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1. INTRODUCTION

Significant tornadoes (defined as EF-2 or greater) in the United States have been well documented (Grazulis, 1993). Nocturnal tornadoes account for approximately 26% of U.S. tornadoes, and nearly 43% of U.S. tornado related fatalities (Ashley 2007). United States tornado climatology studies depict a regional maximum of tornado reports over the Great Plains states (Brooks et al. 2003), but a relatively low temporal frequency of nocturnal tornadoes compared to the late afternoon hours (Kelly et al. 1978). This paper is intended to heighten awareness of several ingredients that are associated with nocturnal tornadoes in the Great Plains.

Conditions that support the development of nocturnal tornadoes are hypothesized to be, in part, a low-level environment characterized by low static stability and low values of mixed layer convective inhibition (MLCIN), and substantial vertical wind shear. The relative infrequency of significant nocturnal tornadoes is thought to be closely tied to decoupling of the boundary layer through radiational cooling. This allows for increasing low-level static stability, which inhibits air parcels from reaching the level of free convection. A better understanding of the mechanisms that maintain boundary layer coupling despite radiational cooling in the will assist in the short-term anticipation of nocturnal tornadoes. Past research has shown that tornadoes are strongly correlated with large values of low-level wind shear and helicity due to the presence of a low-level jet, creating an environment favorable for low-level storm rotation, in the presence of other environmental factors supportive of organized convection (Johns and Doswell 1992; Thompson et al. 2007). The challenge posed to short-term forecasters lies in the identification of a nocturnal environment in which low-level static stability is minimized or can be overcome within an environment of high shear, increasing the potential of tornadoes.

Composite analysis of mesoscale and synoptic scale features and an examination of the low-level kinematic and thermodynamic environment for significant nocturnal tornado events were performed in this preliminary study. This study examines the frequency of nocturnal tornado development in the presence of low-level frontogenetic forcing, low-level moisture maxima, low-level jets, and synoptic boundaries. These kinematic and thermodynamic mechanisms have the ability to modify the low-level environment to make it supportive of tornado development after sunset.

2. DATA AND METHODOLOGY

This study defined nocturnal tornadoes as those that occurred between one hour after sunset and one hour before sunrise. Figure 1 outlines the domain of Great Plains nocturnal tornado events. The National Climatic Data Center (NCDC) Storm Events archive was used to locate significant nocturnal tornadoes that occurred in the Plains from 1990 to 2007. A total of 110 tornadoes in 76 separate tornado days were identified, and their respective environments analyzed.

The North American Regional Reanalysis (NARR) data produced by the National Centers for Environmental Prediction (NCEP) were downloaded from the National Operational Model Archive & Distribution System (NOMADS). These data were used to investigate the mesoscale environments in which the significant tornadoes occurred. The NARR data provided a 32 km horizontal resolution with 45 vertical, 25 hPa layers, in 3-hour increments. Data were collected for each of the 110 tornado cases, and the nearest 3-hr dataset to each tornado beginning time was analyzed. The General Meteorology Package (GEMPAK; desJarndes, 1991) was then utilized to display individual kinematic and thermodynamic elements near the individual tornado track paths.

Frontogenesis was investigated to diagnose ageostrophic upward vertical motions within the nocturnal boundary layer, and was calculated within the lowest 100 hPa for each tornado in the study, with axes of 20 K m^{-1} 1_E10s^{-1} or greater included. This value was chosen to represent "strong" frontogenesis for the purposes of this study. It was assumed that when a tornado and the low-level frontogenetic forcing axis were within 80.5 km (50 mi) or less of one another, the vertical ageostrophic response could play a significant

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role in the mixing of the low-level environment (Schumacher, personal communication, 2009).

Low-level moisture distribution was examined within the lowest 50 hPa for each tornado event. Tornado events that took place in the highest 2-3 degree Celsius low-level moisture axis, within an approximately 400 km (250 mi) radius around the event, were defined to have occurred within the region of deepest moisture. This investigates whether nocturnal tornadoes preferentially occur within a low-level moisture maximum.

The low-level jet (LLJ), defined to have at least a 5.1 ms^{-1} (10 kts) wind speed increase in a 25 hPa layer, and at least a 10.3 ms^{-1} (20 kts) increase in a 100 hPa layer, was investigated to determine its coincidence and frequency with each nocturnal tornado event. The LLJ was examined in the lowest 150 hPa above ground level (AGL), and lies within the bounds of previous studies examining the LLJ in the Plains (Walters and Winkler 2001). The LLJ was examined as one of the primary sources for providing a highly sheared low-level environment that would be favorable for tornadoes.

The presence of synoptic scale boundaries were subjectively analyzed for each event and classified as either a dryline or a warm, stationary, or cold front. This defines the nearest source of low-level synoptic scale forcing, and determine the frequency of nocturnal tornado tracks within 80.5 km (50 mi) of a synoptic boundary.

3. RESULTS

3.1 Frontogenesis

The ageostrophic upward vertical response to frontogenesis on the warm side of the baroclinic zone can provide narrow corridors of intense vertical motion. A local case study performed by the authors investigated the significant tornadoes during the evening hours of 11 June 2008 at Chapman and Manhattan, Kansas. It was determined that intense low-level frontogenetic forcing led to a narrow zone of strong vertical motion and destabilization on the warm side of the frontogenesis axis. Figure 2 shows a narrow zone of strong vertical motion on the warm side of the frontogenesis axis from 11 June 2008. The tornado track is coincident with the vertical box depicted in the figure, on the warmer side of the maximum frontogenesis axis. The environment was characterized by relatively high values of MLCIN (>100 Jkg^{-1}, not shown). Equivalent potential temperature either decreased or remained constant with height within the narrow vertical column highlighted in Figure 2. Convective instability exists in locations where equivalent potential temperature decreases with height. Figure 2 also shows that to the southeast of the frontogenesis axis (to the right of the frontogenesis in the figure), equivalent potential temperature begins to increase with height near the 850 hPa level. This provides evidence that the narrow zone of instability in which the tornado occurred was closely tied to the ageostrophic response to the frontogenetic forcing. Values of frontogenesis greater than 20 $Km^{-1}1_E10s^{-1}$ were found in 48 of the 110 tornado cases, or approximately 44%. These findings suggest that low-level frontogenetic forcing cannot be the only mechanism at work to sustain a coupled boundary layer. However, when present, this forcing may play an important role in vertically mixing the low-level environment, keeping the boundary layer coupled after sunset.

3.2 Low-level Moisture

One of the ways to create potential instability in a relatively stable atmospheric layer is to moisten the bottom of the layer. As the stable layer is lifted, the warmer and drier upper portions of the layer will cool dry adiabatically while the cooler but moist lower portion of the layer will cool moist adiabatically. Given sufficient lift, this process will create potential instability in the once stable layer. In environments supportive of organized convection, some source of lift is assumed to be present; therefore zones of low-level moisture maxima should be good indicators of where potential instability may occur in an initially stable layer. Approximately 76%, or 84 of the 110 tornado tracks, occurred within the previously defined best moisture axis which indicates that zones of low-level moisture maxima may also be effective indicators of zones of potential low-level instability in nocturnal environments. Destabilization of the low-levels due to an increase in moisture can be demonstrated by the tornado case from 20 June 1990. The low level moisture distribution associated with this event is displayed on Figure 3. Dodge City was chosen as the closest representative upper air site to the event, which occurred north of Ulysses, Kansas. The 0000 UTC sounding from Dodge City, Kansas (KDDC), shown in Figure 4, depicts an initially dry low-level airmass with no calculated positive mixed layer convective available potential energy (MLCAPE). GEMPAK's NSHARP sounding analysis tool, utilizing NARR data, was then used to investigate the 0600 UTC thermodynamic environment at Dodge City (KDDC). A marked increase in MLCAPE from 0 to 2116 Jkg^{-1} between the 0000 to 0600 UTC soundings is primarily due to moisture transport as little insolation was present after 0000 UTC (Figure 5). This case demonstrates the importance of low-level moisture in combination with other environmental variables favorable for tornadic development.

3.3 Low-Level Jet

Maddox (1993) found that the diurnal increase of low-level wind speeds in the plains after sunset often increases low-level helicity. Rasmussen (2003) showed that higher values of low-level (0-1 km) storm relative helicity have been favorably correlated with environments for significant tornadoes. These findings suggest that if the LLJ can enhance storm relative inflow helicity, then the LLJ is an important mechanism in creating low-level kinematic conditions favorable for tornadoes. Walters and Winkler (2001) found that convection often occurred in the Plains over areas closely associated with convergence in the LLJ flow configuration. They also noted that the LLJ is a common transporter of warm, moist air into the Plains. Low-level winds meeting the established LLJ criteria were present in 103 of the 110 cases, or approximately 94% of the time. The fact that 94% of the cases in this study occurred in the presence of a LLJ corroborates with the research that suggests highly sheared low-level environments are favorable for tornadoes.

3.4 Synoptic Boundaries

Synoptic boundaries serve as a source of low-level convergence and lift. Convergence along synoptic boundaries and in the LLJ flow configuration could explain the low-level moisture maxima that often occurred with boundaries present in this study. Synoptic boundaries that feature strong horizontal thermal gradients can also be sources of frontogenetic forcing, as was the case during a nocturnal tornado event on 5 April 1990. Figure 6 depicts an image of low-level frontogenesis along a thermal gradient at 0600 UTC. The frontogenesis lies coincident with the cold front in Figure 6. Boundaries themselves may also serve to enhance horizontal vorticity generation as shown by Markowski et al. (1998).

Subjective analyses revealed approximately 72% of the tornado tracks, or 80 of the 110 cases, were located within 80 km (50 mi) of an identified synoptic boundary. This high percentage signals that the presence of synoptic boundaries might play an important role in keeping the near-boundary environment coupled. It is theorized that synoptic boundaries worked in conjunction with the other three discussed mechanisms to serve as foci for conditions that lead to keeping low-level environments coupled. It is important to note that while synoptic boundaries may bring together many conditions favorable for the continued coupling of the near surface environment, 30 events were identified as occurring more than 80 km (50 mi) away from a synoptic boundary. Of these 30 events, all 30 occurred with the presence of a low level jet, and all but 3 occurred within the local low level moisture maximum. These findings indicate that the presence of synoptic scale boundaries is not necessary to support the development of tornadoes at night, but when present, these boundaries can serve as a foci for other mechanisms to work together to promote continued coupling of the boundary layer.

4. CONCLUSIONS

Most nocturnal tornadoes investigated in this study occurred frequently in the presence of low-level moisture maxima, low-level jets, and in close proximity to a synoptic scale boundary. Nocturnal tornadoes also occurred in the presence of low-level frontogenetic forcing, but this was not as common as other mechanisms. It is suggested that a combination of these factors, in the presence of other environmental factors supportive of organized convection, work together to create a low-level environment more conducive to remaining coupled. Within this study no individual mechanism was ever identified as acting alone, therefore a combination of mechanisms seems to provide an environment more favorable for significant tornado development.

Stable low-level environments are often associated with elevated convection during the warm season in the Plains, where storm inflow is elevated above a stable boundary layer (Colman, 1990). The forecasting challenge lies in differentiating environments where the storm inflow is elevated above a near surface layer from those where the storm inflow is rooted near the surface, therefore taking advantage of enhanced low-level horizontal vorticity. This study identifies conditions in a nocturnal low-level environment in which static stability is minimized or overcome in the presence of high shear, promoting favorable conditions for potential tornado formation. Mesoscale meteorologists may be able to recognize mechanisms outlined in this study before they have an appreciable effect on the low-level environment. These, in conjunction with other available parameters, provide operational meteorologists an opportunity to forecast whether a low-level environment could support tornadoes.

5. Acknowledgements

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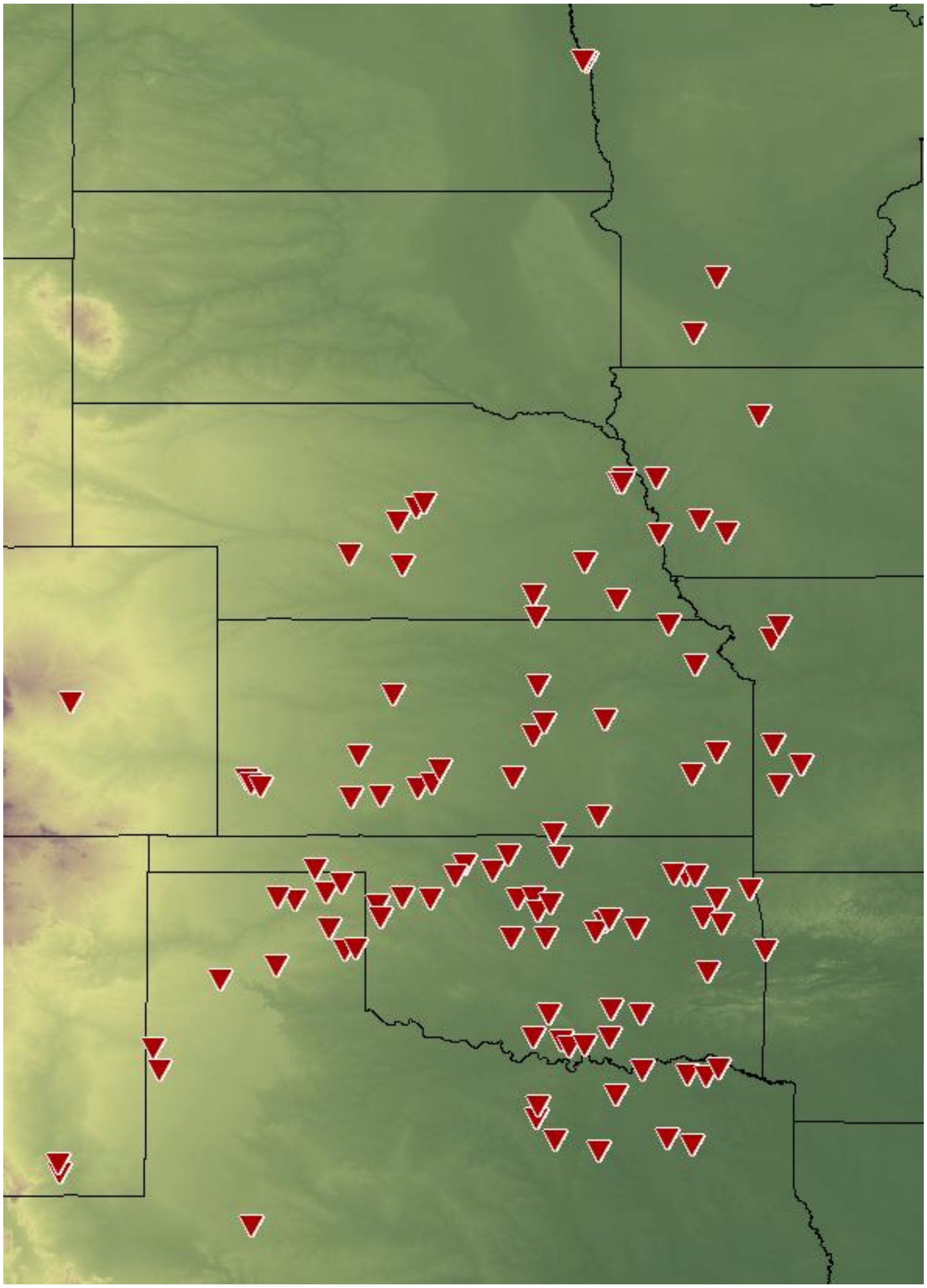


Figure 1: Nocturnal tornado (red triangles) beginning points within the domain area.

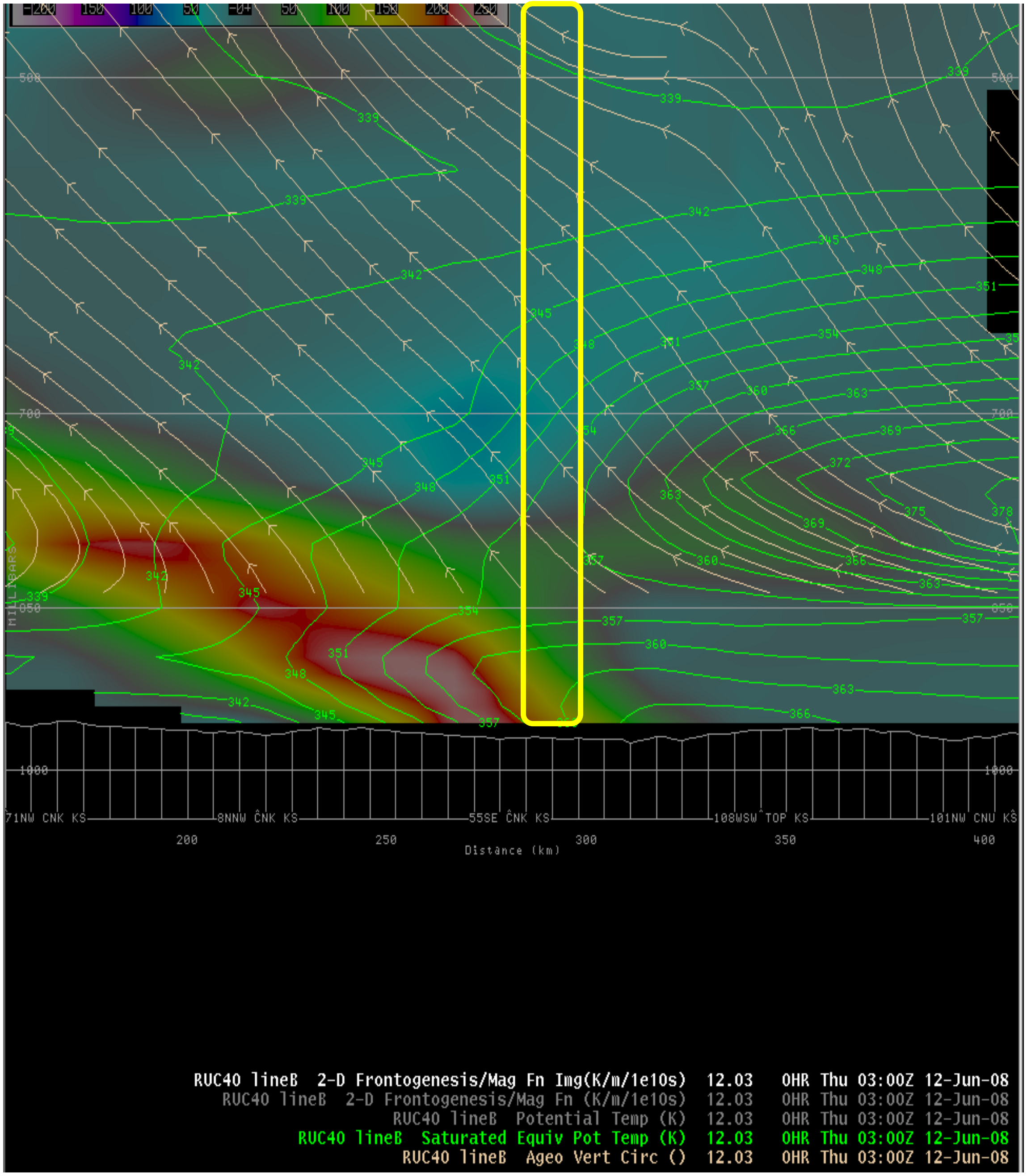


Figure 2: A cross-section of low-level frontogenetic forcing (background image), equivalent potential temperature, (green) and ageostrophic vertical motion (tan) from 12 June 2008 at 0300 UTC. The yellow vertical box indicates the narrow vertical zone where equivalent potential temperature decreases or remains nearly constant from the near surface environment to the 500 hPa level (top of the figure). The tornado track fell within this yellow box. This case was not included within the temporal domain of the study (i.e. 1990-2007). Therefore, this cross section was created using RUC data on a 40 km grid.

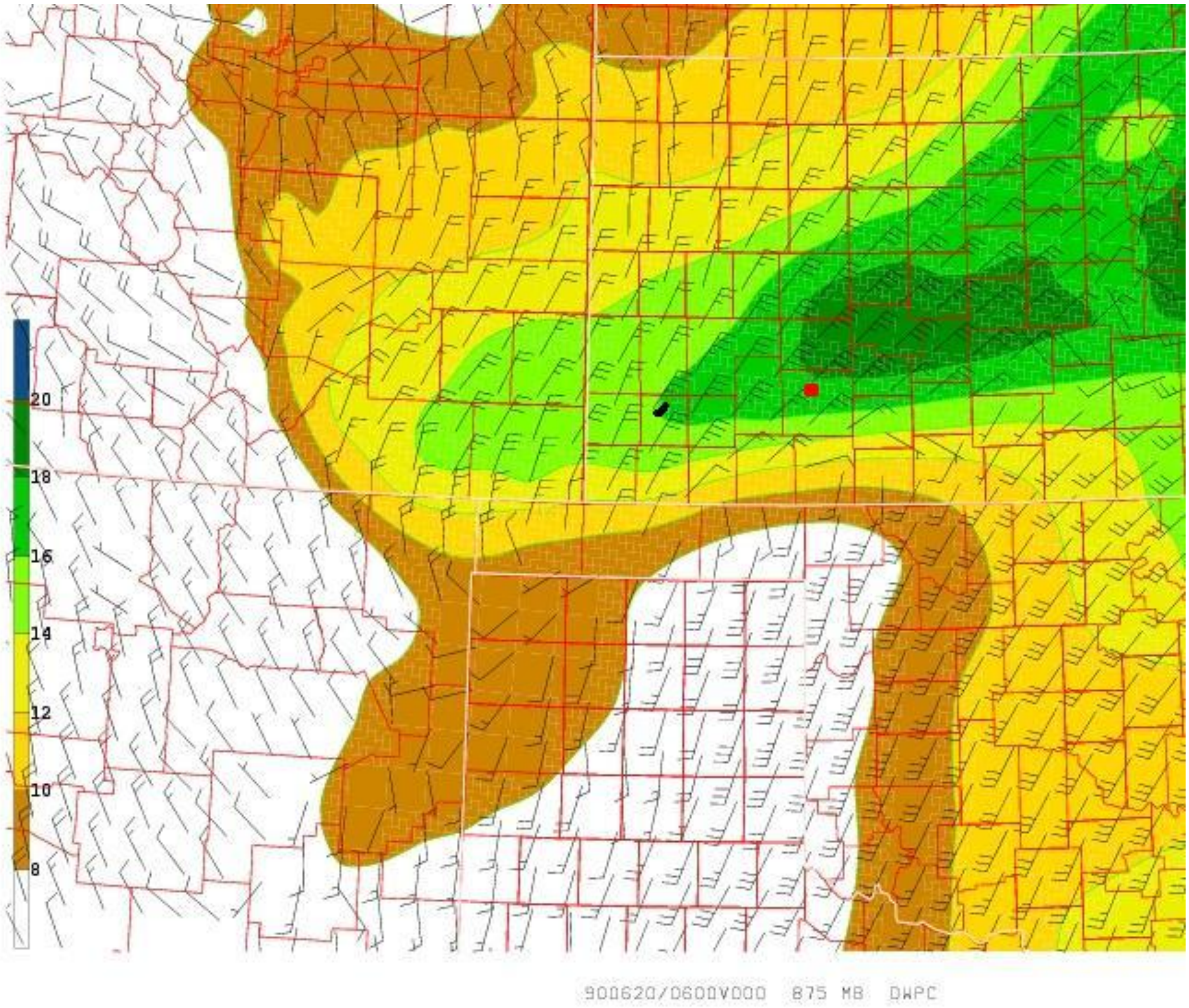
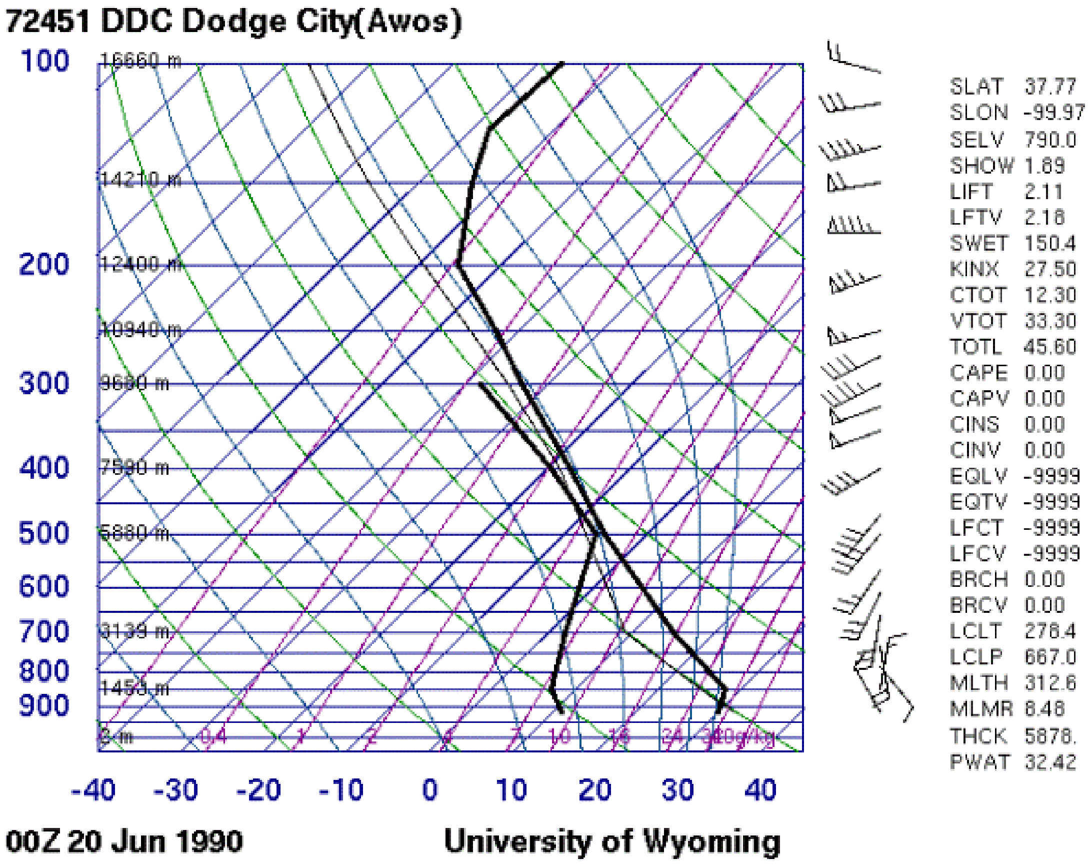
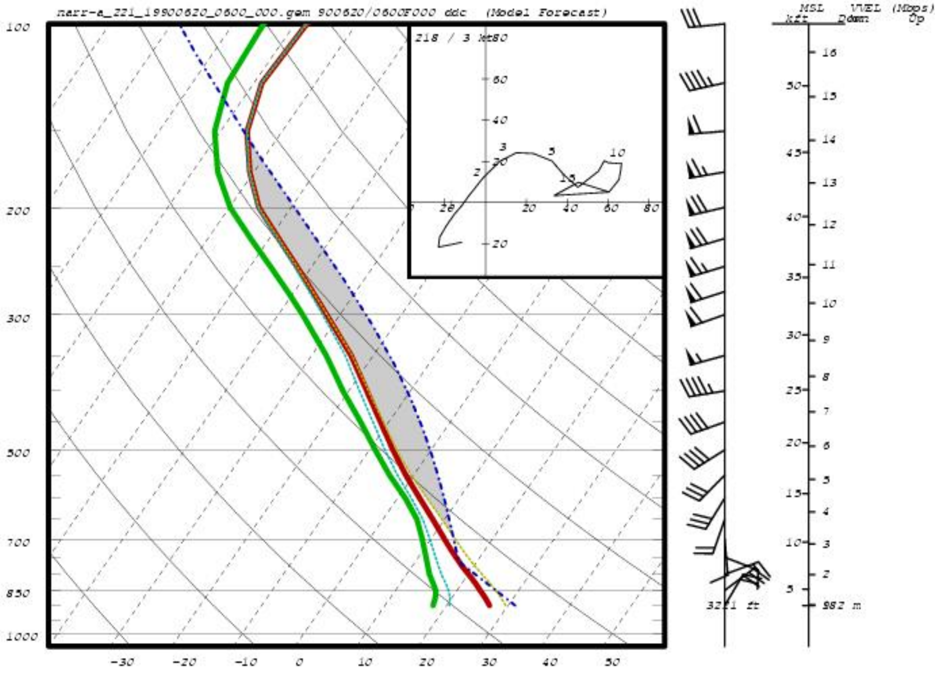


Figure 3: The 875 hPa dew point analysis overlaid by tornado track (black line) and the location of Dodge City, Kansas (red square) from 20 June 1990 at 0600 UTC.



SLAT	37.77
SLON	-99.97
SELV	790.0
SHOW	1.89
LIFT	2.11
LFTV	2.18
SWET	150.4
KINX	27.50
CTOT	12.30
VTOT	33.30
TOTL	45.60
CAPE	0.00
CAPV	0.00
CINS	0.00
CINV	0.00
EQLV	-9999
EQTV	-9999
LFCT	-9999
LFCV	-9999
BRCH	0.00
BRCV	0.00
LCLT	278.4
LCLP	667.0
MLTH	312.6
MLMR	8.48
THCK	5878.
PWAT	32.42

Figure 4: The 20 June 1990 KDDC 0000 UTC sounding. Courtesy of the University of Wyoming Atmospheric Sciences.



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THERMODYNAMIC PARAMETERS

MEAN MIXING LAYER PARCEL
LPL:    900mb       29C/  17C      84F/  63F

CAPE:     2116 J/kg     LI:       -6 C @  500mb
BFZL:      118 J/kg     LImin:    -6 C @  300mb
CINH:      -27 J/kg     CAP:       2 C @  750mb

 LEVEL        PRES        HGT(AGL)        TEMP
   LCL        762mb         4769ft
   LFC        690mb         7516ft        11 C
    EL        150mb        43389ft       -66 C
   MPL         95mb        52370ft

Precip Water:  1.69 in   Mean RH:          66 %
Mean Q:       13.8 g/kg  Mean LRH:         64 %
Top of Moist Layer:      M / M

700-500mb Lapse Rate:   18 C  /  7.1 C/km
850-500mb Lapse Rate:   32 C  /  7.2 C/km

Total Totals:        53  K-Index:          43
SWEAT Index:        367  Max Temp:       90 F
ThetaE Diff:       17 C  *Conv Temp:     82 F
FRZ Level:     13005 ft  WBZ Level:  12358 ft

Output produced by Unidata postscript driver:
NSHARP (SkewT-Hodograph Analysis and Research Program)
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KINEMATIC PARAMETERS

Sfc - 6 km Mean Wind: 206 / 23 kt    (11 m/s)
LFC - EL Mean Wind:    240 / 36 kt   (18 m/s)
850 - 300 Mean Wind:    229 / 15 kt   (7 m/s)

Sfc - 2km Shear:      29 kt     (15 m/s)
Sfc - 6km Shear:      65 kt     (33 m/s)
*BRN Shear:                    138 m2/s2
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STORM STRUCTURE PARAMETERS

Sfc - 3km SREH:  212 m2/s2
Effective SREH:  212 m2/s2     from 0 m.

0-2 km SRW:     20 kt        EHI:            2.8
4-6 km SRW:     33 kt        BRN:             15
6-10 km SRW:    51 kt
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Figure 5: The KDDC sounding from 20 June 1990 at 0600 UTC. This sounding was constructed utilizing GEMPAK's NSHARP sounding analysis tool, utilizing NARR data on a 32 km grid.

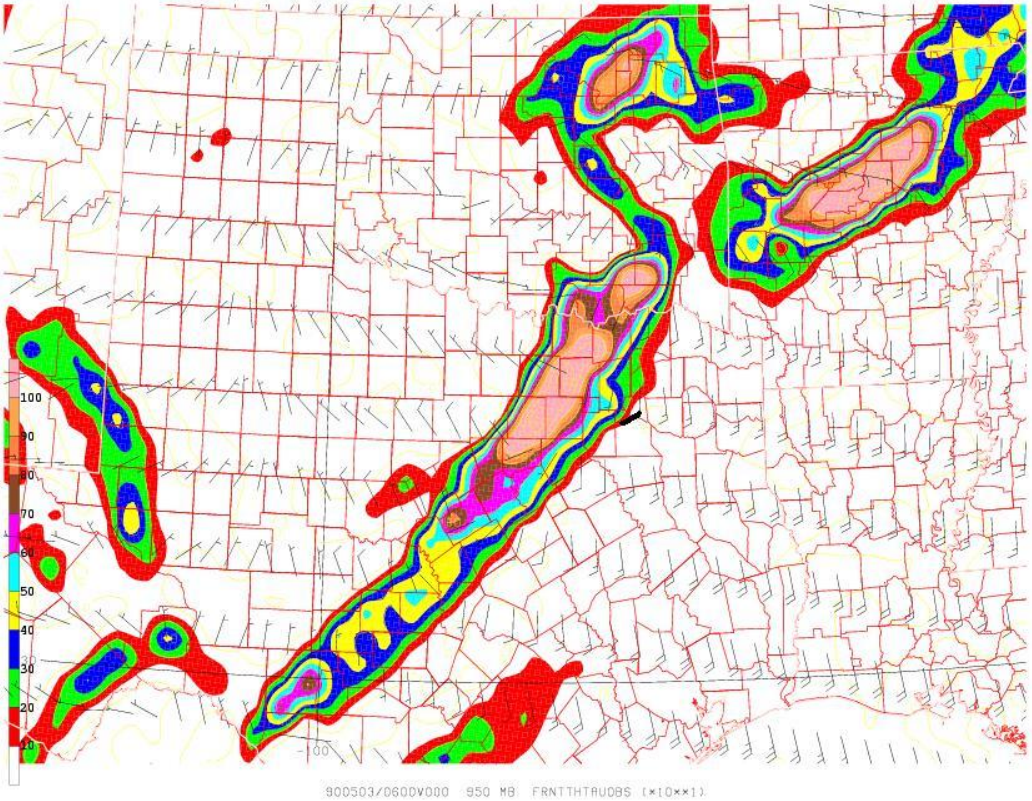

Figure 6: Analysis of 950 hPa frontogenesis overlaid by tornado track (black line) from 5 April 1990 at 0600 UTC. The cold front is roughly co-located within the axis of maximum frontogenesis. The 950 hPa wind barbs (in knots) are also included.