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A Long-Lived Tornadic Supercell over Colorado and Wyoming, 22 May 2008

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ABSTRACT

On 22 May 2008, a slow-moving, meridional trough led to widespread severe weather across the Great Plains, Front Range Urban Corridor of Colorado and Laramie Mountains of Wyoming. The most damaging storm developed near the Denver International Airport and quickly became tornadic. A large tornado occurred with this storm that was responsible for EF3 damage in the town of Windsor, CO. After some weakening, the storm intensified and produced large hail and at least one tornado from the Wyoming-Colorado border northwestward to Laramie, WY. As the storm moved through differing elevations (4700 to 8700 ft (1430 to 2650 m), it also encountered markedly different meteorological environments, making this tornadic event particularly interesting and rare. In addition to the official *Storm Data*, this study will provide supplementary storm documentation based on accounts of local residents. The key synoptic and mesoscale features as well as shear and instability parameters are presented, with an emphasis on observational data.

Additionally, in order for forecasters to gain an understanding of the high-elevation severe storm environment, a comparison is made with relatively low-elevation environments. The importance of assessing the contributing factors to equivalent potential temperature (θ_e) is demonstrated. Recommendations are made for forecasting severe weather at high-elevation locations. Analysis of θ_e is critical when assessing surface data over high-elevation areas, rather than arbitrary judgment (i.e., “it’s too cold”) based on surface temperature and dewpoint.

1. Introduction

On 22 May 2008, a supercell tracked from Colorado into Wyoming over a 4.5 h period. The elevation varied from 4700–8700 ft (1430–2650 m) MSL along a 300 km path. This long-lived supercell (Bunkers et al. 2006) produced an EF3 tornado along the Front Range Urban Corridor of Colorado, and then moved into southeastern Wyoming with EF2 tornado damage and large hail. This event is rare in that there were reports of hail greater than 2 inches (5 cm) in diameter and tornadoes from the same storm in very different environments. Significant tornadoes in high-elevation environments have been documented in the past (Fujita 1989; Evans and Johns 1996; Bluestein 2000), but the unique aspect of this case was the transition in environments due to the storm track over very different elevations. Early in its life cycle, the supercell was in a High Plains severe weather environment characterized by the Miller Type I sounding (Miller 1967) where elevations varied between 4700–5200 ft (1433–1585 m) MSL. Later, as the supercell ascended to elevations between 7500–8700 ft (2286–2652 m) (a mountainous region), the temperature and

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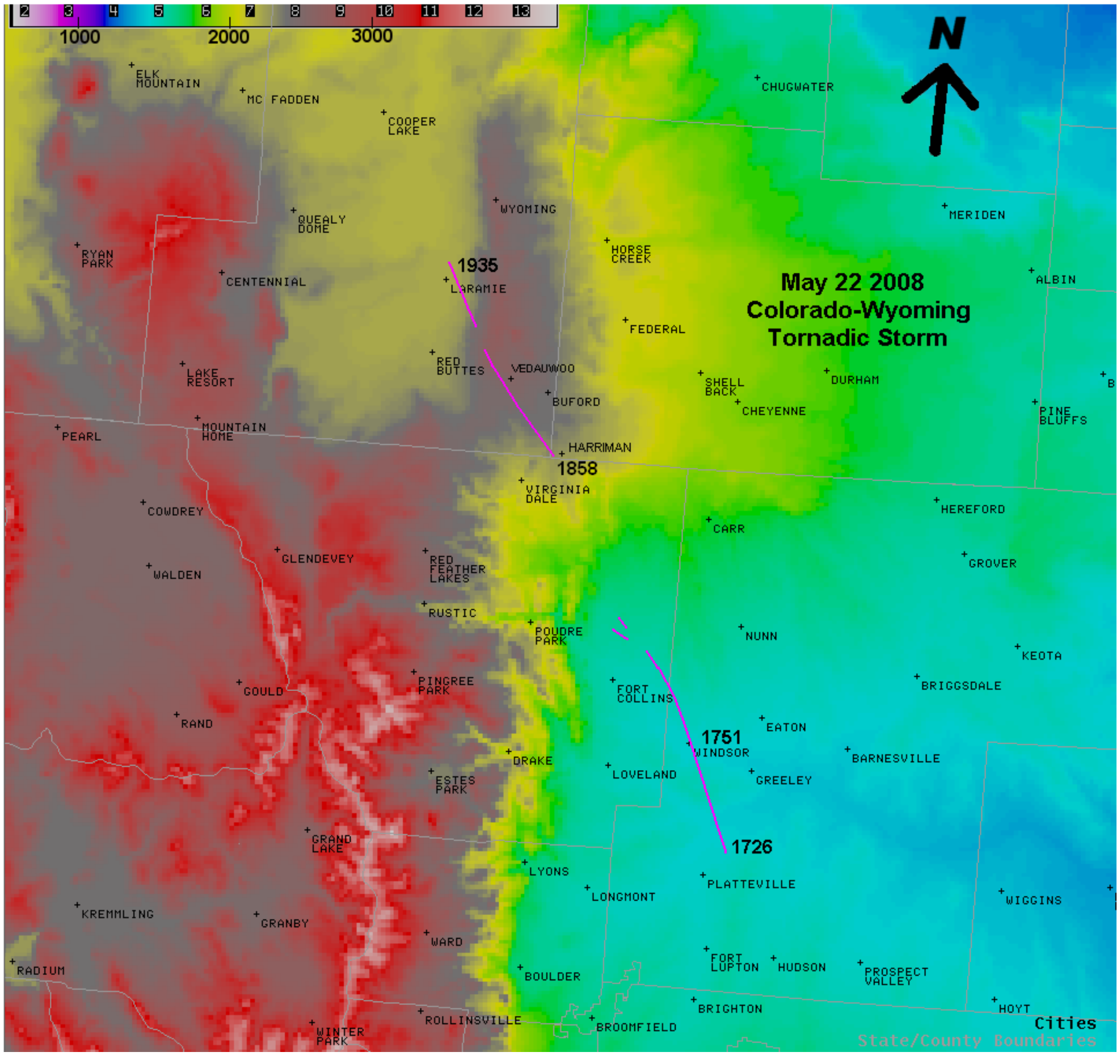

Figure 1. Tornado tracks associated with the 22 May 2008 supercell. Times plotted next to tornado tracks are in UTC. Elevation is shaded with scale in upper left, kft (top) and m (below). *Click image to enlarge.*

dewpoint were in the mid- to upper-40s °F (7–8 °C) (a much "colder" environment). The higher elevation thermal profile was similar to a Miller Type II sounding (Miller 1967) that begins at a lower pressure (higher elevation). The latter environment will be analyzed in terms of θ_e and its components (potential temperature θ and mixing ratio w) instead of temperature and dewpoint, in order to assess the magnitude of the buoyancy.

A quantitative assessment of elevation differences used to discriminate between mountainous versus non-mountainous tornado events is the topographic variation (Seimon and Bosart 2004). The topographic variations along the tornado paths in their study ranged from 150 to 712 m. The 22 May 2008 supercell was associated with severe weather reports for over two hours along a 160 km path extending to Laramie (Fig. 1). The supercell crossed a topographic variation of 1200 m and produced two primary tornadoes. The Colorado tornado path had a topographic variation of 150 m. After a break shown in Fig. 1, a tornado further northwest had a 45 km path length with a topographic variation of 457 m. There may have been a small break in this tornado path before the storm affected Laramie. If so, then the topographic variation was 366 m along a 29 km path. Radar indicated that the storm may have produced additional severe weather in sparsely populated areas northwest of Laramie.

This paper will address the synoptic and mesoscale environments for this event, including an examination of some supplementary observational data. Other cases that occurred in this region are shown for comparison purposes. The evolution of the pre-storm mesoscale environments is provided, including detailed analyses of the air masses and boundaries. The evolving environment associated with the supercell is also discussed. The critical importance of analyzing θ when assessing severe weather in high elevation environments is stressed, including comparisons with lower elevation environments. Finally, a detailed account of storm damage in Wyoming is provided.

2. Synoptic and mesoscale overview

a. 0000–1500 UTC 22 May

At low levels, adequate moisture is typically the missing ingredient for significant severe weather in the lee of the Front Range up to the Laramie Mountains during the spring. At 0000 UTC, rich moisture from the Gulf of Mexico was confined near and south of a warm front from central Oklahoma southward (Fig. 2). In response to the surface low over Colorado, strong southeast winds advected ample moisture northwestward from the Gulf of Mexico that was already in place across the Southern Plains (refer

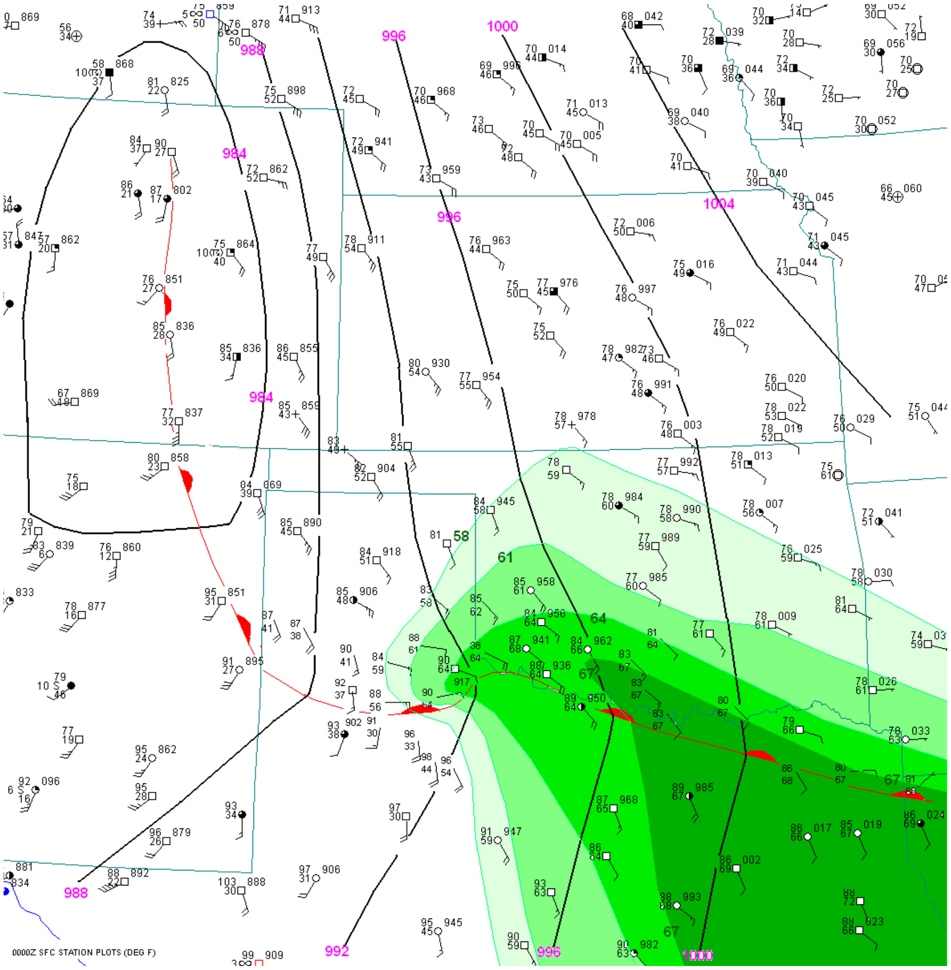

Figure 2. Surface analysis loop between 0000–1500 UTC 22 May 2008. Isodrosotherms of 58 (14), 61 (16), 64 (18) and 67 (19) °F (°C) shaded in a range from light to dark shades of green respectively. Black lines are MSL pressure (hPa); fronts are annotated. Static (initial) image depicted is 0000 UTC. *Click on the image to open animation and enlarge.*

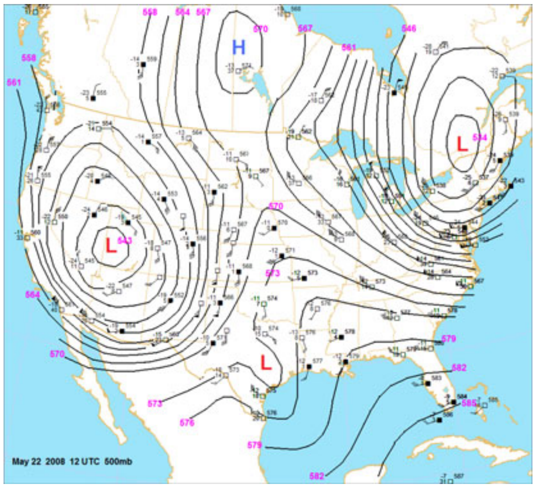

Figure 3. 500 hPa analysis from 1200 UTC 22 May 2008. Heights in dm, temperatures in °C and winds (half barb = 2.5 m s^{-1}, full barb = 5 m s^{-1}, pennant = 25 m s^{-1}). *Click image to enlarge.*

to animation in Fig. 2). Surface moisture was increasing on the cool side of the warm front in the southeastern Texas Panhandle where upslope flow was occurring. A low-level jet in the warm sector, combined with strong upslope flow north of the warm front, helped to advect moisture into Colorado. The primary moisture surge to the north-northwest occurred between 0000–0900 UTC from Oklahoma into eastern Colorado.

The 1200 UTC 500 hPa analysis (Fig. 3) showed a closed low over Utah, with strong meridional (southerly) flow over the Front Range of Colorado extending into southeastern Wyoming. A high-amplitude trough was centered over the northeastern United States. The pattern in the previous 12 hours changed very little due to the slow-moving nature of the western United States upper trough. This meridional upper-air pattern has been associated with past severe weather episodes that affected the same region, notably 23 April 1960 (Finch 2010a) and 15 June 1965 (Finch 2010b). A composite of these three severe weather events illustrates the importance of a particular upper-air pattern for severe weather across the Front Range Urban Corridor / Laramie Mountains (Fig. 4).

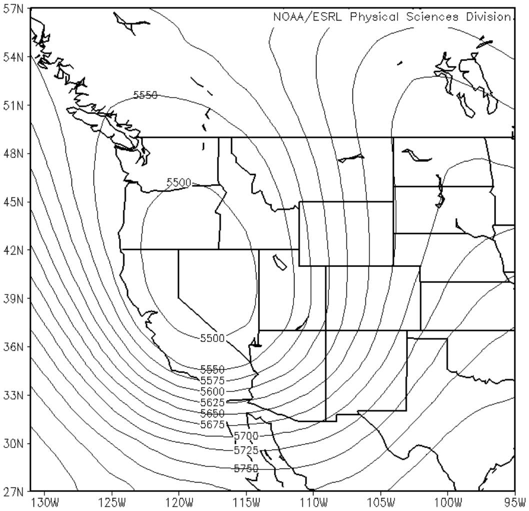

Figure 4. Composite 500 hPa heights (m) for 1200 UTC on 22 May 2008, 23 April 1960 and 15 June 1965 (Image provided by the NOAA/ESRL Physical Sciences Division, Boulder, Colorado from their Web site at http://www.esrl.noaa.gov/psd/). *Click image to enlarge.*

Doswell (1980) stressed the importance of a specific synoptic-scale pattern associated with High Plains severe weather episodes. The composite 500-hPa pattern is characterized by a closed low well west of the region of interest and strong southerly flow. The cases composited here are characterized by storm motion directed toward higher elevation. Since the surface rises from south to north, any storm that initiates to the lee of the Front Range in Colorado moving towards the Laramie Range of Wyoming must be moving upslope (Fig. 1). In this specific synoptic pattern, a storm initiating in one type of environment at a lower elevation can maintain itself while moving upslope into a distinctly different environment. Evans and Johns (1996) investigated composite 500-hPa patterns for significant tornado cases in the Big Horn Range of Wyoming and found that southwest flow was favored. They also noted the upper-level system was an open trough in two of the three cases, with the third starting archetypically as a closed low, then transitioning to an open wave during the day. The case studies of Evans and Johns (1996) were in summertime (and further north in the Big Horn Range), while the studies of interest in this article are in springtime (and further south in the Laramie Mountains of Wyoming and Front Range Urban Corridor of Colorado) when closed lows should be more frequent and positioned farther south. In both studies, the location of the upper trough resulted in an upper-level jet (not shown) over the region that experienced significant tornadoes.

A cold front that resulted from the aforementioned 500-hPa trough over the northeastern US stalled, then retreated northward as a warm front in northern Texas by 0000 UTC. In response to the approach of the upper trough in the Rockies, this warm front surged northward overnight (as shown in the Fig. 2 animation) and was analyzed from east-central Colorado into central Kansas by 1200 UTC. Frontogenesis (not shown) occurred across northern Kansas overnight due to a mesoscale convective system over Nebraska. At 1200 UTC, this nearly stationary front extended from northeastern Colorado into eastern Kansas. The warm front continued to move northward between 1200–1500 UTC. By 1500 UTC, the area between the warm front and stationary front was narrowing, especially across northeastern Colorado. Also during that time, a wind-shift line became more defined south of the warm front (just east of Denver). This wind-shift line separated moist air wrapping cyclonically around the surface low pressure area from much drier air just to the east and southeast of Denver. This feature will be shown in more detail in the next section.

b. 1500–1700 UTC 22 May

The aforementioned stationary front that extended from northeastern Colorado into northern Kansas at 1500 UTC (last frame of Fig. 2 animation) separated low stratus clouds (with some reports of fog) from higher dewpoints and temperatures to the south, in the area between the two frontal boundaries. The warm front that had been moving northward all night and into the morning hours (LT) was beginning to slow in Kansas, but was still surging northward just to the east of Denver. However, this northward surge along the Front Range Urban Corridor ended by 1500 UTC. The western end of this front surged southward as a cold front between 1500–1630 UTC into southern Weld County, as denoted by a radar reflectivity fine line (Fig. 5). The north to south oriented wind shift line at 1500 UTC was progressing slowly westward into western Adams county. This boundary was the focus for convective initiation immediately northwest of the radar site (KFTG) between 1600–1630 UTC.

Changes in location and orientation of the three primary surface boundaries between 1500–1700 UTC were crucial to convective evolution. As shown in the 1545 UTC Geostationary Operational Environmental Satellite (GOES) visible image with surface observations (Fig. 6), clearing developed between the warm and dry air mass to the south and the cloudy and cool air mass (near saturation) further north. Thus, four air masses are identified in Fig. 6. Air mass A is stable (cool and moist) and is characterized by stratus clouds and strong easterly winds. Air mass B is potentially unstable (warm and moist) and is characterized by partial clearing and strong easterly winds. This air mass would continue to destabilize due to insolation and the resultant heating of the moist air mass. Air mass C is warm and dry with clear skies and is characterized by steep low to mid-level lapse rates; however, there is insufficient moisture for deep moist convection. Finally, air mass D is potentially unstable, with variable temperature and dewpoint; however, surface winds are much lighter. Because of moisture wrapping around the surface cyclone, the dewpoints are higher in the northern portion of air mass D while decreasing to the south. Partially clear skies allowed for some insolation.

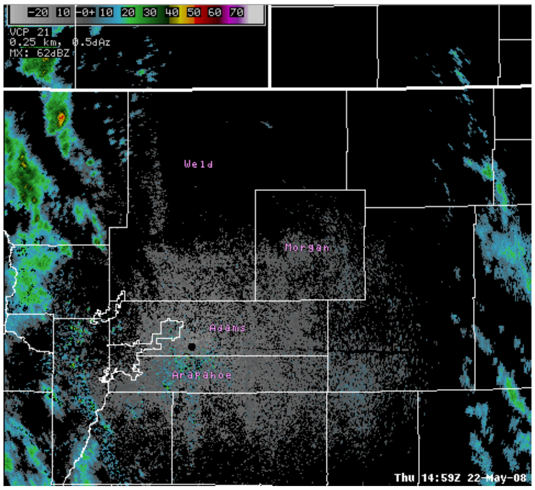

Figure 5. Denver, CO Front Range airport (KFTG) WSR-88D 0.5° reflectivity, 1459–1631 UTC 22 May 2008. Static (initial) image depicted is 1459 UTC. *Click on the image to open animation.*

Air mass B was expanding due to clearing of the southern extent of air mass A, and the southward movement of the front between air masses B and C. This expansion of air mass B was mainly confined to southwestern Weld County. Forecast supercell motion (not shown) toward the north-northwest implies that any potential storm just east of the Front Range

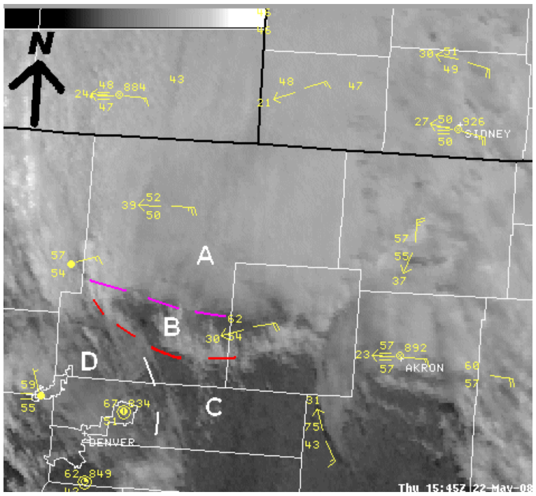

Figure 6. GOES visible image with surface observations (following Fig. 2 convention) at 1545 UTC 22 May 2008. Air-masses indicated by letters and annotated boundaries described in text. *Click image to enlarge.*

would have a longer residence time in the warm sector compared to storms 60–150 km further east. Any potential thunderstorm further east would have a very narrow warm sector and storm motion would result in the storm moving into air mass A and becoming elevated.

Initial convection developed along the boundary between air masses C and D, which was situated near the Denver International Airport (DIA) at 1630 UTC (Fig. 7). By 1700 UTC, the eastern part of air mass B had shrunk to about 10–15 km in width (north–south) while the western part was roughly 80 km wide (north–south). This is illustrated in a radar image with surface observations overlain at 1700 UTC (Fig. 8). After initiating near DIA, the storm moved to the north and quickly became severe after crossing into Weld County. Fig. 8 shows that the southern end (primary updraft location) of the storm was still in air mass D (south of air mass B) and immediately west of the trough that separated air masses C and D. The eastern part of air mass B was not expanding in the north-south direction. In contrast, the western portion of air mass B (to the lee of the Front Range) had become relatively wide (north–south). The 1700 UTC surface chart for the Plains region (Fig. 9) shows the two aforementioned fronts across northern Colorado and the trough through the Denver metro area.

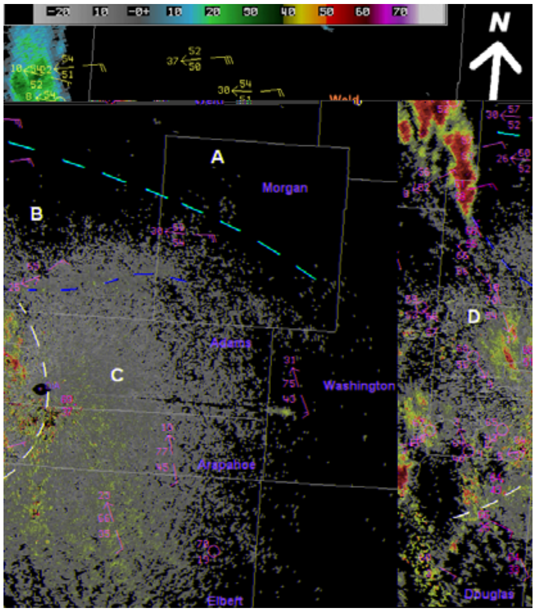

Figure 7. Denver, CO Front Range airport (KFTG) WSR-88D 0.5° reflectivity 1630 UTC 22 May 2008 along with surface observations (following Fig. 2 convention). Air masses indicated by letters and annotated boundaries described in text. *Click image to enlarge.*

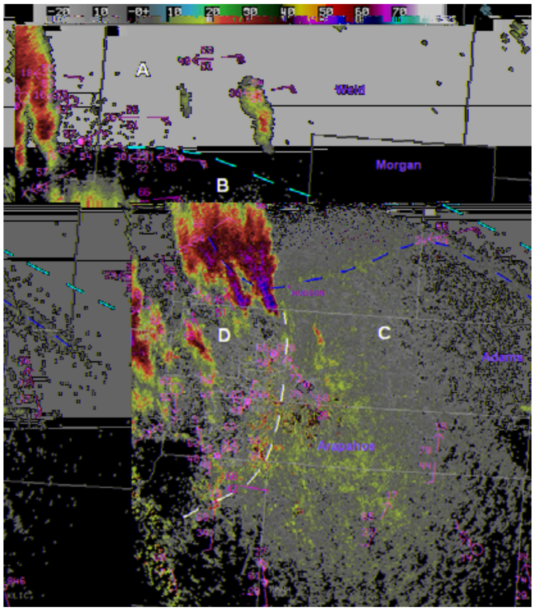

Figure 8. As in Fig. 7, but for 1700 UTC 22 May 2008. *Click image to enlarge.*

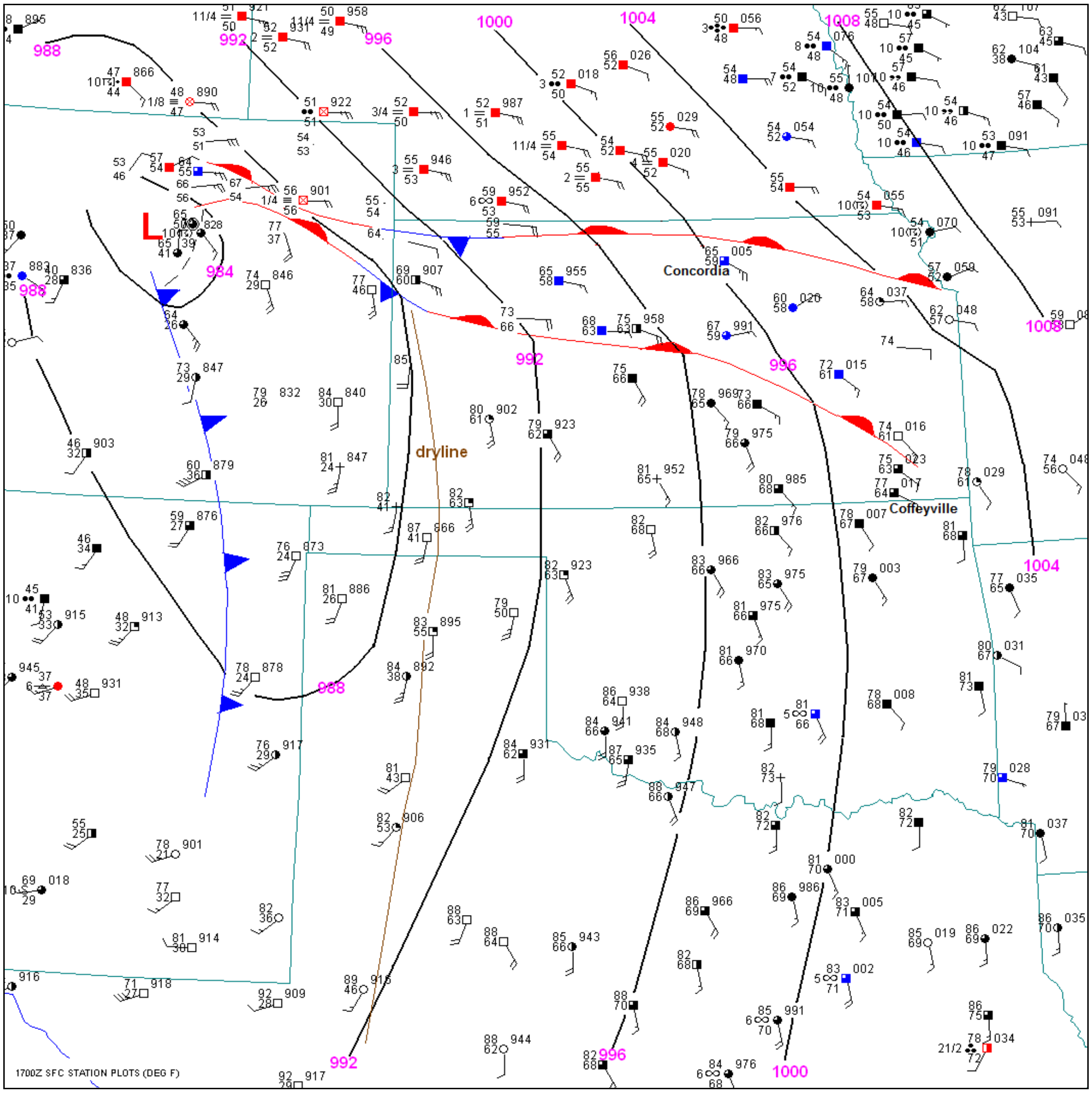

Figure 9. Surface analysis (observations following Fig. 2 convention) for 1700 UTC 22 May 2008. Black lines are MSLP (hPa), fronts are annotated. *Click image to enlarge.*

c. 1700–1800 UTC 22 May

The authors made a few phone calls to document when the storm first produced hail. Hail 0.75 inch (1.9 cm) in diameter occurred 6 km west-southwest of Hudson, CO at 1705 UTC based on radar (location depicted in Fig. 8). The hail became larger as the storm moved north-northwestward. Large hail damaged the siding of a house 14 km northwest of Hudson around 1714 UTC. At 1719 UTC, the first report in Storm Data (NCDC 2008) of 1.0 inch (2.5 cm) diameter hail was 24 km northwest of Hudson. The storm encountered the southern front (between air masses B and D) at ~1720 UTC. The first tornado occurred 8 km northeast of Platteville, CO (location depicted in Fig. 1) at 1726 UTC based on eyewitness accounts. The storm was located along or immediately north of the southern frontal boundary (separating air masses B and D in Fig. 10). Between 1720–1745 UTC, the western segment of the boundary (close to the storm) separating air masses B and C moved northward with the storm. Further east this boundary was still stationary, allowing the storm to ingest air from air mass B (Fig. 11). The boundary orientation between air masses B and C (right next to the supercell) changed from west-east to north-northwest–south-southeast. As a result, the storm was in an environment

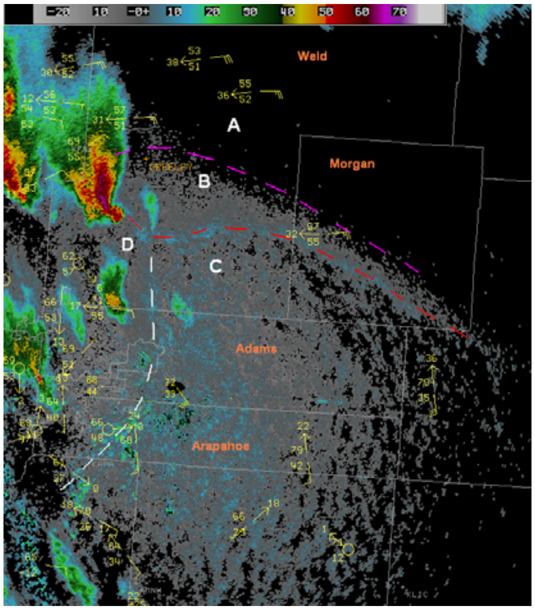

Figure 10. As in Fig. 7, but for 1730 UTC 22 May 2008. *Click image to enlarge.*

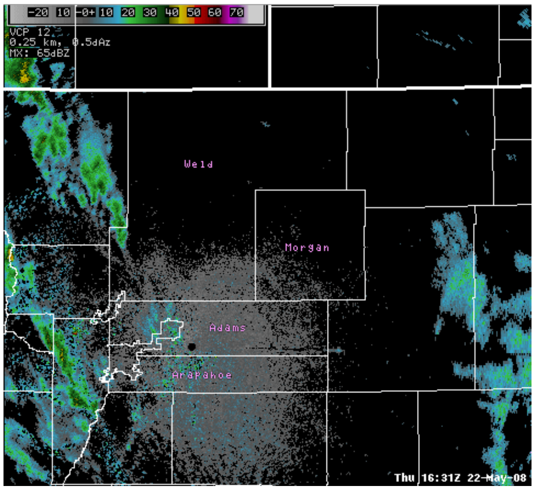

Figure 11. As in Fig. 5, but for 1631-1801 UTC 22 May 2008, static (initial) image is 1631 UTC. *Click on the image to open animation and enlarge.*

characterized by strong easterly winds, low LCLs (Lifting Condensation Level), and moderate CAPE (convective available potential energy) values (to be shown later). Between 1745 and 1800 UTC, the storm crossed from air mass B into air mass A. During this period, EF3 damage occurred with the tornado near Windsor. By 1800 UTC, the storm had just moved into cooler and more stable conditions associated with air mass A (Fig. 12). An areal estimation of surface-based CAPE (SBCAPE) was developed for 1800 UTC. In an effort to get the best possible SBCAPE analysis, the NAM (North American Mesoscale) model point soundings were modified using actual surface observations (Fig. 13). At high elevations, the model terrain representation can be significantly in error, resulting in unrealistic surface pressure values, and thus SBCAPE; we accounted for this aberration when modifying the point soundings. This analysis shows a narrow sliver of greater than 2000 J kg^{-1} SBCAPE through northeastern Colorado. As discussed earlier, a wider warm and moist sector existed farther west along the Front Range. This distribution of SBCAPE, along with storm motion to the north-northwest, implies that any storm in northeastern Colorado would move quickly into the stable region and become less of a severe threat. Meanwhile, any storm that initiated in the western portion of air mass B would have a longer residence time in the warm sector, allowing it to develop and intensify. A modified sounding was created for Greeley, CO at 1800 UTC (Fig. 14). This location was chosen because it was representative of air mass B and since the storm passed just to the west of Greeley. The modification was based on the 1800 UTC sounding from Denver, as well as surface observations. Winds at middle to upper levels

Figure 12. As in Fig. 7, but for 1800 UTC 22 May 2008. *Click image to enlarge.*

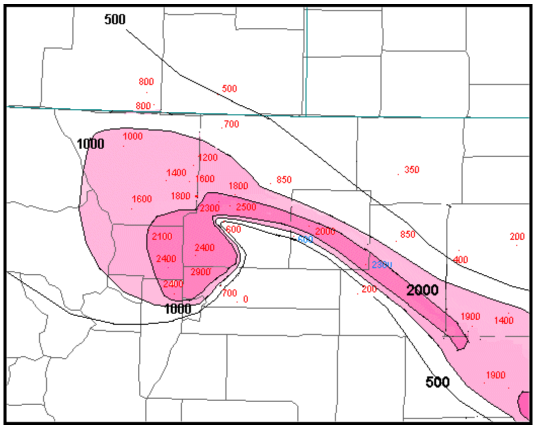

Figure 13. Surface-based CAPE (J kg^{-1}) across north-central and northeastern Colorado, valid 1800 UTC 22 May 2008. Point values indicate locations where modified soundings were derived to estimate surface-based CAPE. *Click image to enlarge.*

were represented well by the 1800 UTC Denver sounding and available ACARS [(Aircraft Communications Addressing and Reporting System); Benjamin et al. (1999)] data. However, the mid-level jet east of Denver was not sampled well. Data from the nearest available wind profiler near Platteville, CO could have been very useful in assessing the strength of the low- to mid-level winds; however, the data were missing after 1600 UTC. The lowest levels were modified with the 1800 UTC Greeley, CO surface observation. Moisture depth is inferred from observations at various elevations, as well as the observed height of stratus clouds in the moist sector using GOES infrared imagery. The modified sounding was characterized as Miller Type I (Miller 1967). Noteworthy attributes of the sounding include SBCAPE ~2400 J kg^{-1}, LCL and level of free convection (LFC) heights of ~1 km and a freezing level of 2.4 km AGL.

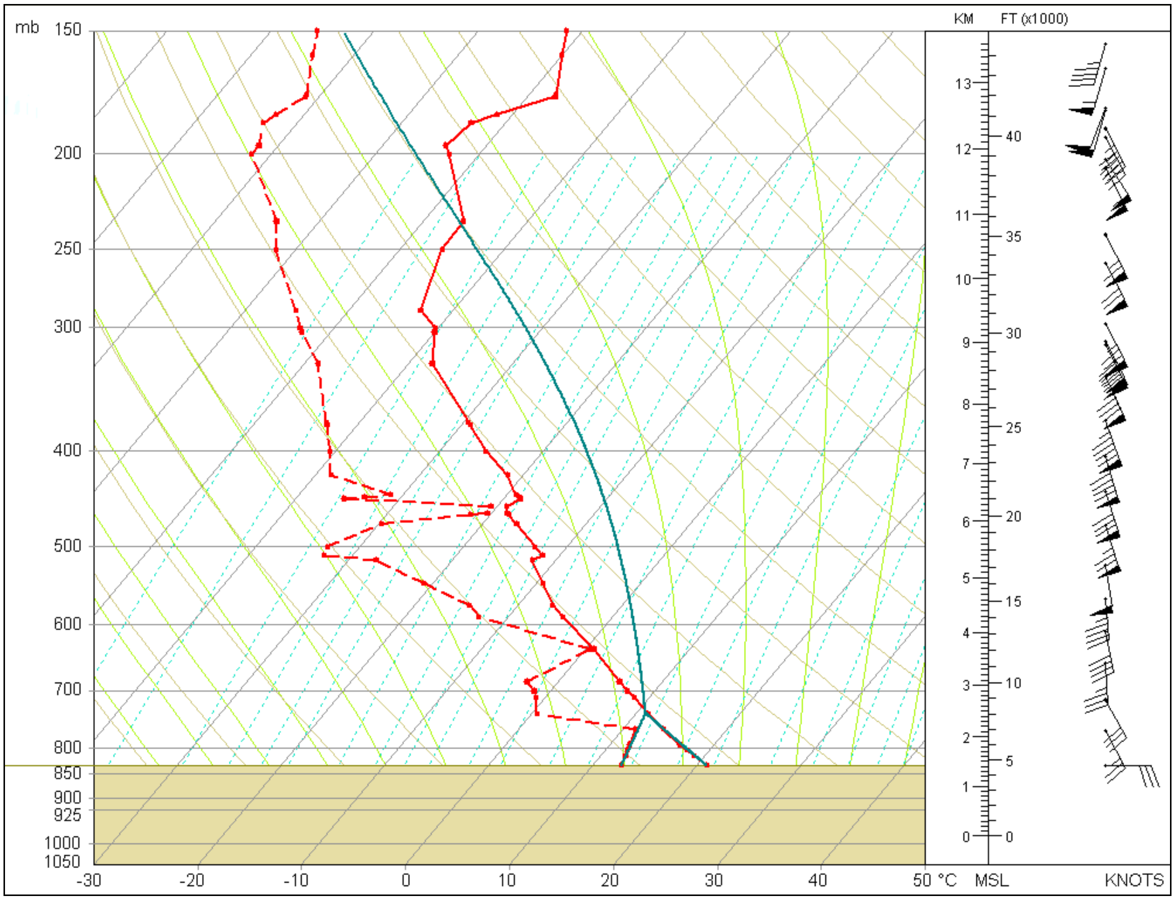

Figure 14. Modified sounding for Greeley, CO valid 1800 UTC 22 May 2008. Temperature (red solid line), dewpoint temperature (red dashed line) and winds (half barb = 2.5 m s^{-1}, full barb = 5 m s^{-1}, pennant = 25 m s^{-1}). Lifted parcel indicated by turquoise line. Location of Greeley depicted in Fig. 10. *Click image to enlarge.*

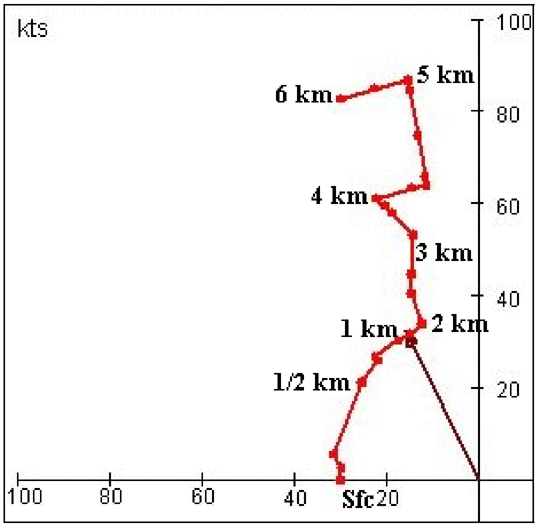

Figure 15. Modified surface to 6 km AGL hodograph for Greeley, CO valid 1800 UTC 22 May 2008. Storm motion vector is 154° at 36 kt (19 m s^{-1}). Location of Greeley depicted in Fig. 10.

A modified hodograph also was created (Fig. 15) to analyze the vertical wind shear. The storm motion vector of 154° at 36 kt (19 m s^{-1}) was calculated from radar and is in agreement with the orientation of the tornado damage path. The 0–6 km shear magnitude of 89 kt (46 m s^{-1}) supported supercell convective mode. Storm-relative helicity may have been greater than given values of 47 m^2 s^{-2} (0–3 km) and 58 m^2 s^{-2} (0–1 km) due to poor sampling of the low- to mid-level winds in the vicinity of the storm. Also, important storm-relative helicity enhancement can be anticipated near similar boundaries (Markowski et al. 1998). The modified sounding and hodograph indicate ample SBCAPE and vertical shear for supercell mode in air mass B.

d. 1800 – 2000 UTC 22 May

A weakening trend in the storm commenced shortly after 1800 UTC, although weak tornadoes did occur through 1820 UTC north of Fort Collins, CO (see Fig. 1 for location depiction) based on eyewitness accounts. The depth of the stable layer was increasing towards the north as the storm moved deeper into air mass A. Table 1 highlights the change in air mass characteristics between air masses B and A. From the table, air mass B was represented well by Greeley (θ = 98°F or 310 K), while air mass A was represented well by Eaton, CO (θ = 87°F or 304 K). This drop in θ, along with an 11% decrease in w, contributed to a decrease of 11 K in θ_e, resulting in lower SBCAPE, higher surface-based convective inhibition (SBCIN) and a weakening of the storm. There were no reports of tornadoes in the mountainous region northwest of Fort Collins to the Wyoming border, as the storm moved over terrain ascending from 5000–7400 ft (1524–2256 m) MSL. Lack of additional severe weather reports could be explained by the low population density in this region. The mesocyclone continued to exist in a weakened form after 1820 UTC.

A modified sounding was created for Harriman, WY at 1900 UTC (Fig. 16). Between 600-150 hPa, the sounding is based on the 1800 UTC sounding from Denver since mid- to upper-tropospheric temperatures were about the same along the Denver to Laramie corridor. The lower part of the Harriman sounding was modified using a Union Pacific Railroad weather station at Harriman and observations from three wind towers (locations depicted in Fig. 18). Data from the wind towers were available in 10-min intervals. The temperature sensors were at the bottom of the towers while the wind direction and wind speed were at 57 and 58 m AGL respectively. In addition, hourly temperatures from Virginia Dale, CO (location depicted in Fig. 1) were obtained from a cooperative observer. The data from these stations were very consistent and deemed to be accurate since they generally were located along the same moist adiabat when plotted on a skew$T$–log$p$ diagram. Since dense fog was present, the temperature was assumed to be approximately equal to the dewpoint temperature. The winds were derived from the WSR-88D base velocity, velocity azimuth display (VAD) wind profile in Cheyenne, WY, and wind tower 1. Wind Tower 1 was < 800 m east of the tornado path. The nearest available wind profiler at Medicine Bow, WY (located 80 km northwest of Laramie) was too far west to be representative, except for upper-level winds.

The modified sounding was characterized by a Miller Type II sounding (Miller 1967) that begins at a much lower (higher) pressure (elevation). The modified sounding was characterized by high RH that extended up to 650 hPa. Noteworthy attributes of the sounding include ~800 J Kg^{-1} SBCAPE, no convective

Table 1: Air mass characteristics based on 1800 UTC observations at various locations. θ is given in °F and K for relational purposes. T_d represents dewpoint.

Station	**Elevation ft MSL (m MSL)**	**T/T_d °F (°C)**	**Pressure hPa**	**Sea-level pressure hPa**	**Mixing Ratio w g kg^{-1}**	**θ °F (K)**	**θ_e K**
Harriman, WY	7450 (2271)	47/47 (8/8)	754	985	9.2	90 (305)	333
Concordia, KS	1466 (447)	67/59 (19/15)	948	1001	11.4	75 (297)	330
Greeley, CO	4700 (1433)	70/55 (21/13)	833	983	11.2	98 (310)	345
Eaton, CO	4880 (1487)	58/52 (14/11)	827	983	10.1	87 (304)	334
Coffeyville, KS	738 (225)	77/65 (25/18)	974	1002	13.7	81 (300)	341

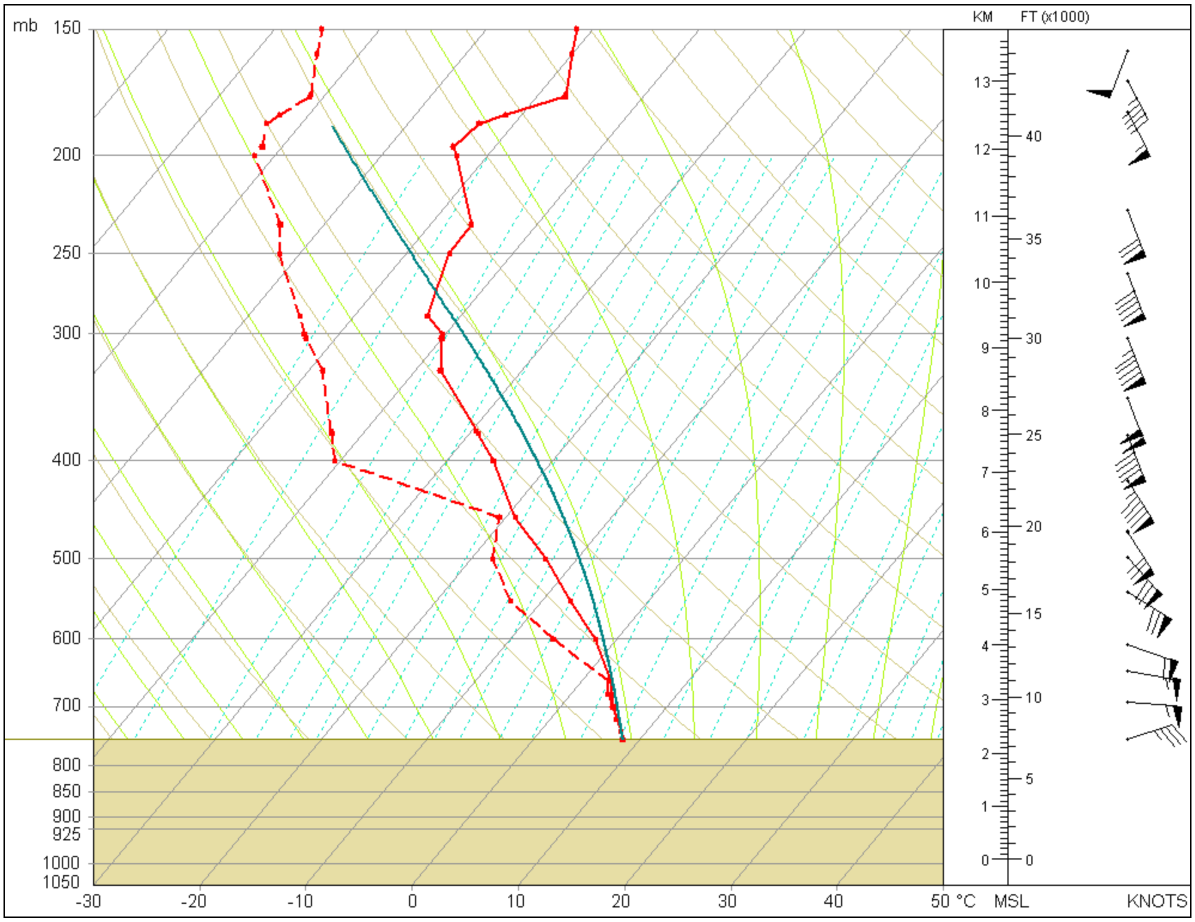

Figure 16. As in Fig. 14, but for Harriman, WY, valid 1900 UTC 22 May 2008. Location of Harriman depicted in Fig. 1. *Click image to enlarge.*

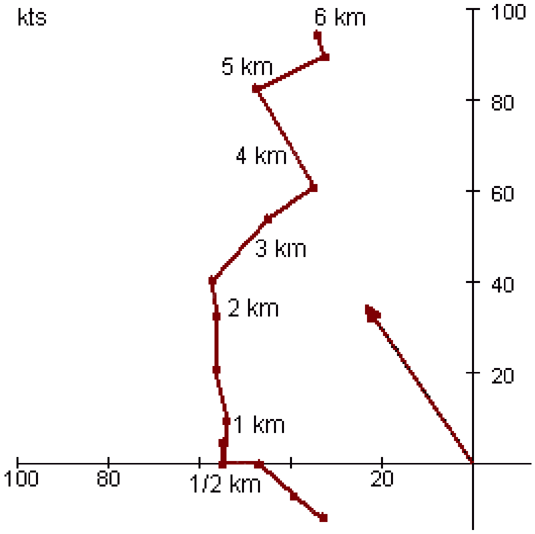

Figure 17. As in Fig. 15 but for Harriman, WY, valid 1900 UTC 22 May 2008. Storm motion vector is 146° at 42 kt (22 m s^{-1}). Location of Harriman depicted in Fig. 1.

inhibition (CIN), LCL and LFC heights near the surface and a freezing level of 1.5 km AGL. The freezing level at higher elevations where the storm moved (7700–8700 ft or 2347–2652 m MSL) was even lower (1–1.3 km AGL). The elevated mixed layer and associated warm mid-level temperatures did not extend as far north as Wyoming. Therefore, despite the apparently "cool" temperatures of air mass A in Wyoming, sufficient SBCAPE existed along with zero CIN. A modified sounding for Eaton (not shown) depicted an inversion at low levels due to: 1) the elevated mixed layer that originated within air mass C being advected northward over air mass A and 2) the lower θ values at low levels. Table 1 illustrates that the θ_e at Eaton and Harriman were comparable, with the key difference being zero CIN at Harriman while there was some CIN at Eaton.

A modified hodograph also was created (Fig. 17) to analyze the vertical wind shear. The storm motion vector calculated from radar agreed with the orientation of the tornado damage path. This was 6 kt (3 m s^{-1}) faster than the storm motion used in the Greeley modified sounding since the centroid of the supercell was at a lower pressure (higher elevation) with stronger ambient flow. The 0–6 km shear magnitude of 106 kt (55 m s^{-1}) was only 19% higher than in the Greeley modified sounding; however, the winds in the lowest 3 km were much stronger and more backed over a deeper layer. Nonetheless, both soundings exhibit extreme values of deep-layer shear. The storm-relative helicity values were 627 m^2 s^{-2} (0-3 km AGL) and 280 m^2 s^{-2} (0-1 km AGL). Multiple data sources indicated that the surface or near-surface winds were locally stronger in southeastern Wyoming along the storm track. Surface and wind tower observations showed a localized region of stronger (east-northeast) flow near the storm track southeast of Laramie, WY (Fig. 18a) at 1800 UTC. The stronger winds shifted eastward by 1900 UTC (Fig. 18b) along and east of the supercell path, and weakened further west.

Wind tower 1, located along the track of the storm northwest of Harriman, WY, measured average winds of 28 kt (14 m s^{-1}) at 58 m AGL over the six 10-min periods between 1800 UTC and 1900 UTC (Fig. 19). The average peak wind gust was 41 kt (21 m s^{-1}) in this same time frame. These data support the enhanced flow in regional mesonet observations, and indicate that the stronger winds started more than an hour before the storm passed. Winds increased substantially when the approaching tornado was between 6 and 21 km from the tower, in the 10-min period from 1850 to 1900 UTC. The average wind at 57 m AGL was 70° at 33 kt (17 m s^{-1}) with a peak gust at 58 m of 56 kt (29 m s^{-1}). Wind towers 2 and 3 (locations depicted in Fig. 18) depicted very strong winds between 1720 and 1840 UTC, with average and peak 58 m wind speeds of 33 and 45 kt (17 and 23 m s^{-1}) respectively, over the eight 10-min intervals. The peak wind gust over the full 80-min period was 50 kt (26 m s^{-1}) at both of these towers. Also, these two towers were located south of the path of the storm and became removed from the inflow as the storm passed to the north and northeast.

The CSU-CHILL radar (Brunkow et al. 2000) located in Greeley, CO also indicated the stronger winds in the Laramie Range. The 1.7° base velocity data (Fig. 20) indicated that the locally stronger winds: 1) existed before the storm entered the vicinity, 2) were oriented east-west in a distinct pattern, and 3) may have been augmented by the storm itself as it approached the Laramie Mountains around 1900 UTC. Surface observations and radar data are in good agreement on this localized region of stronger winds in the Laramie Mountains, and suggest that it cannot be attributed to strong storm-scale inflow alone. A distinct maximum, possibly

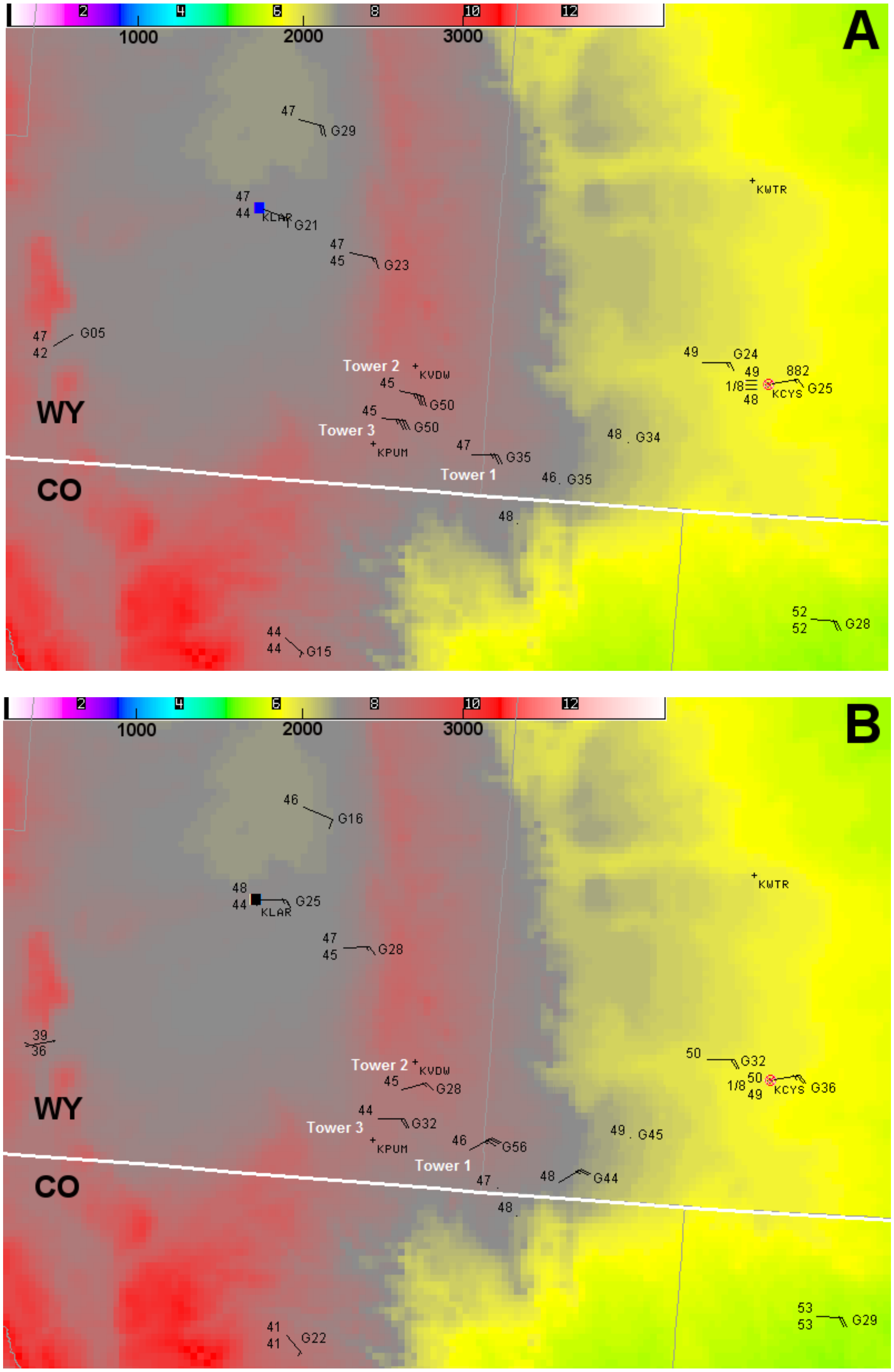

Figure 18. a) Surface observations (thermodynamic variables in °F, full barbs represent 10 kt or 5 m s^{-1}, gusts in kt) at 1800 UTC 22 May 2008. Elevation shaded as in Fig.1. Wind tower locations labeled in white. True north is perpendicular to the state lines, as shown in Fig. 1. b) As in (a) but for 1900 UTC. *Click each image to enlarge and zoom out.*

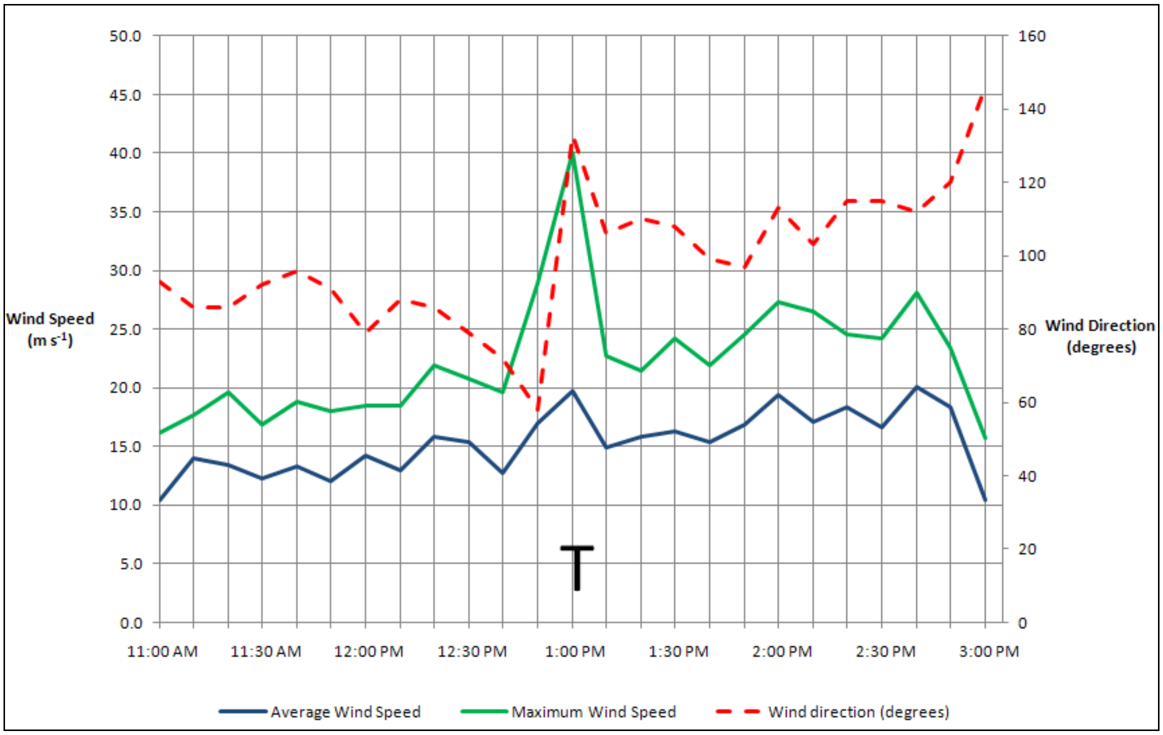

Figure 19. Observations from wind tower 1 (Fig. 18), located > 0.5 mi (0.8 km) east of the tornado path. Wind speeds (m s^{-1}) are taken 58 m AGL, over 10-min time intervals; i.e., 1:00 PM is 10-min. average between 1:00 and 1:10 p.m. Mountain Daylight Time (UTC –6 h). Wind directions were taken at 57 m AGL, over 10-min intervals. Green line denotes maximum wind speed, blue line denotes average wind speed and dashed red line denotes wind direction. T denotes time of closest tornado passage. Data courtesy of Intermountain Wind, Boulder, CO. *Click image to enlarge.*

augmented by storm-scale inflow, was noted between 1850–1900 UTC. The north-south oriented Laramie Mountains acted as a barrier to easterly flow, resulting in a deflection of the flow to the left (backing wind direction) as shown in Fig. 18b. The localized wind maximum may be attributable to acceleration due to blocking effects and/or being at a higher elevation where the flow is stronger. The role of the terrain in developing a localized region of stronger winds may have been important for providing a favorable near-storm environment for tornadogenesis (e.g., LaPenta et al. 2005). A modeling study for this case suggested high potential vorticity generated by the strong southerly flow shearing around the Colorado Front Range as an additional terrain-related influence (Geerts et al. 2009). Isallobaric effects also may have contributed to this localized wind maximum since Greeley, CO and Fort Collins, CO reported pressure falls of 2 and 1 hPa respectively between 1700–1800 UTC.

3. Wyoming storm documentation

Results from the official storm damage survey conducted by the National Weather Service (NWS) Cheyenne forecast office were coordinated with findings from this study. To thoroughly document severe weather along the storm path, strategically placed phone calls were made to the affected area. Frequently, information from one person would include locations and names of other people close to the storm path. Extensive use of the reverse address search feature in the Dexknows online white pages, along with Google Maps, was made to find residences in remote areas. The Wyoming segment of the storm path was the primary focus here due to the very low population density and lack of adequate reporting. Tornado and hail damage photos were gathered from several residents of southeastern Wyoming. These additional reports resulted in a more accurate depiction of the tornado paths. The locations of

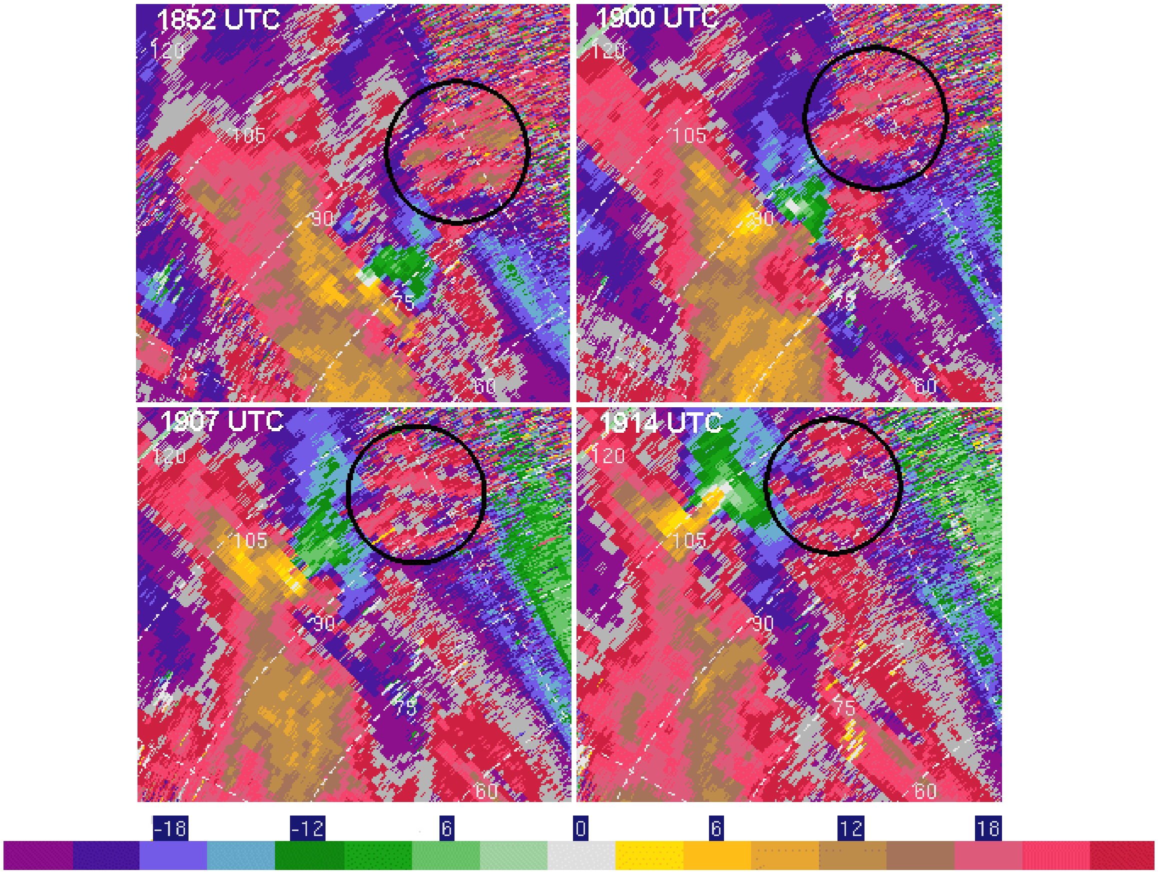

Figure 20. CSU-CHILL radar base velocity at 1.7° elevation angle. Times are indicated for 22 May 2008. Range rings in km from the radar site (located in Greeley, CO). The storm of interest is northwest of the radar moving northwest. Scale in m s^{-1}. Circle represents the region of stronger winds discussed in the text and corresponds to the area from Harriman to Buford, WY (locations depicted in Fig. 21).

damage are denoted by letters A-I (Fig. 21). The first sign of tornado damage was at a residence about 200 m north of the Colorado-Wyoming border around 1858 UTC. Two trees on this property were downed, a garage door was bent, and 1.3 inch (3.2 cm) diameter hail was observed. Immediately to the northwest, 20 ponderosa pines were downed at the C. Hoover residence (Fig. 22a, location A in Fig. 21, or about 360 m north of the state border at 7520 ft or 2292 m MSL) as the tornado passed between the house and a barn around 1859 UTC. Nancy E. Levinger took pictures of additional downed trees (Fig. 22b) and documented the latitude and longitude of the damage (location B in Fig. 21). J. Mitros documented a significant downing of trees (Fig. 22c) at location C in Fig. 21. This tree damage occurred around 1905 UTC. Very old pine trees 1 m in diameter were blown down by the tornado near Imson Pond (depicted in Fig. 21, elevation 7820 ft or 2384 m MSL) around 1908 UTC. Several people were putting fish into Imson Pond in the dense fog, with visibilities ~30 m. Hail ranging in size from 1.0 to 1.5 inch (2.5 to 3.8 cm) caused them to seek shelter in their trucks. This is fortunate since they were then hit by the tornado around 1908 UTC. They described a frightening experience as the tornado buffeted their vehicles. One truck containing a 450 kg fish tank was rocked back and forth by the tornado and most of the windows were smashed out by debris. Another truck reportedly was lifted off the ground and set back down, with windows knocked out as well. A camper shell was broken off one of the trucks and blown 800 m to the south.

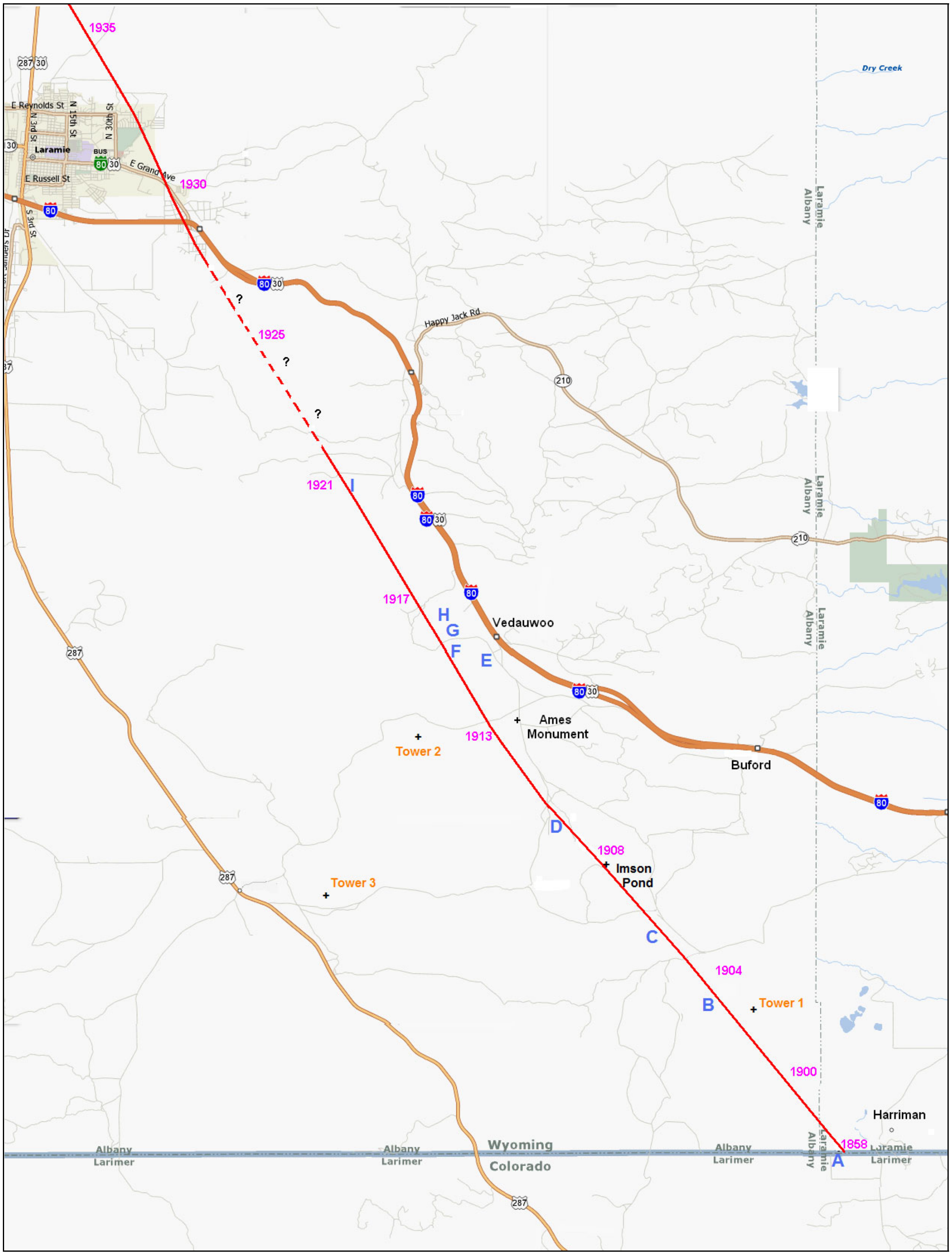

Figure 21. Map of the tornado track (red) in Wyoming, 22 May 2008. Letters indicate location of photos in Fig. 22. Times (UTC, magenta) correspond to the location of the tornado at the given time. Background map courtesy of www.mapquest.com. *Click image to enlarge.*

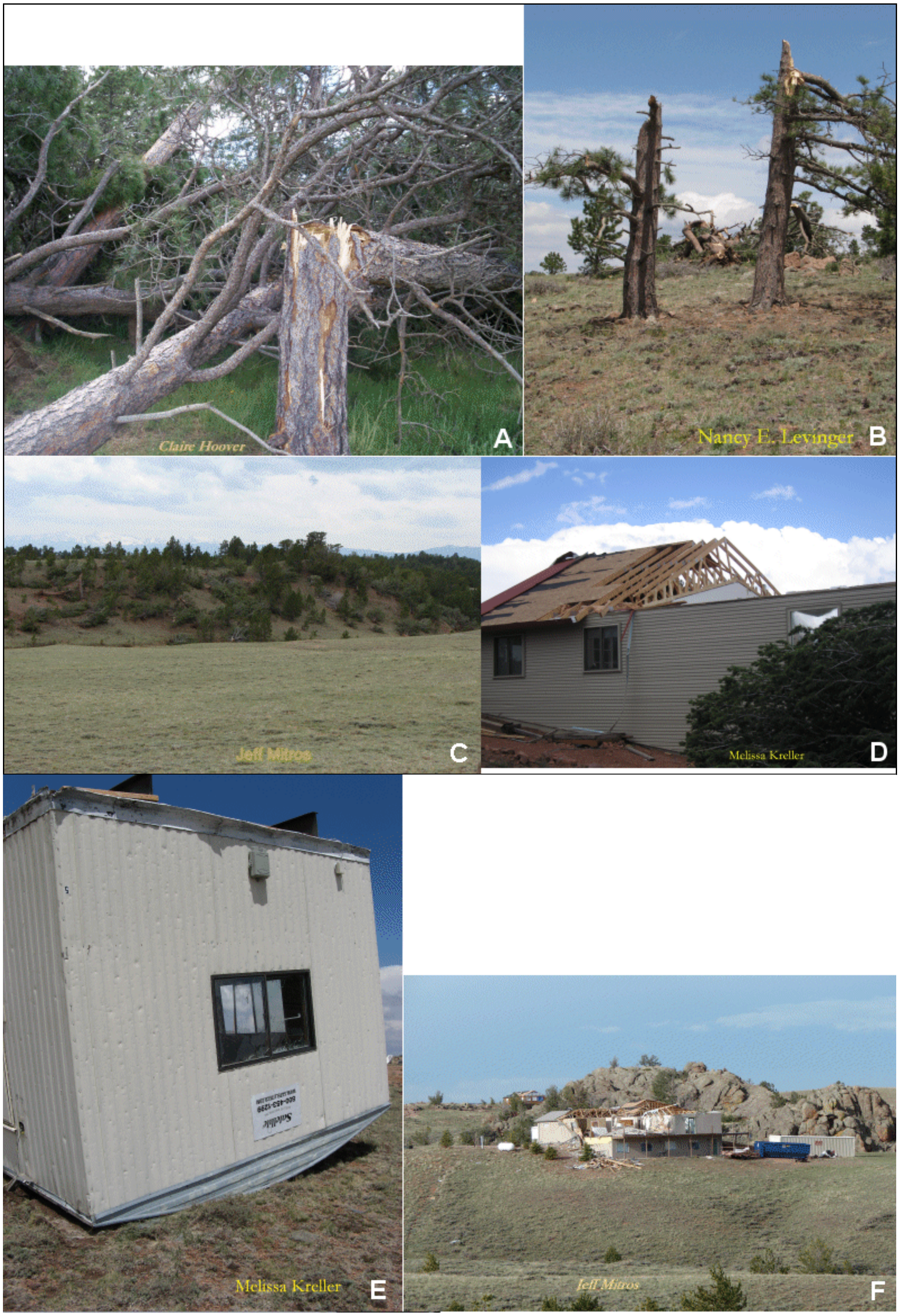

Figure 22(a-f). Storm damage photographs. Letters indicate location given on Fig. 21. Links to full resolution photos with credit: a) Claire Hoover, b) Nancy E. Levinger, c) Jeff Mitros, d) Melissa Kreller, e) Melissa Kreller, f) Jeff Mitros.

Figure 22(g-j). Storm damage photographs. Letters indicate location given on Fig. 21. Links to full resolution photos with credit: g) Stephen R. Rogers, h) Jeff Mitros, i) Jeff Mitros, J) John Myers

After passing northwest of Imson Pond, the tornado moved over open country and destroyed snow fences. T. Lewis, located less than 800 m northeast of location D on Fig. 21 at an elevation of 8100 ft (2469 m) MSL, measured a 133 kt (68 m s^{-1}) gust at 1911 UTC with a Davis Monitor 2 anemometer. His house did not sustain major damage even though trees were blown down. The tornado then hit the P. Hanselmann house (Fig. 22d) about 5.6 km west-southwest of Buford (location D). The front half of his wood roof structure was blown off, with pieces found over 3 km to the northwest. Walls of the Hanselmann house remained, and were well-constructed with insulated concrete forms comprised of steel-reinforced concrete sandwiching Styrofoam blocks. The walls were anchored to a concrete slab foundation.

Farther northwest, the periphery of the tornado hit the Maher residence (immediately northwest of location D) around 1912 UTC, causing extensive damage to the roof cover and minor structural damage. Hail caused roof covering and siding damage and the tornado caused minor roof covering damage immediately south of Ames Monument (location depicted on Fig. 21). Tornado debris was blown northwestward towards Ames Monument. F. Magrath (NWS cooperative observer) reported hail as large as 1.75 inches (4.4 cm) in diameter 1.6 km west of Ames Monument. She reported that the visibility was around 30 m when the hail was falling. About 800 m west of Ames Monument on G. Obssuth's property, a 450 kg utility trailer was blown 90–120 m. South-facing windows of his house were destroyed. The largest hail at the Obssuth residence was 2 inches (5 cm) in diameter. A house was partially unroofed and a patio deck sustained damage 1.6 km northwest of Ames Monument. The tornado downed 100 to 150 trees in an 800-m wide swath centered near the house. Storm damage occurred 1 km northeast of the tornado track line depicted in Fig. 21 at location E as shown in Fig. 22e. The tornado hit the Gayle Wilson house (elevation 8320 ft or 2536 m MSL) around 1916 UTC (location F), removing portions of the roof and exterior walls as shown in Fig. 22f.

The tornado injured a woman in the Vedauwoo area with flying glass as one of the windows in her house blew out. It then moved just west of the house belonging to S. Rogers (location G). His pickup truck was heavily damaged after being hit by boards. Parts of a trailer were scattered and trees were blown down. A 7-m trailer was overturned and moved 150 m. Wind-driven hail shattered ten windows of the Rogers' house and one of the resulting glass shards blew inside and sliced a wall (Fig. 22g). For example, glass from the Rogers' house window blew inside and sliced a wall (Fig. 22g).

Hail at the J. Mitros residence (location H). made large dents in the side of his Pontiac Z-280 automobile (Fig. 22h) and smashed out its south-facing windows. Large hail left circular holes 10 cm in diameter in the outside windows (single-strength, 0.6 cm thick and double-paned) of his house. Even though this is not a direct measurement of large hail, it is apparent from the pictures taken by J. Mitros that very large hail did occur (Fig. 22i). Hail also left numerous holes in the south facing windows of another house about 1.6 km northwest of location H. The tornado moved over the summit of the Laramie Range (>8700 ft or 2652 m MSL) as it approached location I around 1921 UTC. A grove of pine trees (40 to 75 cm in diameter) was downed as documented by J. Myers (Fig. 22j). This region commonly experiences high winds in the cold season, therefore this magnitude of tree damage was noteworthy. Up to 1.75 inch (3.8 to 4.4 cm) diameter hail occurred at the Myers residence.

There was a gap in damage documentation from just northwest of location I to the southeastern outskirts of Laramie (indicated by the question marks in Fig. 21). Either the tornado briefly lifted or the sparse population precluded documentation. The next damage from this tornado was along Interstate 80 where a tractor trailer truck was overturned, resulting in one injury. In Laramie, a gas station was unroofed partially and trees were uprooted. Many structures received minor damage. Hail as large as 1.5 inches (4 cm) in diameter occurred in Laramie. In their official damage assessment, NWS Cheyenne found a path length of ~45 km (including the gap depicted in Fig. 21) with maximum damage of EF2. An approximate tornado path, along with additional damage pictures, can be viewed on this Google Maps page: http://tinyurl.com/22May08-map.

4. Discussion

When forecasting the potential for severe thunderstorms on elevated terrain, one of the important factors to consider is potential instability (i.e., convective instability). However, potential instability magnitude can change significantly across variable elevation. In order to recognize the factors that contribute to significant changes in potential instability, it is best to assess the individual components of θ_e (θ and w). The exclusive consideration of temperature and dewpoint when inspecting high elevation observations will be misleading to a forecaster when assessing thunderstorm potential. Since w values are generally lower at higher elevations, higher θ must exist in order to obtain potential instability. In our case, this is illustrated by examination of station pressure, sea-level pressure, temperature, dewpoint, w, θ, and θ_e at 1800 UTC for selected stations (Table 1). Despite the temperature and dewpoint values being much lower along the Front Range Urban Corridor of Colorado compared to the lower elevations of eastern Kansas, θ_e values were comparable. For example, θ_e was higher at Greeley, CO (345 K) than Coffeyville, KS (341 K – location depicted in Fig. 9) with temperature and dewpoint values being 7 and 10 °F (4 and 5 °C) respectively lower at Greeley. Despite the dewpoint difference between Greeley and Coffeyville, the corresponding w was only 2.5 g kg^{-1} lower. This is because Greeley is 3943 ft (1202 m) higher in elevation. Keep in mind that similar dewpoint values at different elevations have different corresponding w. Given that the θ_e was higher at Greeley, a higher θ at Greeley (98 °F or 310 K, compared to 81 °F or 300 K at Coffeyville) more than compensated for the lower w.

The storm that developed in Colorado moved into Wyoming where "cool" surface temperatures in the mid to upper 40s °F (7–8 °C) existed; however, θ values were high enough to support sufficient SBCAPE. Despite the "cool" surface conditions in Wyoming being unfavorable for convective initiation, the mesocyclone associated with the supercell maintained itself in an environment characterized by negligible SBCIN, adequate SBCAPE and favorable shear. Despite the relatively low temperature and dewpoint values at the higher elevation stations of Wyoming, the θ_e values at these stations were comparable to stations further east at much lower elevations. For example, the temperature and dewpoint were 20 and 12 °F (11 and 7 °C respectively) higher at Concordia, KS (1466 ft or 447 m] – location depicted in Fig. 9) than Harriman, WY (7450 ft or 2271 m); however, θ_e was higher at Harriman (333 K) than at Concordia (330 K). This is due to the θ being 15 °F (8 K) higher at Harriman than at Concordia (90 °F or 305 K versus 75 °F or 297 K), which more than offset the lower w (9.2 g kg^{-1} at Harriman versus 11.4 g kg^{-1} at Concordia). Therefore, when comparing moisture and thermal values at stations with different elevations, one should use w and θ instead of dewpoint and temperature. Soundings also should be evaluated if available. It is important that forecasters do not conclude categorically that "cool" surface temperatures and lower surface dewpoints preclude surface-based severe storms.

In order to compare similar thermal profiles (Miller 1967, Type II) at different elevations, the modified Harriman sounding was compared to a sounding from a significant tornado event that occurred at 0100 UTC 25 January 1964 in Alabama (Fig. 23). The surface temperature and dewpoint on the 0000 UTC Montgomery sounding were increased by 1 °F (0.6 °C) in order for it to be representative of the environment for the tornadic storm (which was only 105 km away). Despite the elevation difference of 7229 ft (2203 m), the surface-based parcels were along nearly the same moist adiabat since the θe values were within 2 K of each other. Both soundings were characterized by relatively low CAPE, low LCL and LFC heights, a deeply moist layer in the lower troposphere, and strong vertical wind shear (0-6 km bulk shear of 70 kt or 36 m s^{-1} at Montgomery). When assessing the ingredients for potential instability, a forecaster may judge the near-surface layer of the Montgomery sounding to be "warm and humid" and the Harriman sounding, erroneously, as too "cold".

5. Conclusions

On 22 May 2008 a supercell storm tracked 300 km from Colorado into Wyoming. This storm moved across elevations from 4700 to 8700 ft (1430 to 2650 m MSL), producing significant damage in differing environments. The storm initiated in Colorado along a wind-shift line near the DIA and moved into a favorable tornadic environment of moderate surface-based CAPE, relatively low LCL and LFC, strong vertical wind shear, and had a relatively long residence time in the unstable air mass. The storm temporarily weakened after crossing into a region of lower θ. The supercell then moved onto higher terrain where "cool" surface temperatures, relatively high θ, sufficient CAPE, no CIN, LCL and LFC near the surface, and extreme vertical shear existed. The storm became tornadic once again where surface temperatures were in the mid- to upper-40's °F (7 to 8 °C) along with dense fog. A significant tornado (officially EF2) and large hail (2 inches [5 cm] or greater in diameter) occurred at elevations between 7450 and 8700 ft (2271 and 2652 m) MSL. A region of locally strong near-surface winds, likely aided by terrain and isallobaric effects, enhanced the low-level shear profile. Although tornadoes have been documented at higher elevations (Fujita 1989; Evans and Johns 1996; Bluestein 2000), this is likely one of the highest-elevation tornado events that produced significant structural damage to residences. This was a geographically rare event that could only occur in a limited number of places.

The authors recommend for forecasters at high elevation locations to: 1) modify soundings with trusted surface observations at the appropriate surface pressure (model modified soundings may have significant errors in surface pressure due to the coarse representation of terrain in the models); 2) Be aware of the individual contributions of w and θ to θ_e, instead of drawing conclusions based solely on surface temperature and dewpoint; 3) assess CAPE and CIN; and 4) pay particular attention to storms that traverse varying elevation.

In order to maintain situational awareness it is important to have knowledge of the synoptic and mesoscale patterns favorable for severe weather on elevated terrain. In this case, the meridional trough and adjacent pattern: 1) provided a favorable synoptic and mesoscale setting for severe weather, 2) contributed greatly to storm motion that affected the Front Range Urban Corridor of Colorado where higher population density exists, and 3) resulted in thunderstorms that traversed widely varying elevations and mesoscale environments. The thunderstorm of interest moved from a Miller (1967) Type I environment to a Miller Type II environment as it moved to higher elevations.

Some reports were not initially known by the NWS, but were shared so that they now appear in Storm Events database. It is particularly important to have thorough storm documentation given the rarity of the event.

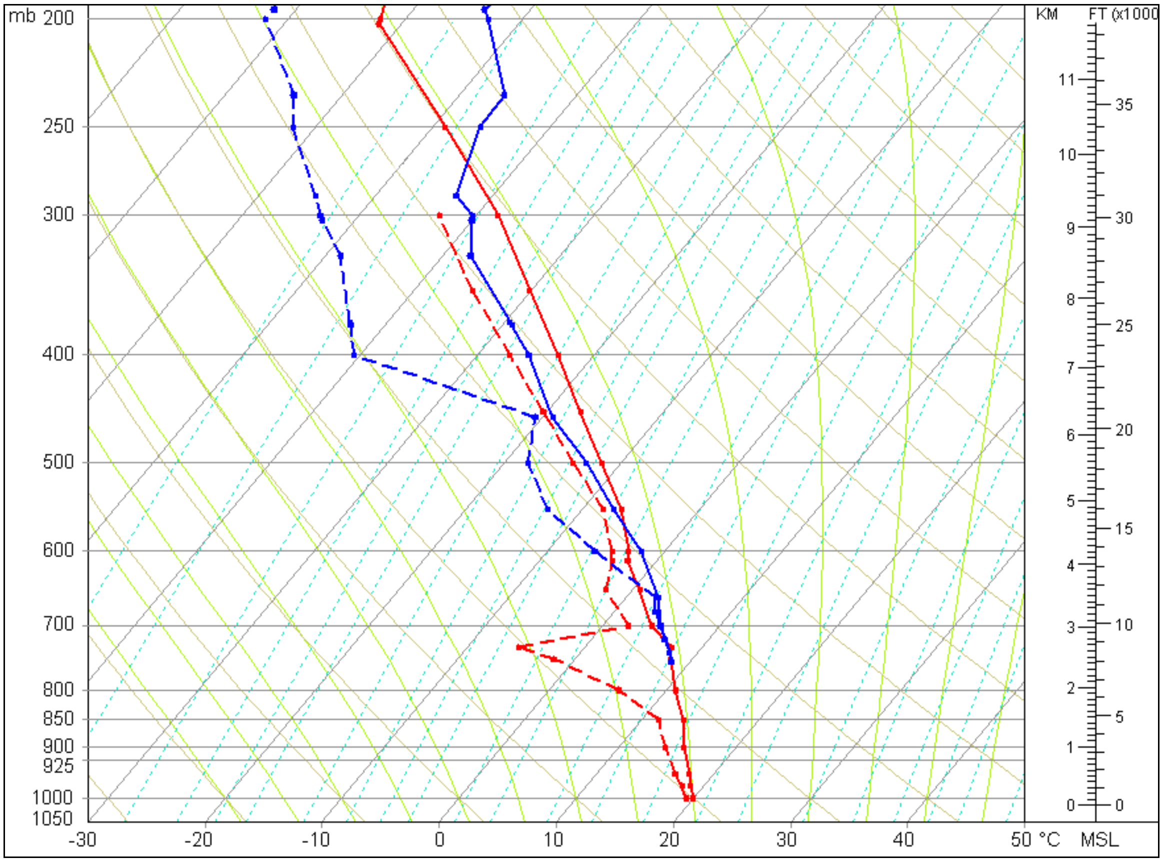

Figure 23. Modified soundings for Montgomery, AL (MXF) 0000 UTC 25 January 1964 (red) and Harriman, WY 1800 UTC 22 May 2008 (blue). Temperature (solid line), dewpoint temperature (dashed line). *Click image to enlarge.*

ACKNOWLEDGMENTS

The authors would like to thank Paul Martin of Intermountain Wind for the wind tower data. Digital Atmosphere (meteorological plotting software developed by Tim Vasquez) was utilized for selected surface analyses. We thank David Imy, Matthew Bunkers, and Timothy Marshall for their beneficial reviews. Supplementary storm documentation was obtained from the following eyewitnesses: Stephen Rogers, Jeff Mitros, Nancy E. Levinger, George Obssuth, John Myers, Gayle Wilson, Paul Hanselmann, Tom Nowak, Francis Magrath, Richard Miller, Glen Smith, Lt. Col. Wylie D. Walno, Claire Hoover, Belinda Scott, Bob Adams and Ted Lewis. Veta Jones provided hourly observations from Virginia Dale, CO. Storm documentation information was also obtained from the NWS Cheyenne official storm damage survey which included Melissa Kreller and John Griffith. Funding was provided by NOAA Grant #NA090AR4320074.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (David A. Imy):

Initial Review:

Recommendation: Accept with minor revision

General Comments: This is a well written manuscript and documents this unusual tornado case, especially in WY, excellently. I recommend it be published with several adjustments, mostly minor. Those comments are below.

Substantive/Major comments

I feel a paragraph needs to be added, at least to the "Discussion" and perhaps even into the "Synoptic/Mesoscale Overview" section, about the storm initiation/maintenance considerations. As you noted on page 8, the deep layer shear was extremely strong (~100 kt). There are many cases where the deep shear felt by the storm, especially over 70-80 kt, is too strong to support more intense updrafts, unless instability is quite strong. The storm that produced the tornadoes in WY originated in northeastern CO, where boundary temperatures were warmer, updrafts were nearly surface based and the air mass was more moist and unstable than in WY. Despite the equivalent potential temperature argument, as far as I can tell, there were no severe storms that originated in WY, probably due to the extreme shear and weaker instability. What was unusual in this case is the flow aloft was from the SSE to NNW, instead of SW to NE. This carried persistent and strongly rotating mesocyclones from northeastern CO into a cooler and more stable air mass (at least relative to the boundary layer conditions in northeastern CO), into southeastern WY. The equivalent potential temperatures consideration probably played more of a role in helping "to maintain" a mesocyclone and consequent severe threat than in severe storm development. At the SPC, rarely do we forecast or observe cases where tornadoes occur with temperatures and dewpoints in the 40s. Obviously, they occurred in this case and a few others, but are very rare. However, if the flow had been from the SSW TO NNE, severe weather and tornadoes likely would not have occurred in WY, even given the equivalent potential temperatures.

We inserted the following in section 2a, 2nd paragraph, after the 6th sentence :

> *"These cases are characterized by storm-motion from lower elevation towards higher elevation. Due to the increasing elevations from south to north, any storm that initiates to the lee of the Front Range in Colorado moving towards the Laramie Range of Wyoming must be moving upslope (Fig. 1). In this specific synoptic pattern, a storm initiating in one type of environment at a lower elevation can maintain itself while moving upslope into a distinctly different environment."*

We put the following into the discussion, paragraph 2, inserted after the second sentence.

> *"However, potential temperature values were high enough so that sufficient SBCAPE values existed. Despite the environment in Wyoming being unfavorable for convective initiation, the mesocyclone associated with the supercell maintained itself due to the combination of negligible SBCIN (surface-based CIN), adequate SBCAPE and favorable shear".*

Also, I wonder if the tornado event was more of the rising elevation intersecting the base of the mesocyclone, instead of the storm actually initiating more tornadoes. Just something to consider.

[EDITOR'S NOTE: To a limited extent, Geerts et al. (2009) discussed this issue in their manuscript, but from the standpoint of the LAR tornado embedded in fog, where the terrain effectively rose into the cloud base as the storm moved along. All evidence so far, whether from their study, yours and NWS survey, is that the LAR event was a true tornadic vortex.]

Otherwise, Great job Jonathan and Dan!

[Minor comments omitted...]

Second review:

Recommendation: Accept

REVIEWER B (Matthew J. Bunkers):

Initial Review:

Reviewer recommendation: Accept with minor revisions

General Comments: This is a well-documented case of an event that is particularly rare, and thus is worthy of publication in the EJSSM. Even though it represents but a single case, the application towards operational forecasting goes well beyond this in terms of the importance of mesoscale analysis, terrain effects, and analyses of θ, θ_e and r (versus T and T_d).

I have listed substantive and technical comments below, and I have also used the MS Word Review Track Changes feature to embed comments and suggested changes in the original manuscript (referred to as the "marked up" copy). I have several minor comments, but no major comments; thus, I recommend the paper be accepted after minor revisions. Moreover, some of my minor technical comments are only indicated in the marked up copy of your paper.

I only ask to see the paper briefly after the revisions are made, but do not need to conduct a thorough second review. Please feel free to contact me for clarification and questions.

Substantive Comments:

1. Supercell lifetime: please define "long-lived supercell" in the first sentence of the Introduction, and/or provide a reference. For example, you could say a "long-lived supercell (4.5 hr; Bunkers et al. 2006)" or you could simply state the duration of the supercell without reference to it being long-lived. I'm not requiring you to reference my paper, but I think writers need to be more specific when referring to supercells as "short lived" or "long lived."

   > Bunkers, M. J., M. R. Hjelmfelt, and P. L. Smith, 2006: An observational examination of long-lived supercells. Part I: Characteristics, evolution, and demise. *Wea. Forecasting,* **21,** 673–688.

   Incidentally, I reviewed the KCYS, KFTG, and KRIW radar data thoroughly, and found that the supercell (i.e., deep, persistent mesocyclone) was initially present around 1700 UTC near DIA, and reached its demise around 2130 UTC about 30 miles south of Casper, Wyoming. As you noted, there was a relative weakness in the supercell between ~1820–1850 UTC, with its weakest point at 1835 UTC, roughly when it appeared to cycle/occlude. Nevertheless, I believe a sufficient circulation was maintained during this time period to state that this was a single, long-lived supercell—as opposed to two separate supercells. The supercell also changed/evolved noticeably after 1835 UTC when it began ascending the mountains near the Colorado–Wyoming border. Per the vorticity equation, I wonder if there was a contribution from low-level convergence and/or tilting during this ascent, because the circulation really tightened up during this time, especially closer to the top. Toward the end of the supercell's lifetime it was rather small and low-topped, but still showed a decent circulation given its size and distance from the nearest radars. Overall, it might be worth placing a bit more emphasis than you do on situational awareness of storms with respect to topography (e.g., viewing radar data on a topographic background).

Revised the first 3 sentences to reflect this change:

> *On 22 May 2008, a supercell tracked from Colorado into Wyoming over 4.5 hour period. The elevation varied from between 4700 to 8700 feet above sea level along the 140 mile path. This long-lived supercell (Bunkers 2006)…*

[EDITOR'S NOTE: This citation will be corrected to reflect the proper "et al." wording.]

2. Figures: This is a relatively major comment in that several of the figures have font sizes that are difficult to read (i.e., too small) in printed form. I know a person can view the online figures and see things more clearly, but I still believe that you need to improve the figure display for those who read the PDF. My suggestion is to printout a hardcopy of your paper, and if you cannot decipher the text or symbols in the figures, then either (a) make the text or symbols larger or (b) remove those items from the figure. For example, in Fig. 1, I can barely make out the town names and tornado tracks and times, and the county lines are almost invisible. And in Fig. 2, the surface plots and contour labels are too small. Other figures especially of concern include ones with upper-air and surface observations, as well as Fig. 20.

   Second, it would be quite helpful for the reader if you have a single fiducial figure that contains all of the points you reference. I found it confusing jumping around from one figure to the next just to find a reference point, which seemed to be scattered about the paper. Making this more difficult is the small font size (e.g., Virginia Dale in Fig. 1; Hudson in Fig. 8—I was looking for this one for a while; Coffeyville, Concordia, and Emporia in Fig. 9, etc.).

   We believe that making 6 of the figures larger (i.e., full page) will take care of the small font issue. We are unable to place every geographic reference on the same image due to the wide spacing between locations (i.e., Virginia Dale, CO to Emporia, KS are far apart) while still showing these locations, particularly in the area of interest where the relationship between the site and the terrain in its vicinity must be shown at the highest resolution possible. This is also true of radar data that must be shown at a high resolution, along with the sites.

   Last, in figures with animations (2, 5, and 11), it would be helpful to include the time of the static image in the caption (e.g., 0000 UTC for Fig. 2).

   Done.

3. Sections 1 & 2: You need a better transition from section 1 to section 2. I felt left hanging at the end of the Introduction, with no real feel for the road that lay ahead. I'm not a fan of spelling out each section in detail like many authors do (e.g., section 2 talks about this; section 3 will discuss this; the results will be presented in section 4, etc.). Nevertheless, the last paragraph of the Introduction just doesn't tie in well with the beginning of section 2.

   We inserted this paragraph at the end of section 1:

   > *"This paper will address the synoptic and mesoscale environments for this event, including an examination of some supplementary observational data. Other cases that occurred in this region are shown for comparison purposes. The evolution of the pre-storm mesoscale environments is provided, including detailed analyses of the air masses and boundaries. The evolving environment associated with the supercell is also discussed. The critical importance of analyzing potential temperature when assessing severe weather in high elevation environments is stressed, including comparisons with lower elevation environments. Finally, a detailed account of storm damage in Wyoming is provided."*

4. Storm-scale inflow: In the [former] second paragraph on p. 11, I'm not sure how the sentence beginning with "Again, this supports…" follows from the previous one. If you rotate the coordinate

system 90 degrees, then the strong easterly flow would be strong southerly flow, and the storm motion would be toward the east—with a typical hodograph. This is a pretty classic configuration, and does not suggest the high winds were not due to storm-scale inflow alone, nor does it suggest the opposite. Please revise.

Removed the majority of the paragraph with this sentence, except for the first 2 sentences, moved them up to the previous paragraph so that it now reads as follows:

> *Wind tower 1, located along the track of the storm northwest of Harriman, WY, measured average winds of 28 knots at 191 ft AGL over the six 10-minute periods between 1800 UTC and 1900 UTC (Fig. 20). The average peak wind gust was 41 knots in this same time frame. These data support the mesonet observations in the region showing the locally stronger winds and indicate that the stronger winds started more than an hour before the passage of the storm. Winds increased substantially as the tornado approached between 4 and 13 miles from the tower in the 10-minute period from 1850 to 1900 UTC. The average wind direction at 187 ft was 70° at 33 kts with a peak wind gust at 191 ft of 56 kts.*

[EDITOR'S NOTE: Metric equivalents to English units will be required as well.]

Then later we inserted this sentence:

> *A distinct maximum possibly augmented by storm-scale inflow was noted between 1850 and 1900 UTC. The motivation here is to separate the maximum observed between 1850-1900 UTC as most likely the time that the storm-scale inflow was influencing the tower 1 data. The period 1800-1850 UTC was weaker than this period, but still strong, as was most likely caused by the hypothesized locally stronger winds due to terrain effects.*

5. Wyoming storm documentation: I think section 3 could be shortened considerably, and/or a substantial portion of it moved to an appendix. Although the information is very interesting, overall I think it disrupts the flow of the paper; I kind of got bogged down in this section. You could succinctly summarize the damages without going into all of the nitty-gritty details, and then refer the reader to an appendix for additional information.

   After revisions suggested by other reviewers it has been shortened some, however we feel this is a critical part of our paper which is summarized by the last sentence in the paper "It is particularly important to have thorough storm documentation given the rarity of the event."

   There is considerably more storm documentation online in the link we provided at the end of section 3:

   http://tinyurl.com/22May08-map

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revision.

General Comments: You have done a great job making revisions, and after reviewing your paper a second time I am really impressed with the level of detail in your analyses and storm report documentation. There are some minor items that need to be addressed to clean up parts of the paper, but overall it is just about ready for publication. Most importantly to me is to increase the dwell time for the first and last images of all animations (as discussed further below). I do not need to review the paper again.

[Minor comments omitted...]

REVIEWER C (Timothy P. Marshall):

Initial Review:

Recommendation: Accept with minor revision.

General Comments: Scientific objectives of this paper have been met and there is contribution to the science here. The paper is acceptable with major revisions.

Further review of the manuscript by the reviewer is needed. See the attached document [minor comments embedded throughout manuscript].

[Minor comments omitted...]

Second review:

Recommendation: Accept.