Wisconsin Tornado Outbreak of July 18, 1996: Formation of Tornadic Supercells

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Introduction

This particular day is etched into the minds of many as the day an F5 tornado ripped through the village of Oakfield, Wisconsin, in Fond du Lac County. The tornado touched down around 00:05 UTC, July 19, 1996, four miles WNW of Oakfield as an F1 and quickly picked up steam, reaching F5 status just east of the village. Wind speeds around the tornado's core were estimated to reach 265 miles per hour. About a half-hour after its initial touchdown, the tornado's funnel weakened and dissolved one mile NW of Eden. A detailed map of the tornado's track can be found in Fig. 1. "Miraculously, no one was killed, but there were 12 injuries. Some of the injured were hospitalized. Along the tornadoes path, 60 homes and 6 businesses were destroyed. An additional 130 homes and businesses were damaged. In Oakfield, a commercial canning company was devastated. Two churches in the village were also destroyed, as well as numerous vehicles. In the rural areas along the tornadoes path, 18 barns and many sheds were destroyed or damaged, and about 500 acres of crops were wiped out. Total damage amounts were $39.5 million in public/private property, and $900,000 in crop losses" (NOAA).

Examining Fig. 1 a bit more closely, one can observe multiple tornado tracks dispersed throughout the counties of Calumet, Fond du Lac, Sheboygan, and Ozaukee. The Oakfield

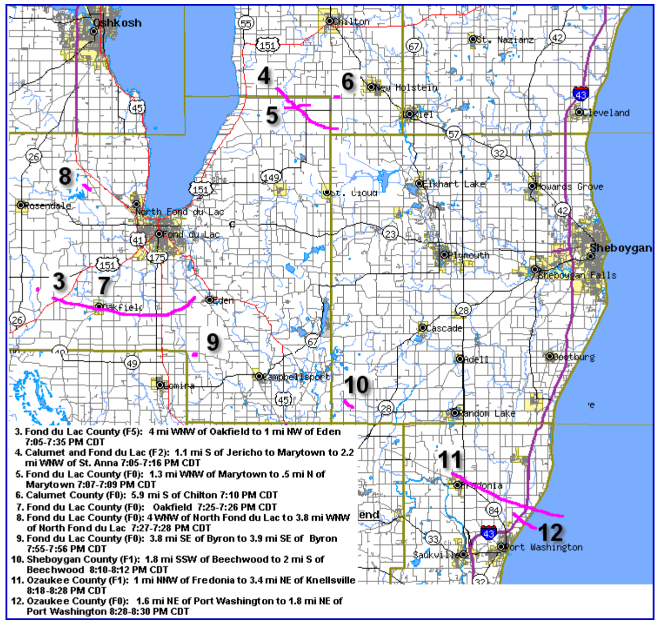


Fig. 1: 7/18/1996 tornado tracks over East-central Wisconsin; explanation of each track can be found in lower left corner (NOAA)

tornado was accompanied by eleven other, weaker, tornadoes. The first tornado, categorized as an F1, traversed through Lincoln County at 22:20 UTC on July 18, 1996. The next tornado, another F1, moved through Green Lake County around 23:15 UTC. The Oakfield tornado is listed as number three, but occurred adjacent to number four, which touched down around the same time. Number four touched down in southern Calumet County and moved through Marytown in Fond du Lac County, where it reached strengths corresponding to an F2 (NOAA). Although the strength of the Marytown tornado did not rival that of Oakfield, it did claim the life of one individual and caused extensive damage to multiple houses and property. The remainder of

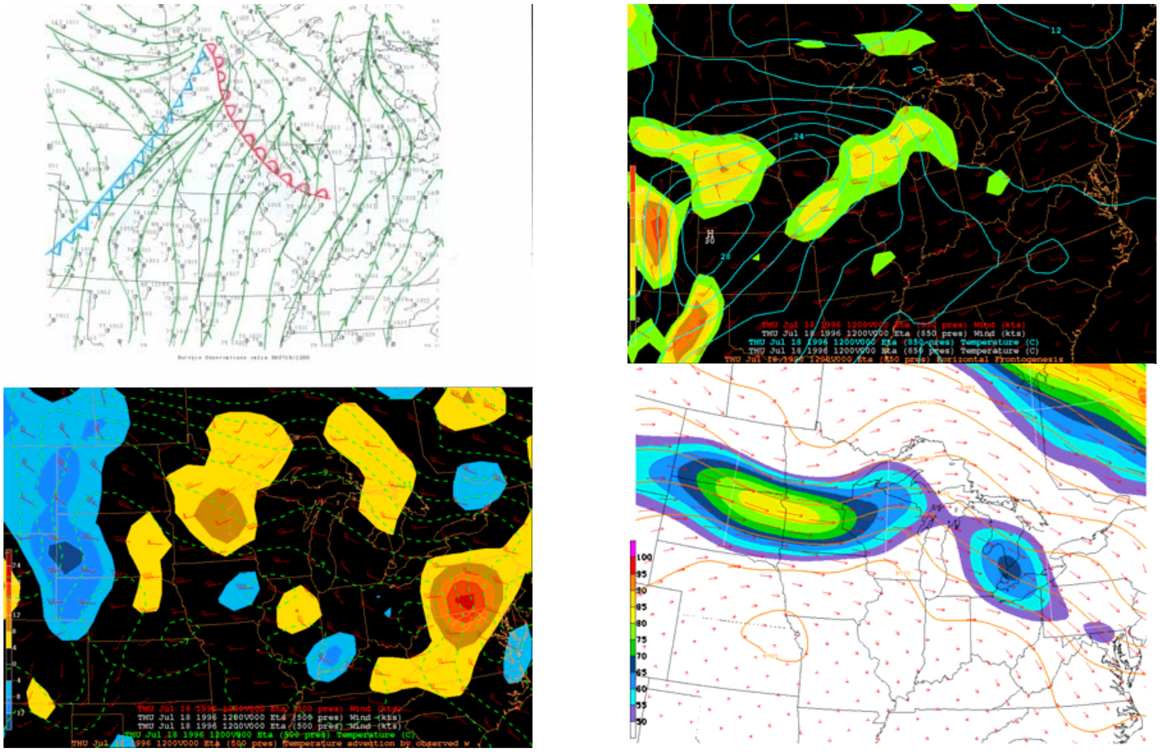


Fig. 2a: (top left) 7/18/1996 at 12 UTC; NAM surface observations; green lines are streamlines; low pressure center is denoted by green “L”; cold (warm) front indicated in blue (red)
Fig. 2b: (top right) 7/18/1996 at 12 UTC; NAM 850 hPa level; winds (knts) are red barbs; isotherms (°C) are solid blue contours; frontogenesis is color fill
Fig. 2c: (bottom left) 7/18/1996 at 12 UTC; NAM 500 hPa level; winds (knts) are red barbs; isotherms (°C) are dashed green contours; temperature advection is color fill
Fig. 2d: (bottom right) 7/18/1996 at 12 UTC; NAM 300 hPa level; winds (knts) are red arrows; heights (m) are solid orange contours; isotaches (knts) are color fill

the tornadoes illustrated in Fig. 1 did not exceed F1 standing and moved through relatively low populated areas. Even so, a combined estimate of $40.7 million in property damage and $1.7 million in crop damage was a result of all 12 confirmed tornadoes (NOAA).

Due to the intensity of the Oakfield and Marytown tornadoes, the majority of this paper will focus on the two supercells corresponding to these two tornadoes. First synoptic dynamics will be presented, setting the stage for the atmospheric setup needed to produce tornadic supercells. Next, mesoscale processes and mechanisms contributing to the event will be highlighted. Both examinations will have an eye toward the forcings needed to break a strong inversion capping high levels of low-level moisture. An initial hypothesis was that a surface baroclinic zone was the primary trigger to puncture the cap and release high amounts of surface moisture convectively. As will be shown, however, this zone was only one piece to the convective puzzle. It was a combination of factors that concentrated their influence over North-central and East-central Wisconsin.

Data

The two times of interest are 12 UTC on July 18, 1996 and 00 UTC on July 19, 1996. For both times, the North American Model (NAM) data is utilized, through the GARP and GEMPAK programs, to produce analysis images at various pressure levels. Certain features on the surface observation images are drawn in by hand. For the mesoscale portion of the paper, a skew-t/log-P diagram from the University of Wyoming website, along with a hodograph, will be analyzed. Two cross-sections, both from Chanhassen, MN to White Lake, MI, will hold valuable data about the vertical structure of the atmosphere across the cold front at 00 UTC on July 19, 1996. One cross-section is based off NAM data once again, while the other is a hand drawn interpretation. Also, radar base reflectivity and velocity from Green Bay aid in visualization of the tornadic supercells. Lastly, a hand drawn conceptual model will enhance understanding of a supercell's structure and a tornado's development within the confines of the supercell.

Synoptic Overview

July 18, 1996 at 12 UTC

As mentioned previously, it is thought that the majority of the dynamic forcing was a result of the instability created by a nearby baroclinic zone. This feature was a result of strong cyclonic rotation around a surface low pressure center. Featured in Fig. 2a are surface observations for July 18, 1996 at 12 UTC to show the morning's surface features leading to the tornadic event. A minimum in mean sea level pressure existed over the heart of Minnesota at that time, marked by an "L" in the image. In order to track the airflow around this center, streamlines, based on the observed winds at the surface, are added in. A dominant trend in the wind pattern appeared over the majority of the Midwest featured in Fig. 2a. This trend was a prevailing southerly flow from the Gulf of Mexico into the Upper Midwest. As a result, warm temperatures and moisture-laden air from the Gulf could make its way deep into Wisconsin, and surrounding regions. As this flow worked its way northward, it also encountered a portion of the United States' corn belt. In July, a variety of crops reach maturity in the growing season. Due to evapotranspiration, the air maintained its high moisture content for a substantial distance. Already at this early morning hour, temperatures in the upper 70s and lower 80s (°F) could be found over the majority of the region. These very warm morning temperatures reflect the high atmospheric moisture content near the surface. Nighttime radiative cooling couldn't cool the surface, where high levels of moisture trap much of the heat. Dewpoints in the lower 70s also dominate the image and help to quantify just how moist the air was at that time.

Based on shifts in temperature, dewpoint, and wind direction, one can estimate the location of surface warm and cold fronts. In Fig. 2a warm and cold fronts are drawn in with careful consideration of the surface observations. After crossing the warm front, streamlines veered to the northwest, toward the low pressure center. A more drastic shift can be observed after streamlines encountered and cross the cold front. Northwesterly winds suddenly switch to southwesterly. Not only did these cross-front winds switch directions virulently, but they also converged with more southerly flow just ahead of the cold front. The confluence line separates maximum dewpoint temperatures from minimum in Fig. 2a. In other words, a weak dryline existed just ahead of the cold front at 12

UTC on July 18, 1996. It will be shown that the cold front absorbed the dryline and its confluent flow following 12 UTC.

Moving up in the atmosphere, the baroclinic zone strengthened at its upper limit of 850 hPa. Moderate frontogenesis at this level can be observed in Fig. 2b. The baroclinic zone, which displayed frontogenetic behavior, extended from the border of South Dakota and Nebraska and curved around to Wisconsin. At the same time, 850 hPa winds crossed the baroclinic zone over Wisconsin. Midway through the baroclinic zone, a diffluence zone emerged. As a result, isotherms packed closer together in response to directional wind changes upstream of the advancing baroclinic zone. In other words, winds slowed ahead of the front, while winds advecting it forward maintained their heading and speed. Therefore, the magnitude of the temperature gradient increased in response to tightening of the isotherms. Strengthening temperature gradients imply frontogenesis, and frontogenesis implies a thermally direct circulation. A thermally direct circulation involves rising warm air and descending colder air. Given that the frontogenesis in Fig. 2b corresponded with advancing warm air, the warm front was the cause of strengthening temperature gradients. As the warm air encountered cooler air to its north, it rose over the cooler air, forcing it down. Frontogenesis acted to enhance this process. As long as the frontogenesis persisted, one could expect strong ascent in the warm sector of the surface low pressure system.

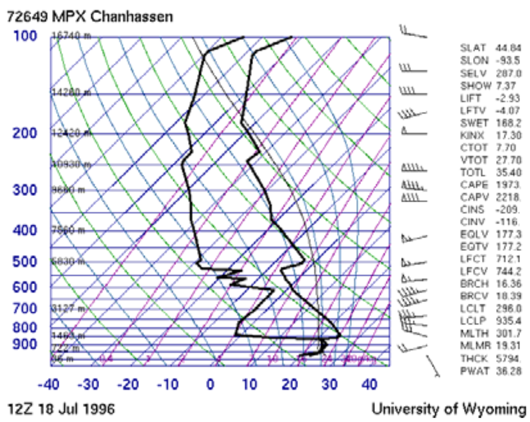


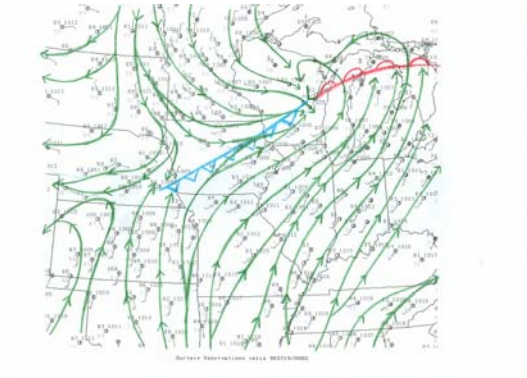
Fig. 3: 7/18/1996 at 12 UTC Skew-T/log-P diagram featuring: temperature (°C), dewpoint (°C), wind barbs (knots), and various indices (University of Wyoming)

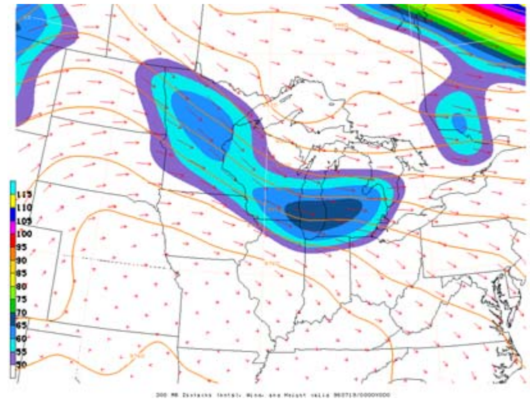
With strong fronts displaying frontogenetic behavior, why did no strong storms develop during the morning hours of July 18, 1996? To help answer this question is a skew-T/log-P image from Chanhassen, MN (Fig. 3). The first feature that stands out is the very moist boundary layer, extending from the surface to about 850 hPa. Right above this layer, however, the atmosphere severely dries out and warms. This is characteristic of the base of an elevated mixed layer (EML). This elevated mixed layer, more than likely, survived from being advected off the higher terrain to the west. Taking note of the wind barbs in the image, winds at the 850 hPa level and above become strong and uniformly westerly, which validates this reasoning. The inversion of the EML can act to cap the moisture at the surface and increase the instability between the overlaid contrasting air masses. Some convective inhibition (CIN) is needed trap lower-level moisture until that moment when the cap is punctured, allowing high amounts of moisture and energy to enter a well-mixed, unstable environment. However, too much CIN can inhibit convection, as the inversion is too strong to break. CIN values greater than 100 are too large for the formation of convection. In Fig. 3, a CIN value of 209 J/kg is observed along with a convective available potential energy (CAPE) value of 1973 J/kg. Both values are not favorable for the breaking of the cap.

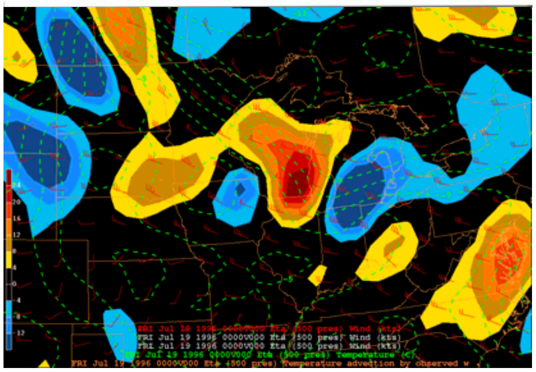
The large CIN value observed over Minnesota at 12 UTC on July 18 was a combination of the EML and another inversion starting at about 550 hPa in Fig. 3. Two factors aided in the formation of this inversion. The first contribution was differential temperature advection in the vertical. Fig. 2c, illustrating 500 hPa winds, temperatures, and temperature advection, helps to explain this differential temperature advection in the vertical. 500 hPa winds, which moved generally eastward, were much stronger than those in the lower troposphere. Also, these winds traversed in a slantwise fashion across 500 hPa isotherms, from warm to cold. As a result, weak-to-moderated positive temperature advection in the horizontal occurred directly over the Chanhassen, MN region. Observations of positive temperature advection at lower levels did not match the strength found at 500 hPa, because these warm advecting winds did not reach the magnitude of those above. Interestingly, the winds in this figure display diffluence across the bull's-eye of positive temperature advection. This diffluence could have been a potential triggering mechanism, if the second factor would not have enhanced the inversion. This second factor was the 300 hPa jet streak (Fig. 2d). The jet streak's core was just entering Eastern Minnesota during the morning hours of July 18. Jet cores aligned with the lower-tropospheric baroclinic zone display the usual Sawyer-Eliassen circulation. However, polar jet streaks tend to advect colder temperatures toward warmer. As a result, the Sawyer-Eliassen circulation will be skewed, concentrating downward vertical motion under the length of the jet's core and upward vertical motion on either side of the jet. This was the case at 12 UTC, with a cyclonically oriented jet crossing an 850 hPa temperature ridge (Fig. 2b) from the ridge's cooler side to it's warmer. Subsidence under the jet's core, therefore, aided in adiabatic compression and warming, which added to the 550 hPa inversion. Even if convection broke through the first inversion, it would find it difficult to break the second, providing an explanation for the high CIN and low CAPE values of that time. One last ingredient missing for why there was no storm formation at 12 UTC was the effect of daytime heating. Insolation, at that time, did not have enough time to interact with Earth's surface to cause heating and its resulting turbulent mixing. It's this mixing from below that can aid in weakening the inversion.

July 19, 1996 at 00 UTC

In contrast to the morning atmospheric setup, the afternoon synoptic dynamics evolved and reoriented in such a fashion as to promote and concentrate convection over East-central Wisconsin. First the low pressure center moved southeastward and situated itself near Green Bay, WI at 00 UTC, as can be seen in a figure of surface observation (Fig. 4a). Along with the movement of the surface low pressure center, the corresponding baroclinic zone adjusted its orientation, with the warm front running from Green Bay, WI northeastward and the cold front running from Green Bay, WI southwestward. The nearness of the low pressure center and baroclinic zone provided forcing for ascent needed to produce tornadic







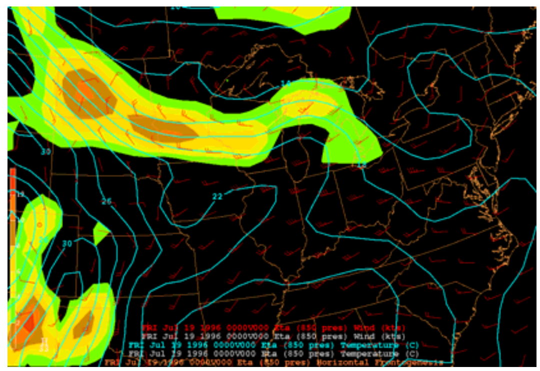


Fig. 4a: (top left) 7/19/1996 at 00 UTC; NAM surface observations; green lines are streamlines; low pressure center is denoted by green "L"; cold (warm) front indicated in blue (red)

Fig. 4b: (top right) 7/19/1996 at 00 UTC; NAM 850 hPa level; winds (knts) are red barbs; isotherms (°C) are solid blue contours; frontogenesis is color fill

Fig. 4c: (bottom left) 7/19/1996 at 00 UTC; NAM 500 hPa level; winds (knts) are red barbs; isotherms (°C) are dashed green contours; temperature advection is color fill

Fig. 4d: (bottom right) 7/19/1996 at 00 UTC; NAM 300 hPa level; winds (knts) are red arrows; heights (m) are solid orange contours; isotaches (knts) are color fill

supercells, but this and the following sections will show that it did not act independently.

Consistent with the previous section, are the persistent southerly winds located in the warm sector between the cold and warm fronts. With the moisture influx from the Gulf of Mexico, evapotraspiration from crops, and daytime heating, air temperatures across much of the Midwest easily warmed into the upper 80s (°F) and lower 90s. With these temperatures at hand, turbulent mixing could begin to erode any lower-level inversion produced by an EML. Behind the cold front, a bit cooler and drier Canadian air pressure center. These streamlines converged with southerly winds directly over the cold front. Confluence associated with the cold front was a result of the absorption of the 12 UTC dryline into the cold front. As a consequence of this confluence, the magnitude of the temperature gradient across the cold front likely increased, resulting in frontogenesis. As cooler, drier, Canadian air rushed southward, due to the low's circulation, warm, muggy air behind the warm front was forced to ascend. Frontogenesis, then, would be expected to enhance this thermally direct circulation and increase ascent in the warm sector, just ahead of the cold front. Lastly, the nearness of the low pressure center to the region of study adds convergence to the equation of ascent. According to Fig. 4a, many streamlines circulated the low only to converge right over East-central Wisconsin. With convergence, mass accumulates and has to go somewhere. Most of this mass will be forced upward, adding to ascent produced by the frontogenetic cold front.

Frontogenesis at the 850 hPa level mirrors that expected at the surface (Fig. 4b). Since the morning hours, this frontogenesis has slightly increased over Wisconsin. In contrast to the previous time step, it is the cold front that is affecting the region of study at 00 UTC on July 19. Also, rather than effects of diffluence, confluence along the cold front was the major contributor to frontogenesis. In Fig. 4b, this confluence zone can be found, formed across an 850 hPa baroclinic zone that spans from Minnesota to Wisconsin and Michigan. One may notice how the 850 hPa cold front lags behind the surface front. This is a common phenomenon, as most fronts tilt upstream with height. After examination of the 850 hPa level, one can be convinced of the presence of a strengthening baroclinic zone, which helped to induce ascent in the warm sector located over Eastern Wisconsin at 00 UTC.

The 500 hPa level paints another picture as well. At this level, winds, temperature, and temperature advection are plotted again, but at 00 UTC on July 19 (Fig. 4c). The region of strongest positive temperature advection moved eastward to situate itself directly over Eastern Wisconsin. Also, it has increased in magnitude due to the tightening of the 500 hPa temperature gradient. This is slightly counterintuitive, as the region of strongest positive temperature advection in the last time step was associated with a heavy inversion. However, with increased ascent, as a result of the aforementioned baroclinic, convergent, and turbulent forcings, breaking through any inversion will not be as difficult as it was in the morning. Also, a few other forcings, which will be mentioned in the ensuing sections, added even more uplift to the atmosphere over Fond du Lac, WI.

Ultimately, a balance between CIN and CAPE creates a desirable environment for tornadic supercells. There must be some CIN, as mentioned in an earlier section. For this reason, the 500 hPa positive temperature advection bull's-eye actually held in low-level moisture until the timing was right and ascent could concentrate and channel convection. A skew-T/log-P diagram from Green Bay, WI at 00 UTC

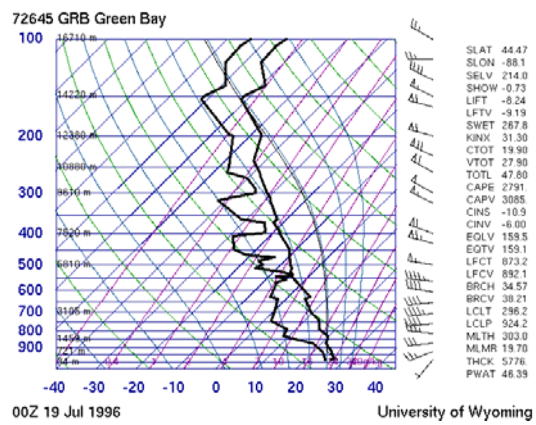


Fig. 5: 7/19/1996 at 00 UTC Skew-T/log-P diagram featuring: temperature (°C), dewpoint (°C), wind barbs (knots), and various indices (University of Wyoming)

demonstrates this point (Fig. 5). This skew-T takes on quite different features from the Chanhassen, MN skew-T. First, any inversion in the temperature profile is minimal, which indicates ascent over Green Bay has broken through any strong inversion(s). Secondly, the dewpoint temperature profile is much more moist than the previous time step. Lastly, multiple mixed layers can be identified in Fig. 5, providing the instability to enhance any ascent. Because of this new structure, CIN is only 10.9 J/kg and CAPE is 2791 J/kg. This is an improvement since the morning hours.

As was previously found, the orientation of the jet streak aided in descent and the formation of a strong mid-level cap. At 00 UTC on the 19th the jet's core moved southeast over Lake Michigan and Michigan (Fig. 4d). It weakened drastically as well. As a result, subsidence under this cold air advecting jet was suppressed substantially. Therefore, any subsistence inversion will be rather weak. Ascent on either side of the jet core, resulting from the skewed Sawyer-Eliassen circulation, added magnitude to the ascent over East-central Wisconsin. The convection in this region plugged into the jet's circulation, becoming the ascending branch. Then the jet took the mass, diverging at upper levels above the convection, to its descending branch, away from the convection itself. As a result subsistence around the storms was minimized allowing the surrounding environment to stay cooler than the storms.

Mesoscale Analysis for July 19, 1996 at 00 UTC

Not only was the upper-level jet beneficial to the convection, a low-level jet was another feature that added to the concentration of ascent over Eastern Wisconsin. The low-level jet core located over Southern Lake Michigan accelerated air entering from the west (Fig. 6). The air entering was also converging at the same time, as can be observed over Southern Wisconsin and Northern Illinois. Confluence and acceleration into the jet core resulted in

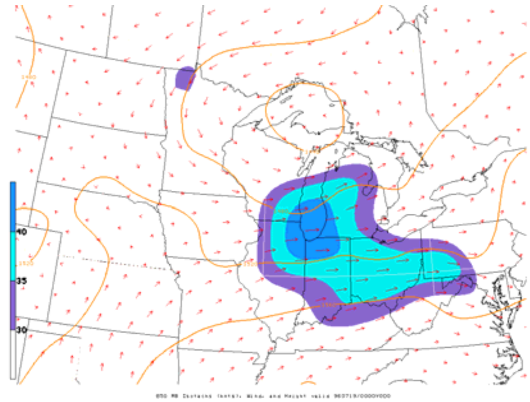


Fig. 6: 7/19/1996 at 00 UTC; NAM 850 hPa level; winds (knts) are red arrows; heights (m) are solid orange contours; isotaches (knts) are color fill

ageostrophic convergence over the region of convection. At 850 hPa, convergence results in ascent into the upper-troposphere. Also, the combination of the upper and lower-level jets created an environment conducive of vertical and horizontal speed shear. Vertical speed shear under each jet core results in vorticity features in the horizontal that can be drawn into the updraft of a supercell. Once there, this rotation can cut off entrainment of dry environmental air, which deteriorates the storms strength. Horizontal speed shear, resulting from the decrease of wind speeds out the jet core toward the northwest, produces vertical vorticity features. This rotation adds to directional helicity needed to add to a storm's rotation and advection of precipitation fallout aloft away from the storm. A hodograph can be used to determine if helicity is sufficient to aid in the formation of a supercell. One such hodograph for Green Bay, WI is shown in Fig. 7. It shows backing of wind with height, as well as a general trend toward speed increases with height. According to the hodograph, helicity was just right over Green Bay and surrounding regions for the formation of tornadic supercells.

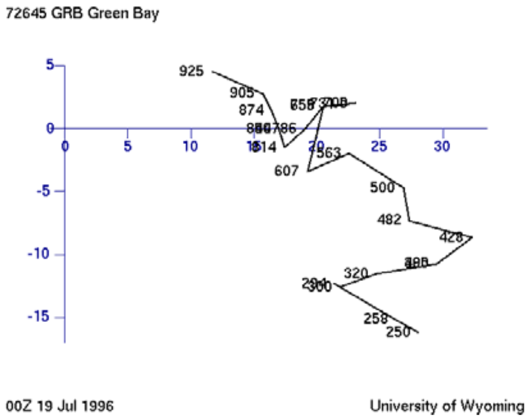


Fig. 7: 7/19/1996 at 00 UTC hodograph (University of Wyoming)

Through the combined efforts of the frontogentic cold front, surface convergence, daytime turbulence, confluence and the low-level jet at 850 hPa, and the upper-level jet at 300 hPa, the strong warm air advection at 500 hPa and subsequent inversion could be overcome over East-central Wisconsin. Two cross-sections, taken from Chanhassen, MN (MPX) to White Lake, MI (DTX), cut across the surface front located in Wisconsin. To verify the existence of the diagnosed ascent, omega

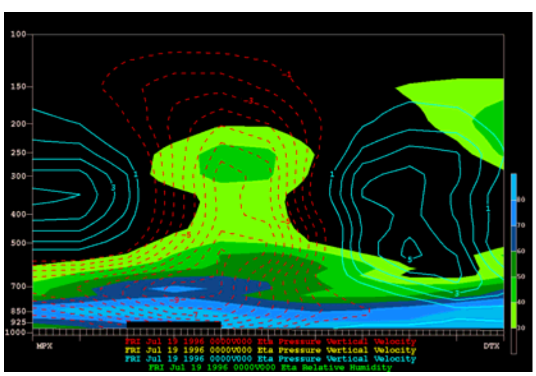


Fig. 8: 7/19/1996 at 00 UTC; NAM cross-section from Chanhassen, MN (MPX) to White Lake, MI (DTX); negative (positive) pressure vertical velocity (µbar/s) are red dashed (solid blue) contours; relative humidity (%) is color fill

is plotted in Fig. 8. Centered in the middle of this cross-section is a strong region of ascent, with a maximum value of –9 µbar/s. Ascent is estimated to extend as high as 150 hPa, indicative of possible overshooting tops. Also, relative humidity, plotted in the same image, displays values greater than 80% concentrated at the surface. This is proof for the existence of a cap trapping moisture below. The highest humidity values remain below 500 hPa, which is the source of the inversion, except where ascent has punctured the inversion. Here, moisture can escape upwards, accounting for the bubble of higher humidity centered on the ascent pictured in the cross-section. Lastly, two descending centers of vertical motion are situated on either side of the strong ascent. These are a result of mass continuity and the jet circulation taking the ascending mass away from the region of convection.

The other cross-section is hand drawn and shows potential temperature and equivalent potential temperature (Fig. 9). Potential temperature dips down near the center of the image, indicative of a cold front. This is expected, as the cross-section runs

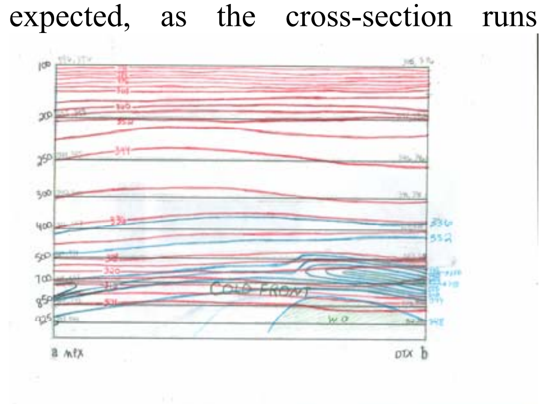


Fig. 9: 7/19/1996 at 00 UTC; NAM cross-section from Chanhassen, MN (MPX) to White Lake, MI (DTX); potential temperatures (K) are solid red contours; equivalent potential temperatures (K) are solid blue contours contoured only to 300 hPa; cold front and warm dome (WD) are labeled

across a cold front. Also, potential temperature isotherms aloft slightly bulge upwards in response to increased mass flux upward. This region corresponds well with the region of ascent in the previous cross-section, as does the dipping potential temperature isotherms with the descending branches on either side. Near the surface,

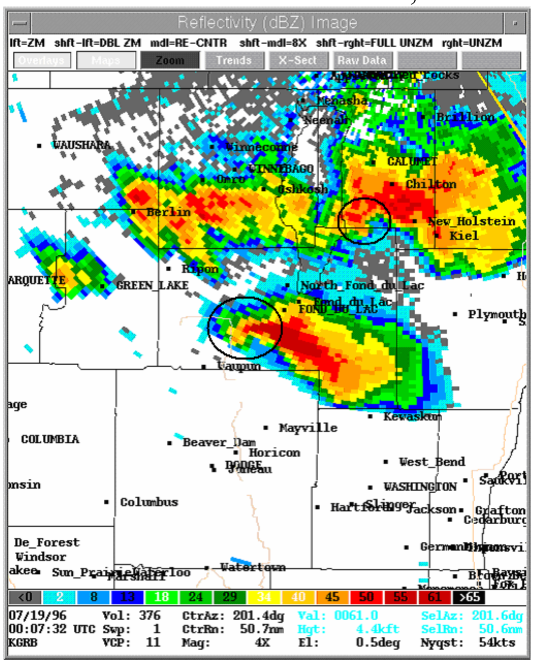


Fig. 10: 7/19/1996 at 00:07 UTC; .5° elevation angle radar reflectivity from Green Bay, WI; large circle corresponds to Oakfield tornado; small circle corresponds to Marytown tornado (CIMSS and UW-Madison AOS Scientists)

equivalent potential temperature displays a warm dome just in front of the cold front, which is consistent with warm temperatures and high moisture ahead of the cold front. As the cold front advances, it will force this warm, moist air aloft, which is represented in Fig. 9 as an elevated warm bubble. Not only will this bubble be forced upwards, it will ride up the slope of the cold front in a slantwise fashion.

As was shown is the previous sections, East-central Wisconsin became a center of convective action in the midst of unique atmospheric characteristics in the late afternoon of July 18, 1996. Radar imagery captured the two tornadic cell that tore through Oakfield and Marytown (Fig. 10). Both tornadoes are reported to have touched down at about 00:05 UTC on the 19th. The radar image is taken only two minutes after their touchdown. Both cells are well formed and display reflectivity values around 55

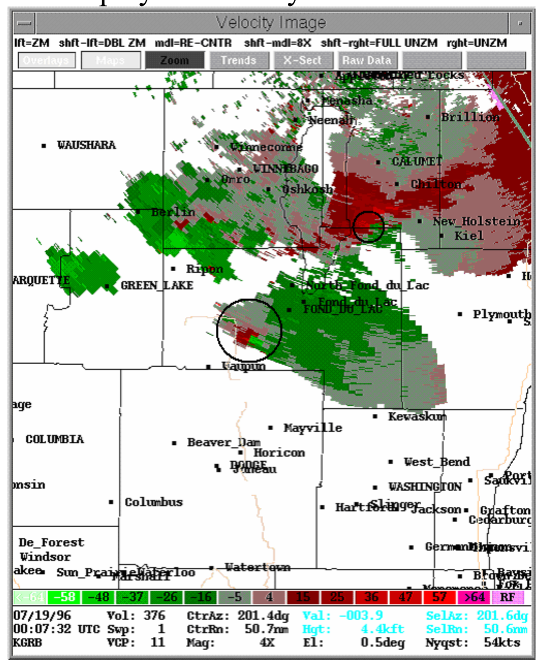


Fig. 11: 7/19/1996 at 00:07 UTC; .5° elevation angle radar velocity from Green Bay, WI; large circle corresponds to Oakfield tornado; small circle corresponds to Marytown tornado (CIMSS and UW-Madison AOS Scientists)

dBz. This is indicative of large rain droplets and even hail. Both also exhibit classic hook echoes in the imagery. A large circle highlights the Oakfield hook echo, while a small circle highlights the Marytown hook echo. Also, rain falling from the anvil is picked up in the image. The anvil extends from the source of strong convection to the southeast. According to the hodograph examined earlier (Fig. 7), upper-level winds are also directed toward the southeast. This northwesterly wind regime begins around the 300 hPa level. The anvil, therefore, must be at or above this level, which means cloud tops extend high into the atmosphere.

As stated earlier, rotation in a supercell forms from horizontal, three-dimensional shear that gets tilted in the vertical by the supercell's updraft. The hook echoes highlighted in radar reflectivity represent the formation of mesocyclones. Therefore, both storms exhibit rotation, which can be observed in radar velocity (Fig. 11). Circles in this particular image highlight both storms once again. Strong gate-to-gate shear is what one looks for when trying to identify rotation. For example, the Oakfield mesocyclone displays very strong shear, with red and green pixels situated in close proximity to each other. The Marytown mesocylone follows suite, but the pixels are not as brightly colored, indicating that the circulation speeds are not as great as over Oakfield.

While radar imagery is important for the diagnosis of severe, rotating storms, it does not yet have the resolution to pick up individual tornadoes forming within the confines of the mesocyclone. To get this resolution, one would have to observe imagery from a mobile Doppler radar station, which does have the resolution necessary to get fine detail. However, one can use a conceptual model to visualize how the tornadoes formed (Fig. 12). In the conceptual model image, a well-developed supercell, with a mesocyclone, rain, hail, and anvil, is drawn. Strong supercells also produce two separate downdrafts, the forward and rear-flanking downdrafts. These downdrafts then produce two rain-cooled gust fronts, which move toward each other and gradually pinch off warm, moist air from the mesocyclone. The mosocyclone, as mentioned earlier will cut off entrapment, creating a tube that

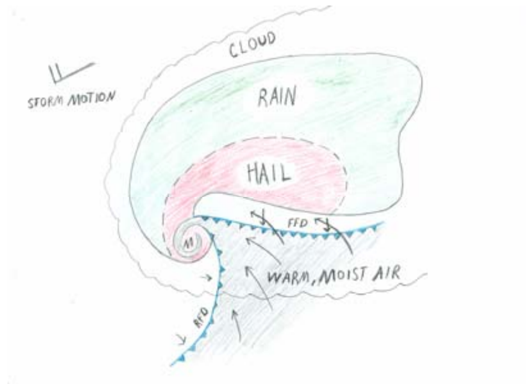


Fig. 12: Hand drawn conceptual model of tornadic supercell; FFD (RFD) denotes forward-flanking (rear-flanking) downdraft; blue triangle shaped lines denote the gust fronts

"vacuums" air from below. The source of this air is the warm, moist sector. As this air is fed into the storm, some of the wind will encounter the gust front and be forced up and over. The resulting shear creates a narrow tube of horizontal, three-dimensional rotation. This tube gets fed into the updraft along the gust front, where it gets tilted in the vertical and stretched. Based on the conservation of angular momentum, the stretching causes increased rotation and the resulting tornado. The same thing can happen along the rear-flanking downdraft, but creates a clockwise rotating tornado, which is a much less common phenomenon.

Conclusion

The morning of July 18, 1996 was the calm before the storm. The atmospheric setup was one not conductive for convection. However, it was shown that each ingredient was beginning to set up at this time. As the day progressed, the atmosphere evolved and reorganized each of the triggering mechanisms necessary to overcome a strong inversion produced by an EML and differential temperature advection in the vertical. The initial hypothesis was shown to be incorrect as a combination of the frontogentic cold front, surface convergence, daytime turbulence, confluence and the low-level jet at 850 hPa, and the upper-level jet at 300 hPa all enhanced and concentrated ascent over Eastern Wisconsin. Consequently, moderate helicity aided in the formation of mesocylones within many of the supercells developing in the late afternoon of the 18th. The mixture of gust fronts and mesocyclones was conducive for the tornado outbreak of that day.

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