THE FARGO F5 TORNADO OF 20 JUNE 1957: HISTORICAL RE-ANALYSIS AND OVERVIEW OF THE ENVIRONMENTAL CONDITIONS

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Abstract

On the evening of 20 June 1957, an F5 tornado struck the city of Fargo, North Dakota killing 13 people and injuring over 100. This tornado was researched extensively by Dr. Tetsuya Fujita, and became a basis for his creation of the F scale (later developed in 1971) and coining of the phrases wall cloud, collar cloud and tail cloud (Fujita 1960).The Fargo tornado was one in a family of at least five tornadoes produced by a single, long-lived, cyclic supercell. Observational data from 1957 were used to examine the synoptic and mesoscale environment from the perspective of present-day tornado research, with a focus on the possibility of an outflow boundary enhancing the tornado potential near Fargo. Strong instability, strong vertical wind shear, high storm-relative helicity (SRH), favorable storm-relative flow (SRF) and lowered lifted condensation levels (LCLs) seemed to play a pivotal role in the strength and longevity of the tornado. In addition, boundary-layer moisture appeared to be enhanced via evapotranspiration (ET) and moisture convergence. Approximately 200 photographs of the supercell and tornado also provided better insight to the storm-scale environment, which was not well understood in 1957.

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1. Introduction

On the evening of 20 June 1957, an F5 intensity tornado on the Fujita scale (Table 1; Fujita 1971) struck Fargo, North Dakota. The tornado killed 13 people, injured over 100, and badly damaged or destroyed over 1,300 homes as it moved through the city beginning around 0027 UTC 21 June 1957. Tornadoes causing F5/

EF5 damage are extremely rare; only 52 have been documented in the United States between 1950 and 2009, and only one other was recorded in North Dakota's history, at Fort Rice on 29 May 1953 (Storm Prediction Center 2009). The Fargo tornado traveled 9 miles (14.5 km) and was about 0.5 miles (0.8 km) wide. This tornado was one in a family of at least five tornadoes that had an intermittent damage track of nearly 70 miles (113 km) from Wheatland, North Dakota to Dale, Minnesota (Fig. 1). The long-tracked and cyclic supercell lasted at least 6 hours, and was tornadic for almost 4 hours, according to eyewitness reports and Fujita's detailed analysis (Fujita 1960).

The synoptic and mesoscale environment has been re-created using the limited data available. Environmental kinematic and thermodynamic properties will be explored and related to present-day research. The long-lived, cyclic nature and

storm motion of the supercell and its possible interaction with an outflow boundary will be discussed. In addition, the development of high surface dewpoints in the area impacted by the tornadoes will be investigated.

2. Data and Methodology

a. Observations of the tornadic event

The Fargo tornado was one of the most widely documented tornadic events of its period. Fujita (1960) collected around 200 photographs of the event, obtained many eyewitness accounts, and provided a detailed analysis in his manuscript. In addition, personal communication with Dr. Ray Jensen (2007), who was on duty at the U.S. Weather Bureau in Fargo at the time of the tornado and who issued public warnings for the event, provided an additional first-hand account of the meteorological conditions associated with the Fargo event. Jensen's fascinating account of the event and 1957 warning operations is available online at http://www.crh.noaa.gov/images/fgf/pdf/Jensen_Fargo_Warning_Paper_11_19_09.pdf.

b. Meteorological reanalysis

The reanalysis of the synoptic environment that produced the Fargo tornado was completed with archived North American mandatory level rawinsonde observations and official surface observation forms (U.S. Department of Commerce Weather Bureau Form WBAN 10A and 10B). Both were obtained from the National

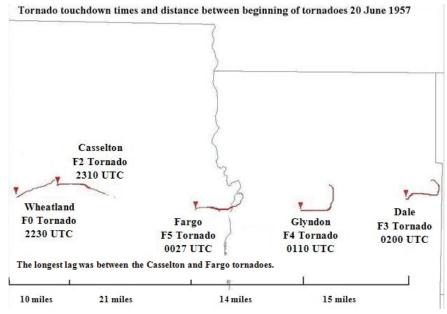


Fig. 1. Tornado tracks of the Fargo tornado family on 20-21 June 1957. Five distinct tornadoes were produced from a long-lived and cyclic supercell in southeastern North Dakota and west central Minnesota.

Climatic Data Center available online at <u>http://www.ncdc.noaa.gov/oa/climate/stationlocator.html</u>. The data were plotted using the Digital Atmosphere software package (version 2.07; Weather Graphics 2010), and then subjective analyses were done by hand after exporting the images out of Digital Atmosphere.

A representative approximated 0000 UTC 21 June 1957 Fargo sounding was also constructed by interpolating mandatory and significant pressure level data from the observed 0000 UTC soundings at Bismarck, North Dakota, and International Falls and St. Cloud, Minnesota. The sounding values were greatly supplemented using data available from the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis (Kistler et al. 2001). The surface data for the sounding was taken directly from the observations at Fargo.

A vertical wind profile was approximated for Fargo at 0000 UTC 21 June 1957, utilizing the same methods described above. However, the vertical wind profile also benefited from actual observed pilot balloon data taken at Fargo's Weather Bureau Office during the late afternoon on 20 June 1957. The pilot balloon data contained wind observations below 3 km, which increased confidence in the low-level shear calculations presented herein. The estimated winds were also plotted as a 0000 UTC 21 June 1957 hodograph using the surface observations at Fargo. Hourly hodographs discussed in section 5 were developed from the 0000 UTC 21 June 1957 hodograph by altering only the surface wind vector observed at Fargo for the time of interest.

Finally, a high-resolution Advanced Research core of the Weather Research and Forecasting model (WRF-ARW; Skamarock and Klemp 2008) simulation was conducted for the case with the numerical model construction utilized at the National Weather Service (NWS) in Marquette, Michigan (Hulquist et al. 2007). The simulation utilized a nested grid with 80 km horizontal grid spacing on the outer nest and 5 km spacing in the inner nest, where no convective parameterization was used. The model was initialized at 1200 UTC 20 June 1957 using NCEP/NCAR reanalysis data. However, the position of the surface boundaries in the model simulation were much different from reality due to the development of an outflow boundary that will be discussed in section 6, and as a result, the model results will only be used to verify the instability present in this case.

The authors recognize the limitations and subjectivity applied to the creation of soundings and hodographs for Fargo. The values interpolated to Fargo were derived twice, and an average was then used in the final production of both the soundings and the hodographs. The resulting diagrams are thus smoothed and certainly do not capture all details of the vertical tropospheric structure during the event, especially where boundary layer processes are important. Several severe weather indices were also calculated from the soundings and hodographs upon their completion. It follows that there is an inherent degree of uncertainty in these values, as well. Where applicable, ranges of results will be presented.

3. Overview of the Fargo Tornadoes on 20 June 1957

Research indicates that supercells associated with most violent tornadoes tend to produce tornado families (Dowell and Bluestein 2002), as was the case with the long-lived, cyclic supercell responsible for the Fargo tornado. In addition to the F5 at Fargo, Fujita (1960) documented an F4 tornado in Glyndon, Minnesota, an F3 tornado in Dale, Minnesota, an F2 tornado near Casselton, North Dakota, and an F0 tornado near Wheatland, North Dakota. Each tornado is shown in Fig. 1, with distances and times indicated between each successive tornado. Fujita's (1960) investigation "confirmed that these tornadoes were produced by a rotating cloud something like a miniature hurricane," known today as the rotating wall cloud. The storm structure was visible from greater than 20 miles (32 km; Jensen 2007, personal communication). This contributed to the large number of photographs available for study by Fujita, which helped him coin the phrases wall cloud, collar cloud, and tail cloud.

The Fargo supercell produced intermittent tornadoes from the first touchdown in Wheatland, North Dakota around 2230 UTC 20 June 1957 until the last tornado ended around 0215 UTC 21 June 1957 in Dale, Minnesota. Therefore, non-continuous tornadoes occurred for about 3.75 hours with a total damage path length of approximately 47 miles (76 km). However, NOAA Storm Data [available online at http://www.ncdc.noaa. gov/oa/climate/sd/] shows that seven buildings were destroyed by high winds around 2000 UTC in Stutsman County, North Dakota, which is upstream of and directly in line with the later reports associated with the long-lived supercell. Baseball size hail and funnel clouds were also reported in the area. If in fact this damage was also the result of one or more tornadoes, the time during which non-continuous tornadoes occurred may be significantly longer. At the very least, this suggests that the parent supercell responsible for this event likely had a path length of at least 110 miles (177 km) over a period of at least 6 hours.

The first tornado, described as a "long and ropelike waterspout," developed near Wheatland, North Dakota and moved east-northeast for around 11 miles (18 km). No property damage was reported, although some haystacks were picked up and there was some crop damage. This tornado was rate as F0 (Fujita 1960). The second tornado, an F2 with a path length of approximately 5 miles (8 km), developed near Casselton, North Dakota around 2310 UTC, shortly after the Wheatland tornado dissipated. The initial stages of the tornado are seen in Figs. 2-3 (Fujita 1960). As Fig. 1 shows, the path directions of the Wheatland and Casselton tornadoes are distinctly different from one another, and from the later three tornadoes. The latter three tornadoes demonstrate nearly identical paths indicative of relatively steady-state supercell motion, and cyclic mesocyclone paths similar to those shown in Burgess et al. (1982). It is therefore possible that the comparably different paths of the Wheatland and Casselton tornadoes are indicative of an immature supercell, or cell mergers which may have taken place upstream of Fargo.

The third tornado of the series was the Fargo F5 tornado. The supercell moved eastward for 15 miles (24 km) from Casselton, North Dakota before producing a tornado 2.5 miles (4.0 km) west of Fargo near 0027 UTC. The tornado had a path length of 9 miles (14 km; Fujita 1960), which included a distinct left (northward) curve

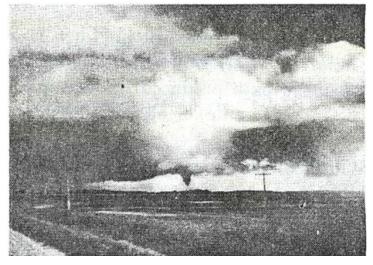


Fig. 2. Image of Casselton, North Dakota tornado around 2310 UTC on 20 June 1957. View was to the east-southeast and the tornado was approximately 10 miles (16 km) from the photographer. Photograph taken by Faught (Fujita 1960).

that occurred during the occlusion process of the cyclic supercell.

The fourth tornado produced by the cyclic supercell was an F4 that occurred near Glyndon, Minnesota around 0110 UTC. The tornado traveled eastward, then northeastward causing severe tree damage as it crossed the Buffalo River and destroyed one family farm. Significant damage was done to a second farm before the tornado veered sharply to the north. The damage path was 10 miles (16 km) long (Fujita 1960). The fifth and final tornado, an F3, was the cone-shaped Dale, Minnesota tornado, which began around 0200 UTC. The tornado destroyed a family farm as it turned northward during the occlusion process at 0205 UTC, a time known due to the fact that a clock at the farm stopped at that time. The damage path of the Dale tornado was around 7 miles (11 km; Fujita 1960).

4. Photographic Overview of the Fargo Tornado

The wall cloud preceding the Fargo tornado was first photographed 10 miles (16 km) west of the city at 0005 UTC, approximately 25 minutes before entering Fargo (Fig 4). This wall cloud was already well-developed with a precipitation-free updraft and rain-free base. The next picture of the wall cloud, shown in Fig. 5, was approximately 7 miles (11 km) west of Fargo. The tail cloud extended to the north with a classic appearance of a large tornadic supercell (Figs. 5-6).

In Fig. 6, the tail cloud and base of the wall cloud are nearly on the ground indicating a very low lifted condensation level (LCL). As Markowski et al. (2002) have noted, "environments characterized by high boundary

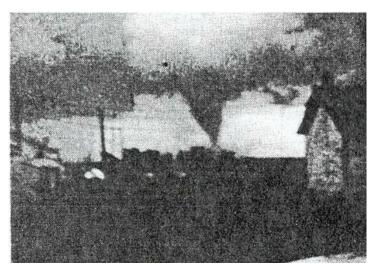


Fig. 3. Image of Casselton, North Dakota tornado around 2315 UTC on 20 June 1957; view was to the east-southeast. Distance to tornado was approximately 2.5 miles (4.0 km). Photograph taken by Madsen (Fujita 1960).

layer relative humidity (RH), and low cloud base may be more conducive to rear flank downdrafts (RFD) associated with relatively high buoyancy than environments characterized by low boundary layer RH." The absence of significant precipitation near the updraft implied that evaporationally-cooled air was likely not being recycled into the updraft. Both characteristics suggest that there may have been greater potential for a relatively warm RFD just prior to the Fargo tornado than earlier in the storm's life cycle.

The tornado was first observed 3.5 miles (5.6 km) west of Fargo at 0027 UTC (Fig. 7). Three minutes later, the tornado rapidly intensified and approached the

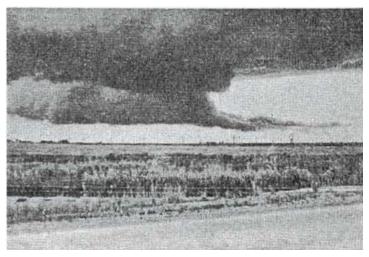


Fig. 4. First image of Fargo wall cloud located about 10 miles (16 km) west of Fargo around 0005 UTC on 20 June 1957. View was to the northeast and the wall cloud was approximately 5 miles (8 km) from the photographer. Photograph taken by Stensrud (Fujita 1960).

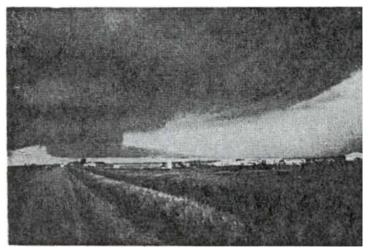


Fig. 5. Classic image of Fargo wall cloud located approximately 7 miles (11 km) west of Fargo around 0015 UTC on 20 June 1957. View was to the west-southwest and the wall cloud was approximately 6.5 miles (10.5 km) from the photographer. Photograph taken by Bergquist (Fujita 1960).

western parts of the city (Fig. 8) (Fujita 1960). According to Fujita, the Fargo tornado went through the entire life cycle of a typical large and destructive tornado, which he referred to as the "dropping stage, the rounded bottom stage, shrinking stage and the rope stage." The tornado's life cycle from its F5 stage to "roping out" stage can be seen in Figs. 9-13. Note the extensive precipitation-free area around the Fargo tornado. The highly visible nature of the tornado and early warning allowed many people to evacuate Fargo before the tornado struck the city, which saved countless lives (Jensen, personal communication, 2007).

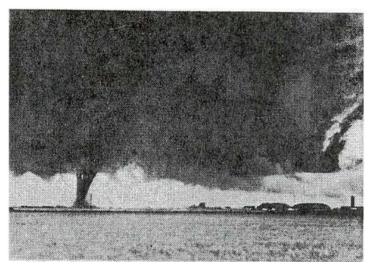


Fig. 8. The Fargo tornado was located about 3 miles (5 km) west of Fargo around 0030 UTC on 20 June 1957. View was to the southwest and the tornado was approximately 3.5 miles (5.6 km) from the photographer. Photograph taken by Gebert (Fujita 1960).

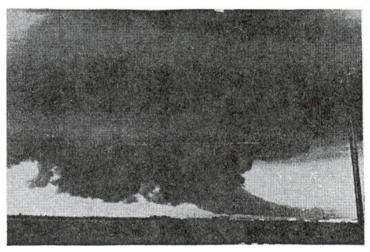


Fig. 6. Image of Fargo wall cloud located about 5 miles (8 km) west of Fargo around 0025 UTC on 20 June 1957. View was to the northwest and the wall cloud was approximately 5 miles (8 km) from the photographer. Photograph taken by Olsen (Fujita 1960).

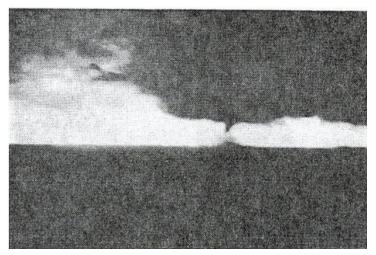


Fig. 7. The first image of the Fargo tornado located about 3.5 miles (5.6 km) west of Fargo around 0027 UTC on 20 June 1957. View was to the southwest and the tornado was approximately 3 miles (5 km) from the photographer. Photograph taken by Frahm (Fujita 1960).

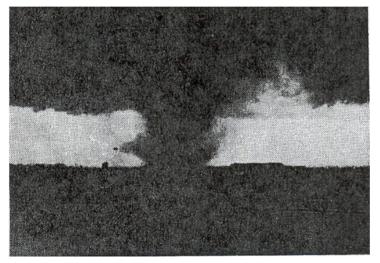


Fig. 9. The Fargo tornado was located about 1 mile (1.6 km) west of downtown Fargo around 0034 UTC on 20 June 1957. View was to the southwest and the tornado was approximately 1.5 miles (2.4 km) from the photographer. The tornado was nearing Golden Ridge, where F5 damage was produced. Photograph was taken by Kittelsrud (Fujita 1960).

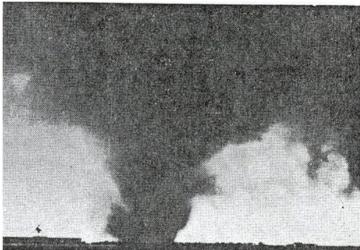


Fig. 10. The Fargo tornado was located about 0.5 miles (0.8 km) west of downtown Fargo around 0036 UTC on 20 June 1957. View was to the south and the tornado was approximately 1 mile (1.6 km) from the photographer. The tornado was in or very close to Golden Ridge, where F5 damage was produced. Photograph was taken by Hagen (Fujita 1960).

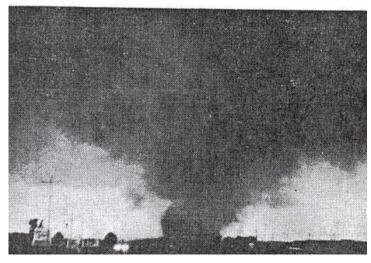


Fig 11. The Fargo tornado was located about 0.3 miles (0.5 km) west of downtown Fargo around 0039 UTC on 20 June 1957. View was to the south and the tornado was approximately 1 mile (1.6 km) from the photographer. The tornado was in Golden Ridge, producing F5 damage. Photograph was taken by Hagen (Fujita 1960).

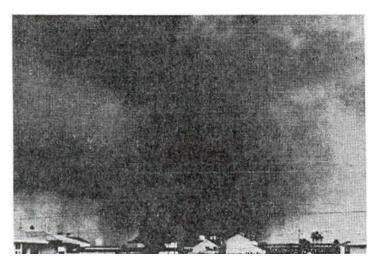


Fig 12. The Fargo tornado was in downtown Fargo around 0041 UTC on 20 June 1957. View was to the south and the tornado was approximately 0.7 miles (1.1 km) from the photographer. The tornado had weakened to an F3 at this point. Photograph was taken by Gebert (Fujita 1960).

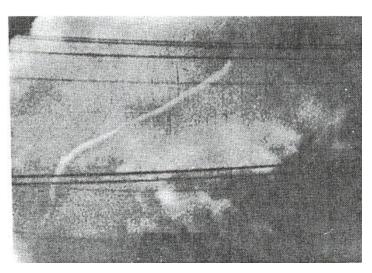


Fig 13. The Fargo tornado had crossed the Red River into Minnesota, and was 4 miles (6 km) northeast of downtown Fargo around 0110 UTC on 21 June 1957. The tornado survived until 0130 UTC, before dissipating. View was to the north and the tornado was approximately 4 miles (6 km) from the photographer. Photograph was taken by Mickelson (Fujita 1960).

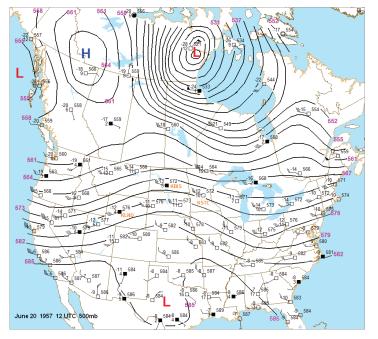


Fig 14a. 500-hPa observations at 1200 UTC 20 June 1957 in conventional form (temperature and dewpoint depressions in °C and wind speed in kt) with height contours (solid black contours, contour interval [CI] = 30 m).

5. Synoptic Environment

Inspection of the 1200 UTC 20 June 1957 500-hPa chart revealed a shortwave ridge centered over North Dakota (Fig. 14a). This ridge translated eastward through 0000 UTC 21 June 1957, which allowed significant moisture advection and increasing mid-level flow to take place over the Northern Plains. At 0000 UTC 21 June 1957, a 500-hPa longwave trough axis was located near 115º W, with an embedded shortwave trough over Wyoming and Utah (Fig 14b). Flow aloft increased downwind of the trough, with a 40-50 kt (\sim 20-25 m s⁻¹) 500-hPa jet extending northeastward from Lander, Wyoming (KLND) to Bismarck, North Dakota (KBIS). An 80 kt (\sim 40 m s⁻¹) 250-hPa speed max also extended from northeastern Montana into southern Ontario at 0000 UTC (Fig. 15). The location of the upper-level trough with respect to the eventual tornado event suggests that the large-scale ascent directly associated with that feature was likely weak at best in that area. Even the 700-hPa short wave trough shown in the observed data was only as close as western North Dakota by 0000 UTC (Fig. 16). Also, the 1200 UTC 850-hPa chart did not reveal a notable lowlevel jet across the region with southerly flow of only 20 kt $(\sim 10 \text{ m s}^{-1})$ or less across the Dakotas (Fig. 17a). The 1200 UTC 850-hPa analysis showed maximum dewpoints in the Dakotas around 10° C, but also revealed a significant dry layer upstream across the central Plains where 850-hPa dewpoints were at or below 0° C. At 0000 UTC, the 850hPa chart showed a slight increase in dewpoints over the

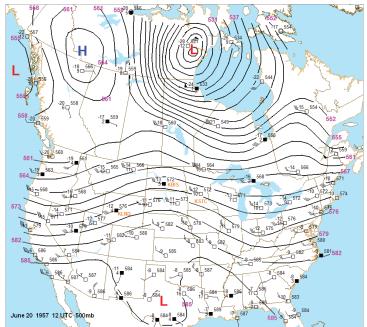


Fig 14b. As in Fig. 14a except at 0000 UTC on 21 June 1957.

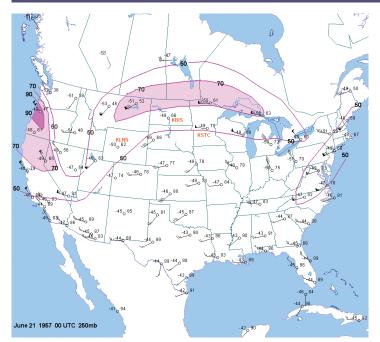


Fig 15. 250-hPa observations at 0000 UTC 21 June 1957 in conventional form (temperature and dewpoint depressions in °C and wind speed in kt) with isotachs for wind speeds at or above 50 kt (colored lines and solid fill, CI = 20 kt).

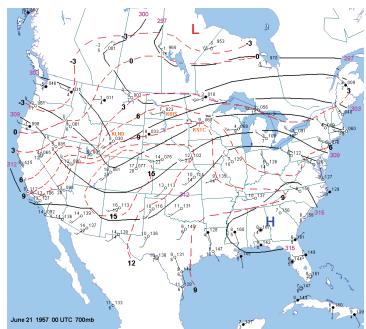
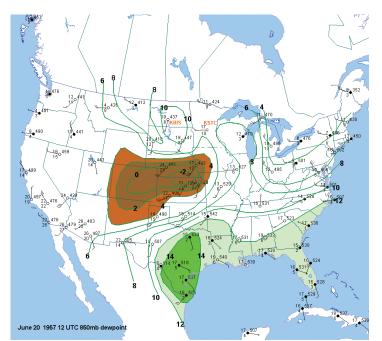


Fig 16. 700-hPa observations at 0000 UTC 21 June 1957 in conventional form (temperature and dewpoint depressions in °C and wind speed in kt) with isotherms (dashed red contours, $CI = 3^{\circ}$ C) and heights (solid black contours, CI = 60 m).



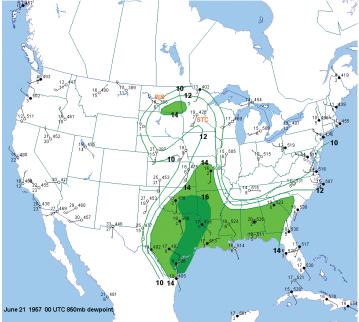


Fig 17a. 850-hPa observations at 1200 UTC 20 June 1957 in conventional form (temperature and dewpoint depressions in °C and wind speed in kt) with dewpoint temperatures (solid colored contours with CI = 2° C, solid fill with brown shading for dewpoint temperatures at or below 4° C, and solid fill with green shading for dewpoint temperatures at or above 12° C).

Fig 17b. As in Fig. 17a except at 0000 UTC 21 June 1957, and with green shading for dewpoint temperatures at or above 14° C. Some uncertainty exists in the depiction of dewpoints due to the absence of a 0000 UTC 21 June 1957 sounding from KHON.

The Fargo F5 Tornado of 20 June 1957

eastern Dakotas, as well as a shift of the winds to the west at Bismarck, implying the passage of a weak front at that level (Fig. 17b).

Despite the displacement of the strongest mid- and upper-level forcing for ascent from the Fargo area, the upstream trough did result in the formation of a surface low pressure system. This low pressure system moved from southwestern North Dakota at 1200 UTC to the central part of the state, just west of Bismarck, by 1500 UTC (Figs. 18a-b). By 1800 UTC, the surface low was located just

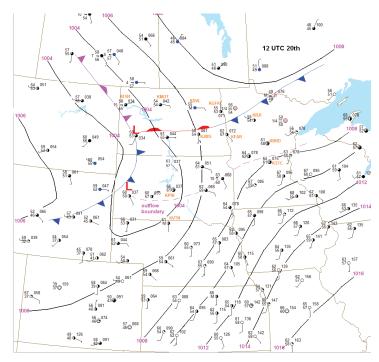


Fig 18a. Standard surface observations and subjectively analyzed pressure (CI = 2 hPa) and fronts at 1200 UTC 20 June 1957. FAA station identifiers are shown for locations mentioned in the text. Outflow boundary is labeled.

southwest of Bismarck, and had deepened 6-hPa to ~998hPa during the preceding six hours (Fig. 18c). During that period the surface cyclone displayed a classic structure with a surface warm front extending northeastward from the low center to near Bemidji, Minnesota (KBJI), while a cold front extended southward from just west of Pierre, South Dakota (KPIR) and Valentine, Nebraska (KVTN). Notice in Fig. 18c that Fargo (KFAR) was well into the warm sector of the system as by 1800 UTC the warm front had lifted northward past Grand Forks, North Dakota (KGFK), which is approximately 75 miles (120 km) north of Fargo. The surface moist axis at 1800 UTC contained dewpoints of 62 to 66° F and was located to the west of Fargo, over northeastern South Dakota and southeastern North Dakota.

Although the significant tornado event was likely driven by mesoscale processes, the synoptic setting did

foster an environment suitable for severe convection, both by strengthening the mid- and upper-level winds and advecting an elevated mixed layer (EML) with steep lapse rates aloft atop a warming and moistening boundary layer in advance of the surface cyclone. Although the 0000 UTC 21 June 1957 St. Cloud, Minnesota (KSTC) sounding shown in Fig. 19 was taken well away from Fargo and did not indicate the rich low-level moisture that will later be shown to exist in the tornado area, it does exemplify the synoptic-scale, deep-layer wind shear that was in place

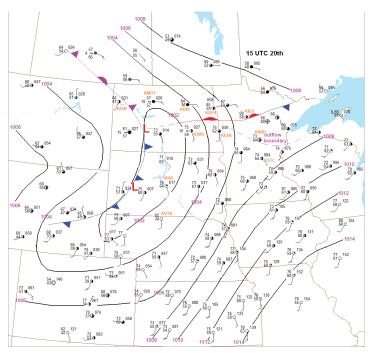


Fig 18b. As in Fig. 18a except at 1500 UTC on 20 June 1957.

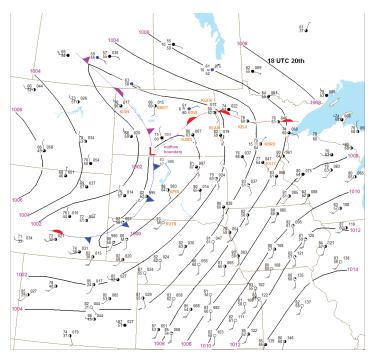


Fig 18c. As in Fig. 18a except at 1800 UTC on 20 June 1957.

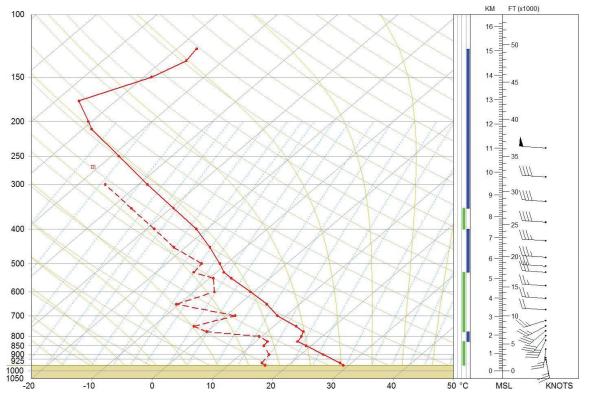
across the region, as well as the presence of steep lapse rates aloft. The sounding contained bulk shear vectors from 0-6 km above ground level (AGL) in the range of 30 to 40 kt (~15 to 20 m s⁻¹). These values suggested supercells were possible (Rasmussen and Blanchard 1998). The 0–8-km AGL bulk shear was 40-50 kt (~20-25 m s⁻¹), which is slightly below the threshold at which long-lived supercells are favored (Bunkers et al. 2006b).

The synoptic setting seen in this case is a relatively common occurrence across the Northern Plains during the warm season. Similar situations occur many times during the year and do not necessarily result in violent tornado outbreaks such as that which occurred on 20 June 1957. As a result, the mesoscale evolution which occurred after 1800 UTC appears to have played a pivotal role in the Fargo tornado. This is not an uncommon characteristic, as Edwards and Thompson (2000) have noted that outbreaks of strong and violent tornadoes are not necessarily associated with synoptically evident patterns, and Rasmussen et al. (2000) noted that mesoscale enhancements to similar synoptic environments may be one key to the formation of significant tornadoes. Finally, Rasmussen and Blanchard (1998) suggested that even when combinations of convective available potential energy (CAPE) and storm-relative helicity (SRH) values appear supportive of significant (F2 or greater) tornadoes, synoptic environments featuring those conditions only rarely yield such events.

6. Mesoscale Environment

a. General mesoscale characteristics

Observations across northern North Dakota shown in the series of surface charts in Fig. 18 suggest that a band of precipitation progressed across that portion of the state during the day. In Fig.18a, light rain was reported at Williston (KISN), in the northwestern corner of the state, and in Fig. 18b, the same weather was reported at Minot (KMOT), in the north central part of the state. The 1800 UTC surface chart in Fig. 18c shows a thunderstorm at Devils Lake, North Dakota (KDVL). These sites are aligned along a similar latitude with a spacing of approximately 130 miles (209 km). Given the westerly flow aloft, the surface observations at these cities likely captured a complex of convection that had an eastward movement of approximately 35 kt (18 m s⁻¹). At 1800 UTC, the surface temperature and dewpoint at Grand Forks were 80° F and 62° F, respectively. Grand Forks is approximately 90 miles (145 km) east of Devils Lake, and as previously mentioned, the warm front appeared to move just through the station by 1800 UTC. Successive observations from Grand Forks indicated that a thunderstorm also passed through that station between 1900 and 2000 UTC. By 2000 UTC (Fig. 20a), the surface wind had shifted to the northeast and the temperature had dropped substantially to 68° F. A similar drop in surface temperature was





just north of the city prior to 0000 UTC, and isallobaric

ageostrophic adjustment of low-level winds due to

pressure falls. Surface pressure falls could be due to

either the deepening synoptic surface low, which was

located southwest of Jamestown, North Dakota (KJMS) by

0000 UTC (Fig. 20c), or to the possibility of a mesolow

forming near the outflow boundary, coincident with

observed in the following hours at downstream sites in northwestern Minnesota. Given the earlier advancement of the surface warm front, it is hypothesized that this abrupt change associated with passing convection signaled the development of a surface outflow boundary (Fig. 20a). The surface outflow boundary became the 'effective warm front' demarking the northern edge of the

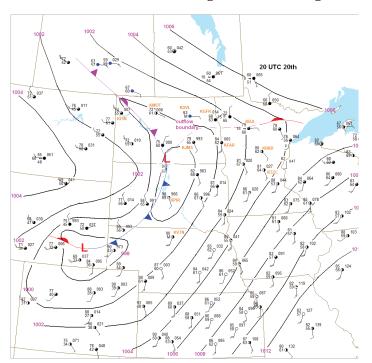


Fig 20a. As in Fig. 18a except at 2000 UTC on 20 June 1957.

warm sector, southeast of the developing surface low. The elevated convection north of the warm front, combined with strong heating within the warm sector, allowed the boundary to sharpen during the day. The absence of surface observations between Grand Forks and Fargo makes it impossible to determine with certainty where the outflow boundary may have been situated by 0000 UTC, though hourly temperature observations taken at that time by National Weather Service Cooperative Observers does help refine its position. However, given the magnitude of cooling associated with its passage and sharp change in wind direction at both Grand Forks and Bemidji, the latter of which is at a latitude that is approximately 40 miles (64 km) north of Fargo, it is very possible that the outflow boundary was just north of Fargo and Brainerd (KBRD) by 2300 UTC (Fig. 20b), and thus may have been pivotal in the evolution of the tornadic supercell that impacted the area.

Surface observations at Fargo indicate a significant backing in surface winds to a southeasterly direction just before 0000 UTC. This distinct change in surface winds may be attributed to the close proximity of the surface outflow boundary, which is believed to have been
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Fig 20b. As in Fig. 18a except at 2300 UTC on 20 June 1957.

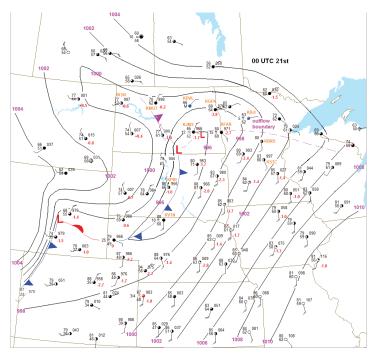


Fig 20c. As in Fig. 18a except at 0000 UTC on 21 June 1957, and with the addition of the three-hour surface pressure change (in hPa) shown in red in the lower-right corner of each station plot.

the tornadic supercell. Just after 0000 UTC, the winds shifted to an east-northeasterly direction and increased in speed, which is likely indicative of either the passage of the outflow boundary through the city or the forward flank downdraft of the approaching supercell. Although it is impossible to know for sure what increased the easterly component of the surface winds at Fargo prior to the violent tornado given the limited data available, that change corresponded to an increase in surface dewpoint to 69° F at the station, and thus suggested an enhancement in the low-level convergence zone in the vicinity of Fargo. This change was instrumental in modifying the ambient thermodynamic and kinematic environment in a manner that favored significant tornadogenesis.

The mesoscale environment which developed near Fargo shortly after 0000 UTC 21 June 1957 resemble the patterns which Johns et al. (2000) identified as being favorable for strong and violent tornadoes in the northcentral United States. This work suggested that most of these events were closely tied to the cool side of a warm frontal or quasi-stationary boundary with the surface moisture axis coincident with the frontal zone.

b. Mesoscale thermodynamic characteristics

100

150

200

250

400

500

The approximated 0000 UTC sounding developed for Fargo suggested that the enhanced boundary layer moistening that took place in the vicinity of the station

contributed to an estimated surface-based CAPE (SBCAPE) near 3000 J kg⁻¹ and a surface-based convective inhibition (SBCIN) of almost zero, using the observed surface temperature and dewpoint of 80° F and 69° F, respectively (Fig. 21). The magnitude of the approximated instability is supported by the 12-hour forecast from the WRF-ARW simulation valid at 0000 UTC (not shown). That forecast shows SBCAPE over 3000 J kg⁻¹ and minimal SBCIN in southeastern North Dakota with surface temperature and dewpoint values similar to those observed, despite the fact that the surface wind fields in the model do not match the observed winds since the simulated primary surface cyclone and warm front were predicted much farther north than the observations indicated. Also, given the observed moisture convergence that was occurring in the area, it is likely that the low-level moist layer was deeper than that shown by the approximated sounding.

The 0000 UTC Fargo sounding suggested an LCL for a surface-based parcel was near 700 m AGL. This is in line with the LCL heights Craven and Brooks (2004), Edwards and Thompson (2000), and Johns et al. (2000) suggested are typically associated with strong and violent tornadoes, and further supports the hypothesis that the local increase of dewpoints in the vicinity of Fargo led to a much more favorable low-level thermodynamic environment for significant tornadoes. In fact, careful observations of photographs taken during the event strongly suggest that the LCL with the parent updraft

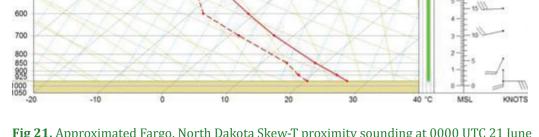


Fig 21. Approximated Fargo, North Dakota Skew-T proximity sounding at 0000 UTC 21 June 1957.

was actually much lower than 700 m AGL. This could be a reflection of the supercell ingesting not only air from the warm sector, but also rain-cooled air from the north side of the outflow boundary.

c. Mesoscale vertical wind shear characteristics

The backing surface winds at Fargo had a pronounced effect on the local vertical wind shear. Hourly hodographs were constructed for Fargo from the period 1800 UTC 20 June 1957 (Fig. 22a) through 0023 UTC 21 June 1957, the time of the last surface observation before the tornado (Fig. 22b). The hodographs were constructed by altering only the surface wind vector from the mandatory pressure level winds developed for Fargo using the methods described in Section 2. Significant temporal changes in the deep-layer shear can be attributed to the change in surface winds in the vicinity of Fargo. The 0-6 km bulk shear was in the 60 to 70 kt (30 to 35 m s⁻¹) range, which was very supportive of supercells (Rasmussen and Blanchard 1998). This extremely large shear value was likely a significant contributor to the longevity of the parent supercell responsible for the tornado event (Bunkers et al. 2006b).

The low-level vertical shear at Fargo also increased substantially in the hours leading up to the tornado. This is not surprising since low-level vertical shear has been

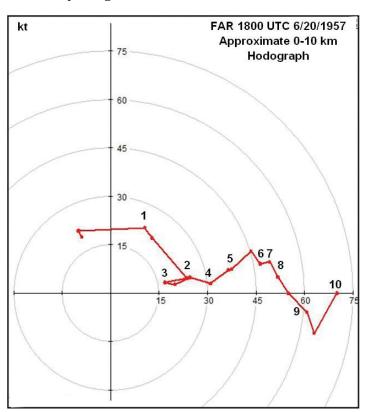


Fig. 22a. 1800 UTC hodograph at Fargo, North Dakota. Wind speeds are in kt and heights AGL are labeled in 1 km increments.

found to vary significantly both temporally and spatially in tornadic events (Markowski et al. 1998). As the surface winds backed and increased in magnitude, the 0–1 km and 0–3 km bulk shear vectors lengthened considerably (Fig. 23). Both the 0-1 km and 0-3 km bulk shear were estimated to be over 20 kt (10 m s⁻¹) at Fargo using the 0023 surface observation taken immediately prior the tornado, which displayed a decidedly easterly direction.

Storm-relative helicity (SRH) has been shown to be an important tool in tornado forecasting (Davies-Jones et al. 1990). The SRH was derived for each hodograph in the time leading up to the tornado utilizing a storm motion of 270° at 15 kt (~8 m s⁻¹). This motion was derived utilizing the information provided on the path of the storm documented by Fujita (1960). The estimated SRH further supports the hypothesis that the backing surface winds created a more favorable tornadic environment with time at Fargo (Fig. 24). By 0023 UTC, the SRH was estimated around 325 m² s⁻² in the 0-1 km layer and over 350 m² s⁻² in the 0-3 km layer.

Storm-relative flow (SRF) was strong, and also likely played a role in the maintenance of a strong, long-lived, low-level mesocyclone by providing a favorable balance between the inflow and outflow of the supercell for an extended period. According to Brooks et al. (1993), "the intensity of storm-relative winds" appears to play an important role in the maintenance and longevity of strong

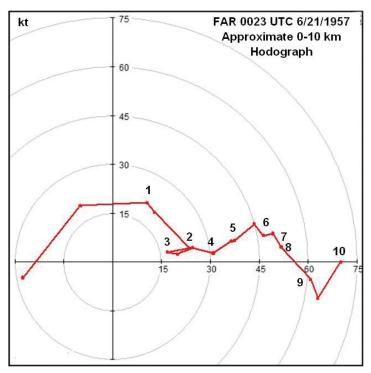


Fig. 22b. 0023 UTC ("tornado time") hodograph at Fargo, North Dakota, which uses the last surface wind observation before the F5 tornado passed the weather office. Wind speeds are in kt and heights AGL are labeled in 1 km increments.

Bulk Shear Versus Time at Fargo

Time (UTC)



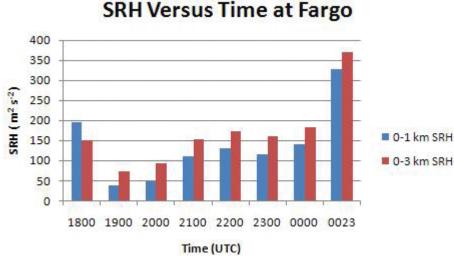


Fig 24. As in Fig 23 except for storm-relative helicity (SRH).

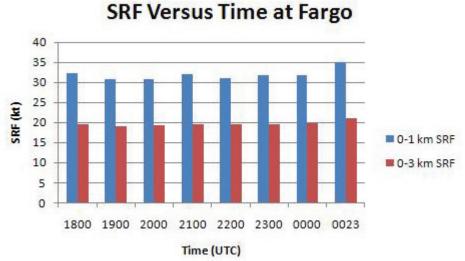


Fig 25. As in Fig. 23 except for 0-1 and 0-3 km storm-relative flow (SRF).

low-level mesocyclones. Furthermore, "some storms with high inflow speeds produce significant long-lived, low-level rotation" (Brooks et al. 1993). SRF likely played a key role in its maintenance and longevity of what photographs infer was a very strong low-level mesocyclone in this case. The inflow, or low-level 0-1 km SRF was around 30 kt (~15 m s⁻¹), with the 8-12 km SRF outflow winds also strong near 40 kt (\sim 20 m s⁻¹). Fig. 25 shows that the SRF increased markedly in the lowest kilometer AGL as surface winds became east-northeasterly and increased to 27 kt (14 m s⁻¹) before the tornado struck Fargo.

7. Supercell Longevity and Storm Motion Considerations

a. Supercell longevity

The supercell that produced the Fargo tornado lasted for approximately 6 hours according to Fujita (1960), and was therefore classified as a longlived supercell (Bunkers et al. 2006a). If a tornado is produced by a longlived supercell, "then the probability of significant tornadoes is enhanced" (Bunkers et al. 2006a). The supercell longevity of the Fargo event was similar to other significant tornado outbreaks, including the supercell that produced an F5 tornado during the 3 May 1999 Oklahoma outbreak (Thompson and Edwards 2000).

Recent research indicates that long-lived supercells are favored in environments characterized by strong, deep-layered shear and SRF. The Fargo tornado had 0-8-km bulk shear values of 70 to 80 kt (~35 to 40 m s⁻¹). SRF in the 0-8-km layer was around 40 kt (20 m s⁻¹), conducive to long-lived supercells (Bunkers et al. 2006b). The SRF appeared to have played a pivotal role in lofting hydrometeors downstream and sustaining the supercell. Strong deeplayered SRF acted to keep hydrometeors lofted downstream from the updraft, and prohibited evaporationally-cooled air from being ingested into the updraft. This allowed prolonged ingestion of moist, unstable air, making formation of a warm-type RFD more likely (Markowski et al. 2002). The Fargo supercell had little or no precipitation near the updraft, which was evident from the photographs of the tornado development stages (Figs 8-10.). This lack of precipitation near the updraft enhances the hypothesis that a near perfect balance occurred between the updraft and downdraft interface in relation to hydrometeors.

b. Storm motion in relation to the surface boundary

Model simulations by Atkins et al. (1999) indicated that mesocyclones tracking along surface boundaries were stronger than storms moving across or perpendicular to boundaries. There is a strong possibility that the Fargo supercell either interacted with or tracked along the outflow boundary that sagged southward during the late afternoon and early evening. The environmental setting in the vicinity of the boundary likely caused the mesocyclone to become stronger at times, and more persistent than if no boundary was present. That is, the combination of increased surface moisture, localized enhancement of boundary layer convergence and backed easterly winds near and just north of the front provided an ideal setting for tornado development. Storm motion along this boundary would have provided the supercell an opportunity to interact with increased values of storm scale instability and shear. These localized enhancements may have maximized near Fargo. Atkins et al. (1999) observed in their simulations that "the strongest storm, determined from vertical velocities, was the one that propagated along, parallel to the boundary." It appears that the surface boundary played a key role in the maintenance and longevity of the Fargo supercell, in addition to the production of multiple significant tornadoes.

8. Potential Effects of Evapotranspiration (ET) on Low-Level Moisture Characteristics

It has been shown that a direct contributor to the favorable thermodynamic profile associated with the Fargo tornado was the presence of significant, low-level moisture. ET appeared to have played a significant role in the surface dewpoint increases for this case.

The maximum surface dewpoints shown in the region on the 1200 UTC surface chart in Fig. 18a were just over 60° F in an area extending from northeastern South Dakota into west central Minnesota. At that time, the maximum dewpoints within the southerly flow regime across the central plains were only between 55 and 59° F as far south as southern Kansas. Comparing this with the 0000 UTC chart in Fig. 20c reveals the marked increase

in low-level moisture that took place in southeastern North Dakota, northeastern South Dakota, and west central Minnesota by early evening. At Fargo, dewpoint temperatures climbed from 59° F at 1800 UTC 20 June 1957 to 69° F at 0000 UTC 21 June 1957. Persistent, moderate surface flow continued through that time across the Central Plains, but dewpoint temperatures upstream in the well-mixed air mass across Kansas and Nebraska remained lower than those observed in the area impacted by the tornado event. Thus, it appears that simple advection of moisture did not alone explain the increase in surface moisture in the Fargo area.

The growing season in the north-central United States is well underway by the latter half of June. Raddatz (1998) demonstrated the correlation between vegetative development to the seasonal pattern of convection and the period of greatest ET. Raddatz (2000) showed ET as a secondary, but significant moisture source for the Canadian Prairie Provinces. Kellenbenz et al. (2007) linked moisture from ET to the agroecosystems of the Northern Plains and a violent tornado event. Johns et al. (2000) also suggested that ET plays an important role in the occurrence of strong and violent tornadoes in this region. The Fargo F5 tornado event appears to fall into this category.

Climatological data for the spring and early summer of 1957 shows a surplus of precipitation in the area immediately upstream of Fargo. Precipitation amounts were from 2.5 to 7.5 centimeters (1 to 3 inches) above normal from far southeastern North Dakota into northeastern South Dakota during May and the first half of June. The Palmer Z index (Palmer 1965) can be used as a measure of short-term moisture adequacy. This index indicated extremely moist conditions in the region during May 1957 and moderate to extreme moisture conditions for June 1957 (Fig. 26a-b). The increase in surface dewpoints in the region occurred locally on 20 June 1957 during the period of maximum heating without evidence of significant surface moisture advection. A time series of dewpoints at Fargo showed a similar rise in dewpoints during the 1800 to 2200 UTC time frame for the days immediately preceding the tornado (Fig. 27). The repeated signal of moisture increase during the afternoon and evening hours under differing synoptic regimes in the days prior to the violent tornado provides some evidence of a possible local moisture source enhancement. Thus, the increase in ambient surface moisture may be partly attributed to enhanced ET due to above-normal precipitation during the active vegetative growth phase of crops in the area during the early summer of 1957. However, it must be emphasized that ET alone likely did not result in the local increase in surface moisture. Strong moisture convergence likely existed in the vicinity of and

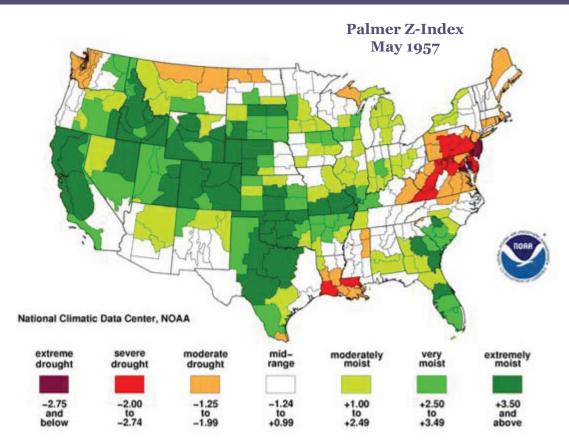


Fig. 26a. Observed Palmer Z Index for May 1957.

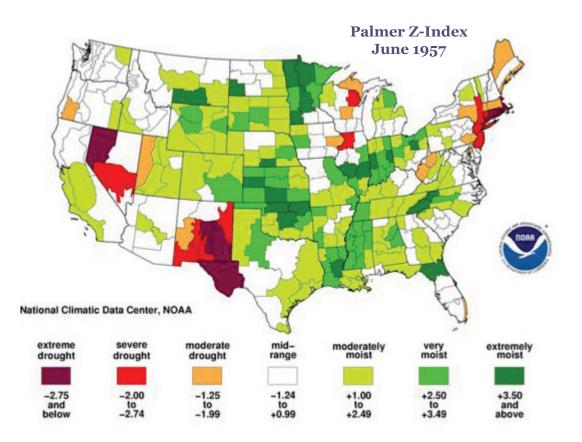
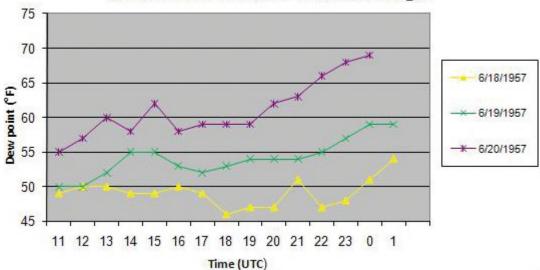


Fig. 26b. As in Fig. 26a except for June 1957.



Dew Point Versus Time at Fargo

Fig. 27. Hourly dewpoint trace for Fargo on consecutive days leading up to the tornado. For clarity, the hourly dewpoint traces from the 16th and 17th of June 1957 are not shown, but they displayed similar tendencies.

south of the surface fronts from eastern North Dakota into eastern South Dakota. This convergence likely played a critical role in elevating moisture levels, or at the least, enabled ET processes to contribute to increased surface dewpoints beneath the EML, which was likely important in inhibiting mixing in the boundary layer. Finally, the 1200 UTC 900-hPa dewpoint analysis shown in Fig. 28 shows a maximum in dewpoints over northeastern South Dakota. It is possible that downward mixing of this moisture may have also slightly increased surface dewpoints during the afternoon.

Johns et al. (2000) found that 63% of strong and violent tornado cases in the region exhibited higher dewpoints along or north of a warm frontal or quasistationary boundary. This appears to be the case in the 20 June 1957 event. That is, the enhanced moisture (as well as vertical wind shear) in the vicinity of the boundary allowed the supercell to maintain an inflow of adequate boundary-layer moisture during its prolonged life cycle.

9. Conclusions

The Fargo F5 tornado of 20 June 1957 was a significant historic event. It is arguably one of the most well-documented and photographed tornadoes of all time, and propelled Fujita's interest in quantifying tornado damage. It is in part due to his extensive research of the Fargo tornado that the original F scale was developed. Fujita's intense study and photogrammetric work of the supercell's structure enabled him to coin the phrases collar cloud, tail cloud, and wall cloud that are widely used today. The Fargo tornado remains to this day one of only

two F5/EF5 events in North Dakota's history.

A complicating factor in examining the 1957 F5 Fargo tornado is the limited data that existed decades ago, forcing the authors to rely on observed surface and upper air data. However, the ample photographs of the Fargo storm, along with a present-day perspective of tornado research, allowed for additional insights to be gleamed from the observed data. Indeed, the analyses from this study are comparable with those from more recent events and contribute to our understanding of relatively rare and violent tornadic events.

In the case of the Fargo tornado, it appears that enhanced wind shear and instability in the presence of a well-defined surface boundary greatly influenced the tornado potential, much like many present-day studies suggest. It also appears that ET, in combination with focused moisture convergence, played a key role in augmenting local boundary-layer moisture in the days leading up to and during the event. Rain that had fallen in previous months likely provided needed moisture to growing crops into June of 1957. This enhanced boundarylayer moisture, coupled with both high bulk shear and SRF parameters, aided in the development of a longlived supercell. It is hypothesized that the supercell may have either interacted with or tracked along an outflow boundary. This may have contributed to the occurrence of several significant tornadoes, including an F5 that brought devastation to North Dakota's largest city - but not before many residents heeded a successful early warning and left.

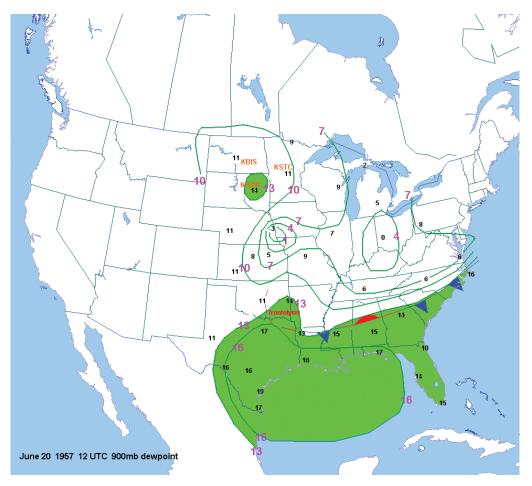


Fig 28. 900-hPa dewpoint observations at 1200 UTC 20 June 1957 (solid green contours and fill, $CI = 3^{\circ} C$) and subjective frontal analysis.

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