Maddox, R. A., M. S. Gilmore, C. A. Doswell III, R. H. Johns, C. A. Crisp, D. W. Burgess, J. A. Hart, and S. F. Piltz, 2013: Meteorological analyses of the Tri-State tornado event of March 1925. *Electronic J. Severe Storms Meteor.*, **8** (1), 1–27.

Electronic Journal of
SEVERE STORMS METEOROLOGY

Meteorological Analyses of the Tri-State Tornado Event of March 1925

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(Submitted 30 July 2012; in final form 30 March 2013)

ABSTRACT

Severe thunderstorms occurred across portions of the central United States on 18 March 1925. The deadly, long-track Tri-State tornado was the most publicized storm event of 18 March and remains the most significant single tornado in the nation's history. There has been only one formal paper regarding the Tri-State tornado and its meteorological setting. Several reports concerning the tornado and its setting had inaccurate surface analyses and incorrectly stated that the tornado had formed in cold air well west of a surface cyclone. Results are presented from a study of the event using all relevant Weather Bureau data that could be obtained. The storms of 18 March were associated with a rapidly moving, synoptic cyclone that was not unusually intense. New analyses indicate: a) the tornado was produced by a long-lived supercell that developed very near the center of the cyclone, possibly at the intersection of a warm front and a distinct dryline; b) the south-to-north temperature gradient ahead of the cyclone was very pronounced due to cooling produced by early morning storms and precipitation; c) the tornadic supercell tracked east-northeastward very rapidly [from ≈250 degrees at an average speed of ≈59 mph (≈26 m s^{-1})], moving farther away from the cyclone with time; and d) the storm remained very close to the surface warm front. It is likely that the tornadic supercell remained isolated from other storms throughout its life. There was no singular feature of the meteorological setting that would explain the extreme character of the Tri-State tornado; however, as the supercell and dryline moved rapidly eastward, the northward advance of the warm front kept the tornadic supercell within a very favorable storm environment for several hours. Apparently, this consistent time and space concatenation of the supercell, warm front, and dryline for more than three hours was extremely unusual.

1. Introduction

On 18 March 1925 the most significant tornado in the nation's history occurred. The tornado tracked from southeastern Missouri, across southern Illinois, and into southwestern Indiana. This event is referred to as the Tri-State tornado because of three states being affected. The tornado's path length has been reported as 219 mi (352 km) by Henry (1925), which is the longest continuous track on record (Grazulis 1993). The tornado's approximate path is shown in Fig. 1. The number of fatalities caused by the tornado was approximately 695, which remains the greatest death toll to occur with a single tornado (Changnon and Semonin 1966).

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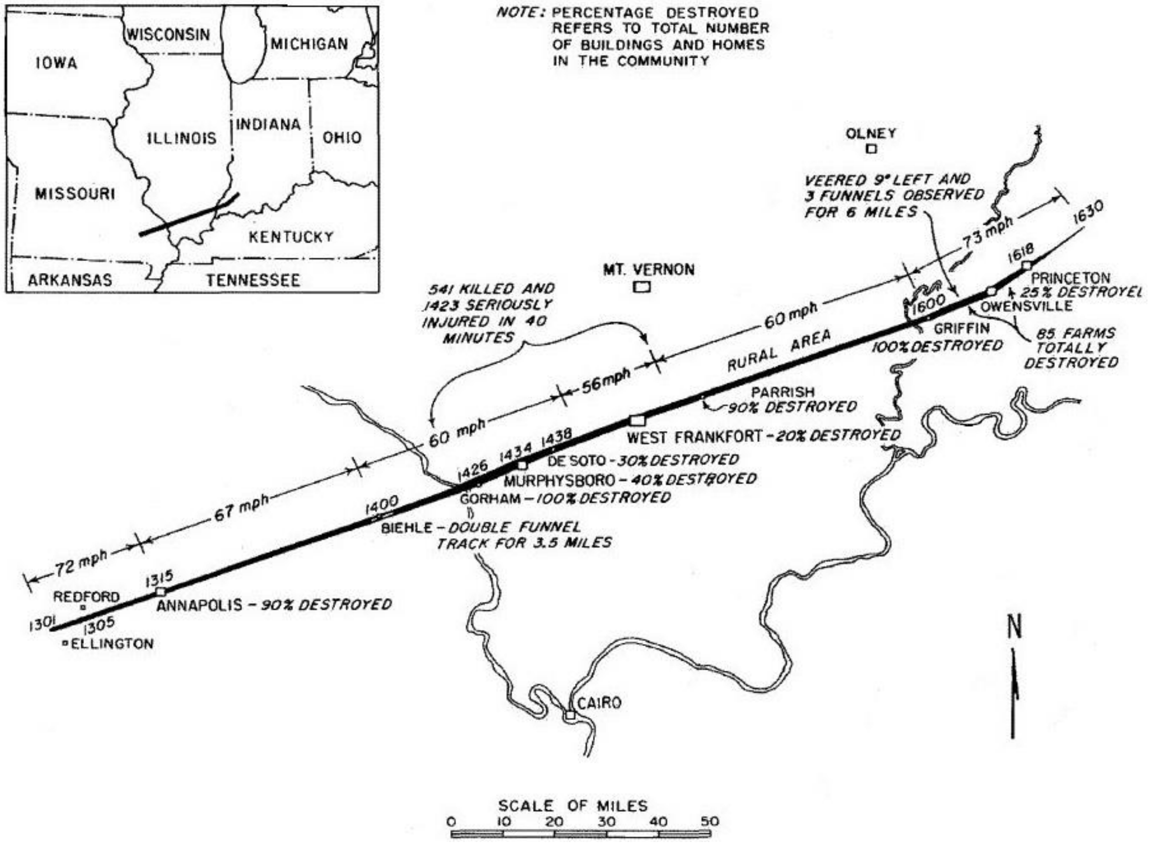

Figure 1: Track of the Tri-State tornado as published by Changnon and Semonin (1966). Speeds they deduced for the tornado's progression are shown, as well as various details regarding damage and fatalities along the track. *Click image to enlarge.*

Although a number of other tornadoes and severe thunderstorms occurred on 18 March, the focus through the years has been upon the deadly Tri-State tornado (e.g., Felknor 1992; Akin 2002).

Because of the authors' interests, as well as limited literature about this extreme event, a new study of the meteorological aspects of the Tri-State tornado, and the related severe weather outbreak, was undertaken even though 80 years had passed. The initial motivation was to examine the unusual synoptic setting and spatial relationships between the tornado and the associated surface low reported in the past. The scope of the study gradually expanded to consider possible reasons for the extremely long track of this tornado and to include fieldwork to attempt a new mapping of the damage path (Johns et al. 2013). This paper presents results from our examination of the meteorological conditions associated with the Tri-State tornado event.

2. Background

By the middle of the 19th century, the general population of the United States (U.S.) was well aware of the dangers of tornadoes (Galway 1985a). However, during the first half of the 20th century, the U.S. Weather Bureau (WB) did not try to forecast tornado events; in fact, the use of the word "tornado" in forecasts was explicitly banned (Galway 1992). Surface conditions that appeared to favor tornado occurrences had been studied during the late 1800s by the Signal Corps, particularly by Lt. Finley (Galway 1985a,b). However, efforts in the Signal Corps to forecast tornadoes had waned and were not carried into the WB of the early 1900s. Upper-air sounding systems were being developed during the 1920s and there was no way to study important tornado events, except by using surface observations. This situation would change little until after World War II (Galway 1992). The WB began severe-storm forecasting

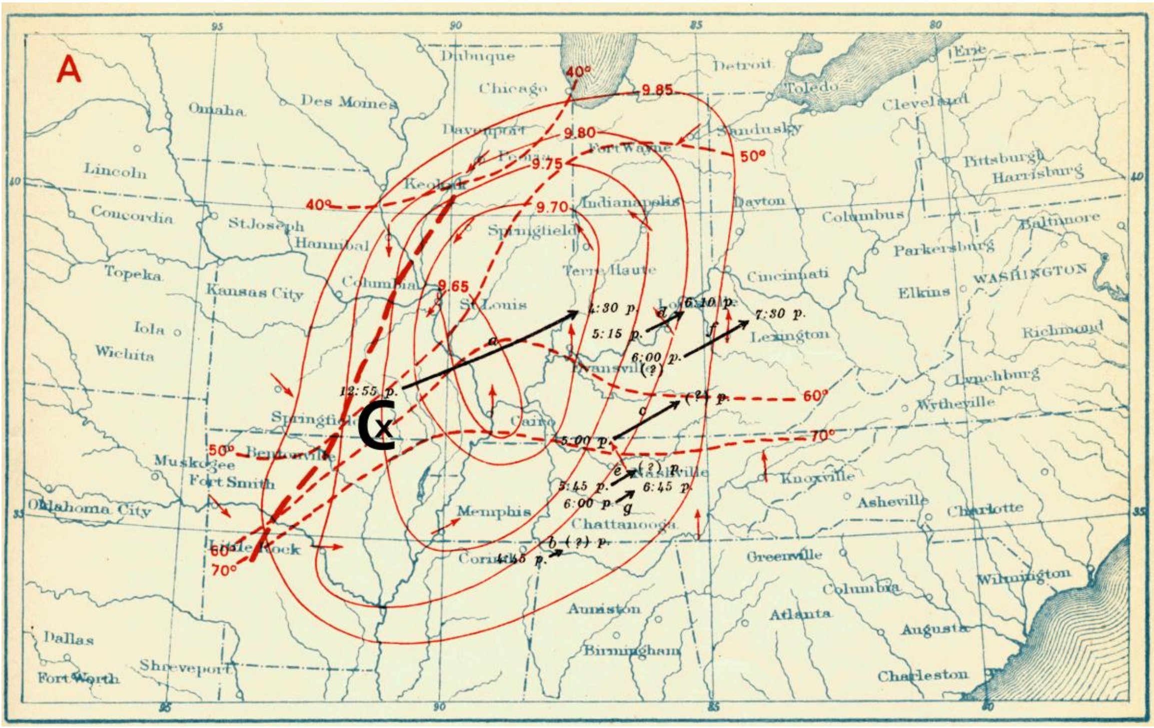

Figure 2: Surface chart for 1300 CST (1900 UTC) 18 March 1925, as published by Henry (1925). Surface wind directions are indicated by red arrows; isotherms (10s of degrees F) are dashed lines; and isobars (in Hg, labeled with leading "2" not shown) are solid lines drawn at 0.05 in Hg (1.7 hPa) intervals. Tracks of all tornadoes documented on the 18th by the WB are indicated by the black arrows, with start and end times. It is not known what the heavy, dashed red line was meant to indicate. The black "C" and "X" have been added to the figure to indicate where Henry stated that the cyclone associated with the tornado was located at 1300 CST. *Click image to enlarge*.

in the 1950s. There were a large number of studies done for severe local storms during the early 1950s (Galway 1992), and significant research continues to the present. However, there has been little research exploring possible reasons for the Tri-State tornado's unusual severity and very long path length.

The fields of synoptic and mesoscale meteorology have advanced tremendously since 1925, as has the understanding of severe thunderstorm structures and tornadoes. The Norwegian cyclone model and frontal concepts were being developed in the 1920s (e.g., Bjerknes and Solberg 1922), and there had been a failed attempt to convince the WB to use frontal analysis techniques in 1926 (Namias 1980). The supercell thunderstorm was identified as an important, distinct type of deep, moist convection during the early 1960s (Browning 1962), and the Tri-State tornado was produced by a long-lived, supercell thunderstorm (Johns et al. 2013). Interested readers can find overviews of modern knowledge of tornadoes and supercells in Church et al. (1993) and in Doswell (2001). Because long-track tornadoes are extremely rare (Section 5e), there is no focus on conditions associated with such events in either monograph.

The one paper published in the formal scientific literature regarding the Tri-State tornado was by Henry (1925), which appeared in the April 1925 issue of *Monthly Weather Review*[1], shortly after the event. Henry's 1300 Central Standard Time (CST[2], referred to by the WB in 1925 as "90th meridian time") surface analysis is shown in Fig. 2. This chart indicated

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[1] Alfred J. Henry was a Principal Meteorologist at Weather Bureau Headquarters, Washington, D. C., in 1925. His primary assignment at that time was as Editor, *Monthly Weather Review*, then published by the WB.

[2] UTC = CST + 6 h; CST is used hereafter for brevity.

that the center of lowest pressure was about half way between Cairo, Illinois (IL) and St. Louis, Missouri (MO). At this time the tornado had just begun, well to the west-southwest of the center of observed lowest pressure, in a region where Henry's analysis indicated surface temperatures as low as 50°F (10°C). The observed station winds, however, indicate a cyclonic circulation centered somewhere in southeastern Missouri. Indeed, Henry noted the following:

"The center of the cyclone at 1 p. m., 90th meridian time, was probably 100 miles or thereabouts west-southwest of Cairo, possibly in Ripley County, Mo., or 40 miles south of Reynolds County, where the tornado was first seen."

The difference between the surface isobars and Henry's description of where the cyclone probably was located seems strange (the original figure has been modified to show the approximate cyclone location that Henry described). He apparently considered the observed winds and concluded that there was a cyclonic circulation centered west of Cairo. The fact that the pressure analysis indicated a different location for the lowest pressure was apparently not of concern for WB synoptic analysts in 1925. Henry realized that the cyclonic circulation west of Cairo was directly associated with the Tri-State tornado. Namias (1980) commented on the backward state of the WB in the 1920s and noted that Chief Forecasters worked with a series of surface charts that each showed a synoptic plot of a different weather element. This complicated procedure may partially explain the lack of consistency between the observed winds and the pressure analysis.

Changnon and Semonin (1966) redid the WB 0700 CST synoptic chart and Henry's afternoon surface analyses, adding frontal features, for their article in *Weatherwise* magazine. In their version of the 1300 CST surface chart (Fig. 3), they showed a simplified chart that did not include plots of the actual surface observations. The figures in their article indicate that the Tri-State tornado developed far to the west of the cold front and the surface low pressure center. It appears that Changnon and Semonin used Henry's isobar analysis to define the cyclone and fronts, while neglecting winds and temperatures. They also lowered surface pressures drastically (apparently based solely on a barograph trace from the edge of the tornado damage path through West Frankfort, IL). Their surface isobars are seriously in error, disagreeing markedly with Henry's charts and with the WB surface observations across the region. Their low-pressure bias was nearly equal to the difference between the background pressure and the low-pressure spike observed with the tornado. The surface charts shown in Changnon and Semonin have been reproduced in a number of other publications (e.g., Akin 2002).

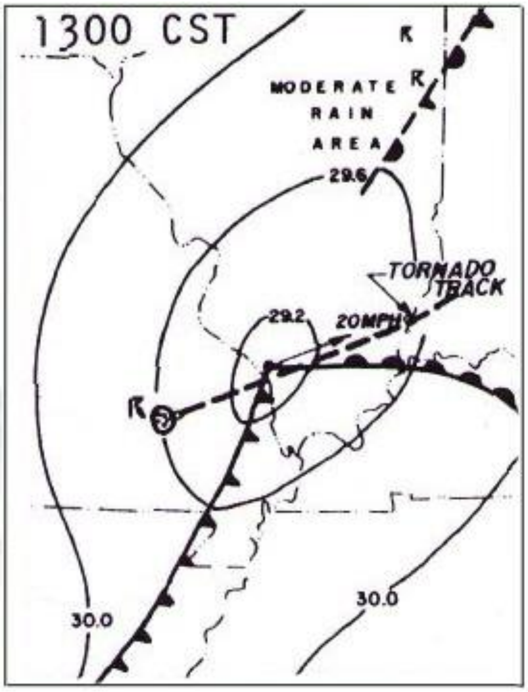

Figure 3: The 1300 CST surface analysis as published by Changnon and Semonin (1966). They added fronts and weather symbols and their isobars were drawn at intervals of 0.40 in Hg (13.5 hPa). *Click image to enlarge*.

Changnon and Semonin concluded that the tornado moved very rapidly, with the synoptic low and tornado becoming collocated by about 1500 CST, as the tornado overtook the leading, low pressure center. They hypothesized, without explanation, that this unusual interaction between the tornadic thunderstorm and the synoptic cyclone might have been the cause for the tornado's intensity and long duration. This sequence of events is unlikely, within the context of the body of work that forms our current understanding of supercells (e.g., Browning 1964; Barnes 1970; Marwitz 1972), tornadic thunderstorms (e.g., Showalter and Fulks 1943; Browning and Donaldson 1963; Fujita 1965), and their synoptic settings (e.g., Fawbush and Miller 1954; Beebe and Bates 1955; Miller 1959; Miller 1967; Galway 1977).

3. Observations and methodology

During the 1920s, the WB was an agency of the Department of Agriculture. Because of this, surface observing procedures, and reporting of significant weather events, had evolved primarily to support agriculture operations and climatological studies. There were many differences between procedures used in the 1920s versus synoptic and aviation observation procedures during the middle to late 20th century. The procedures used for WB observations[3], and forms analyzed in the reconstruction of surface charts for the Tri-State study, are summarized here.

The WB had no official severe thunderstorm forecasting or reporting procedures during the first half of the 20th century. If a tornado was reported within 25 mi (40 km) of a WB office, the official-in-charge was supposed to investigate and report his findings as part of the station's monthly record. Storms that produced hail were usually noted in WB records, but hail was typically categorized as light, moderate, or heavy, based upon the degree of crop or property damage that had occurred.

Comprehensive surface observations were taken at primary WB offices only twice per day, at 0700 and 1900 CST. These observations included temperature and dewpoint, station pressure, surface pressure reduced to sea level (SLP), and a 5-min average wind (observed any time within 20 min of the hour), as well as weather and sky conditions. Unfortunately, surface wind directions were observed only to an eight-point compass (north, northeast, east, etc.).

The WB did its first reanalysis project during the early 1940s (U.S. Weather Bureau 1944; Namias 1980) and produced 0700 CST surface charts that depicted frontal features, as well as pressure analyses. These reanalyzed surface charts are useful for documenting the large-scale features that moved across the U.S. and Canada during the days surrounding the Tri-State event, and will be discussed in the next section.

a. Observational forms used

Copies of many WB forms were obtained from the National Climatic Data Center (NCDC) through hardcopy data requests and from their online archives. We were able to obtain copies of WB surface observation Forms 1001 and 1014 for many stations in the central U.S., and these have provided the bulk of the data analyzed. We also obtained copies of original barograph and thermograph traces for a number of WB stations located near the path of the surface low and the track of the tornado. Cooperative observer climatological reports also have been used. The WB was taking a limited amount of upper-air data in 1925, during kite and pilot balloon (pibal) flights, and we obtained some of these data from three stations: Groesbeck, TX; Broken Arrow, OK; and Royal Center, IN. We also located data from a single pibal flight at Memphis, TN. These upper-air data were considered in the study.

The 13-page WB Form 1001 was used primarily to record the 0700 and 1900 CST synoptic observations, other parameters, and to summarize key aspects of the station's weather. These forms were prepared monthly and were most complete for major WB stations (e.g., St. Louis, MO, or Indianapolis, IN). Many smaller stations (e.g., Cairo, IL, or Terre Haute, IN) only completed some of the pages of the Form 1001. Many stations reported hourly average winds on the form and some reported the observed temperature at the top of each hour. Some stations recorded their 1001 observation only at 0700 or at 1900 CST. Most stations did take a special noon observation that included the temperature and the dewpoint (thus, information on the surface dewpoint was available, at most, for three times during a given day). These special observations were taken at solar noon (1200 local mean time) and are asynchronous data.

A single-page form, WB Form 1014, was completed daily at most stations, to record hourly temperature, wind, cloud cover, and precipitation observations. A local noon observation, a summary of the day, and comments regarding local weather such as thunderstorms, hail, extreme winds, etc. were also recorded. The beginning and ending times (to the minute) of precipitation and its type were

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[3] Observing procedures of the WB during the 1920s were described in a document we obtained, "Instructions for Preparing Meteorological Forms, Climatological Division." We used pages 3–17 of this document. The first few pages were missing and we were unable to find a complete copy. The document we used was bound with WB forms from 1925 and was found at the Cairo, IL, Public Library.

noted on both 1001 and 1014 forms (many stations were not staffed through the night, leading to situations where the beginning or ending time was recorded as "unknown"). The times of occurrence of thunder sometimes were noted on the 1001 monthly summaries, but were recorded more frequently on the 1014 forms. Barograph and thermograph traces were included as part of this form. Generally, the information on the WB Form 1014 was more detailed than that entered on the 1001 (the local 1014 forms were used to prepare the 1001 forms, which were mailed monthly to WB Headquarters in Washington, D. C.).

Winds reported on the surface observation forms were hourly-averaged speed (mph) and eight-point compass direction (except at 0700 CST and 1900 CST as noted above). The hourly average winds included a notation if the maximum, 5-min average speed, during a given hour, exceeded a specific threshold. The thresholds were determined based on station climatology and differed from site-to-site. Nevertheless, specific information on high wind speeds proved useful, especially since some observers noted the time and direction. Additionally, an extreme wind speed was recorded for each day. The extreme wind was defined as the speed of the fastest mile of air flow [i.e., an average wind of 60 mph (27 m s^{-1}) for 1 min equals 1 mi (1.6 km) of air flow] observed during the day. Again, some observers would note the time and direction of the extreme wind.

The difference between information reported on the two WB surface observation forms can be illustrated by comparing the hail reported at Lexington, KY, on 18 March 1925. The form 1001 reports only that hail occurred on that day; whereas, the 1014 form reports that there were four separate thunderstorms during the day and that around 1915 CST hail fell in Lexington with a circumference of up to 4.5 in (11.4 cm). In contrast, the 1014 form for Columbia, MO, illustrates extreme inconsistencies in reporting detail among various WB stations. This form reports only that thunderstorms occurred from 0718–1915 CST on the 18th, providing no details on when individual storms actually occurred at the station.

We were able to obtain both of these forms for about 70% of the WB stations in the central U.S. Since the 1014s were primarily for local use, most of them were not archived at NCDC. Many of these forms were located during field trips by some of the authors to National Weather Service (NWS) offices, local libraries and university libraries in the primary study area (Missouri, Illinois, and Indiana). Postal mail, e-mail, and electronic queries and searches also were used.

b. Methodology

Converting the various WB surface observations to synoptic-like plots was difficult, given the averaged or asynchronous character of much of the data. The surface observations for 18 March were plotted on charts in as high detail as possible from 0700–1900 CST (at 3-h intervals and at each hour during the period of the tornado). The averaged wind masks changes during each hourly period and determining the precise time of wind shifts is not possible. The times of wind shifts and/or significant speed changes rarely were noted on the forms. Temperature was observed at the hour. The beginning and ending times for precipitation allowed determination of whether precipitation was falling at the top of each hour. Dewpoints could be plotted only at 0700 and 1900 CST, and on the complicated noon chart.

The surface charts were plotted essentially as a synoptic chart is today. We were able to find observation forms for more stations than were plotted on the WB surface charts, and analyzed more detailed charts than have been examined previously for this event. The temperature and pressure (when available) and current weather were plotted at the station locations. The winds were considered representative of conditions at the half hour[4], and were space-shifted relative to the station location using the translation vector

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[4] The WB's use of hourly average winds makes synoptic analysis difficult. Consider an hour during which there was a change in direction (e.g., from southeast to southwest). If the wind shift occurred before the half hour, then the hourly average wind direction would be southwest, but if the shift occurred after the half hour then the average direction would be from the southeast. For most hours, the average wind direction would best represent the wind at the half hour. Changes in speed during an hour were only reflected in the average speed. Obviously, caution must be used in interpreting the winds reported on the WB forms of 1925.

of the synoptic cyclone [i.e., from 235° at 48 mph (21 m s^{-1})]. Two winds were plotted on these charts: the average wind for the hour ending at the time of the map was plotted 24 mi (39 km) to the northeast of the station, and the average hourly wind for the next hour was plotted 24 mi (39 km) to its southwest.

The determination of approximate SLP was the most difficult challenge the 1925 data presented. Each WB station had a specific set of tables and adjustment charts to use in reducing station pressure to sea level. These charts and tables have not survived in the data archives. Station SLP was estimated for the sites for which a barograph trace was available. We had hard copies of the original barographs for 17 stations along the track of the surface low, and the 1014s for other stations also had barograph traces. Additionally, we had to have the 0700 and 1900 CST observations, which included both the SLP and the recorded barograph pressure. The SLP correction relative to the station barograph trace was noted for 0700 and 1900 CST. These corrections then were interpolated linearly across the intervening 11 h and applied to the hourly barograph readings. This procedure results in an estimated SLP that does not reflect actual, nonlinear, intervening temperature trends. Nevertheless, analyses of the resulting pressure fields were consistent and displayed reasonable time–space continuity, indicating that the estimated SLPs are probably accurate to within ±1 hPa.

The surface plot for "noon" was complicated, since there were observational data for both 1200 CST and noon local mean time. The plotted chart used the procedures described above for LST observations of weather, winds, and SLP. However, the local mean noon temperature and dewpoint were plotted at each station. This produces a chart that has asynchronous data mixed with synoptic data. The time difference of the local mean noon observations (4 min per degree of longitude) is only significant far from the 90th meridian. Since the important features at noon were close to the 90th west meridian (the longitude of Memphis, TN), this approximation had minimal impacts on the accuracy of the noon analysis.

Detailed meteograms were constructed for all the reporting stations surrounding the region where the synoptic low and the tornado tracked. The event occurred across a region that was, and remains, relatively devoid of surface observation sites (i.e., southern Missouri, southern Illinois, and southwestern Indiana). The only WB station in 1925 that was located relatively close to the tornado track was Evansville, IN, about 25 mi (40 km) south of the track and near the end of the damage path. Cairo, IL, was a bit more than 50 mi (80 km) south of the tornado track when the tornado was just east of De Soto, IL (Fig. 1), and Terre Haute, IN, was about 70 mi (113 km) north of the end of the tornado track. The meteograms were used to establish continuity for the fast-moving, synoptic cyclone and associated features. These plots also facilitated extrapolation of the analyses into the data void.

4. Synoptic conditions

The late winter and early spring of 1925 had been unusually warm and dry over most of the central U.S. The tracks of cyclones for March 1925 (Fig. 4), from *Monthly Weather Review*, appear to indicate a mean ridge along the west coast, with a broad trough over central portions of the country. The path of the synoptic cyclone (labeled VIII) eventually associated with the Tri-State tornado began in northwestern Montana and then moved south-southeastward to northern Oklahoma. The cyclone then turned eastward and northeastward and accelerated across the eastern Great Lakes region and into Canada.

In retrospect, it is likely that a short-wave trough in the middle and upper troposphere approached the northwest coast of the U.S., moved rapidly through the top of the persistent ridge, and then tracked southeastward across the northern Great Basin and central Rocky Mountains. The lowest surface pressures, within a lee trough east of the mountains, gradually shifted southward as the short wave approached Colorado. Our analyses (not shown) indicated that the surface low and a distinct cyclonic circulation developed in the classic "Colorado Low" genesis region of southeastern Colorado (Hosler and Gamage 1956; Whittaker and Horn 1981). The cyclone moved eastward onto the southern Plains as the short-wave trough crossed the mountains. Recent upper-air reanalyses support this hypothesized scenario—see Appendix A.

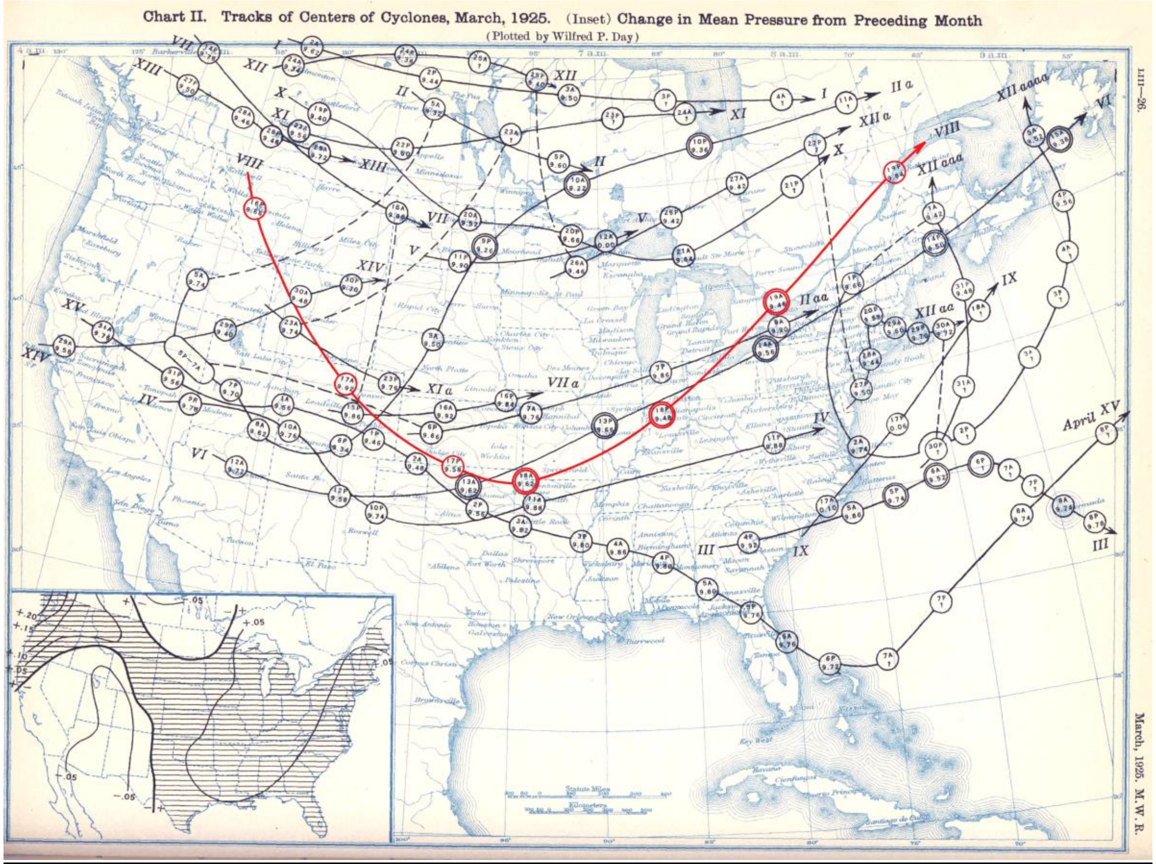
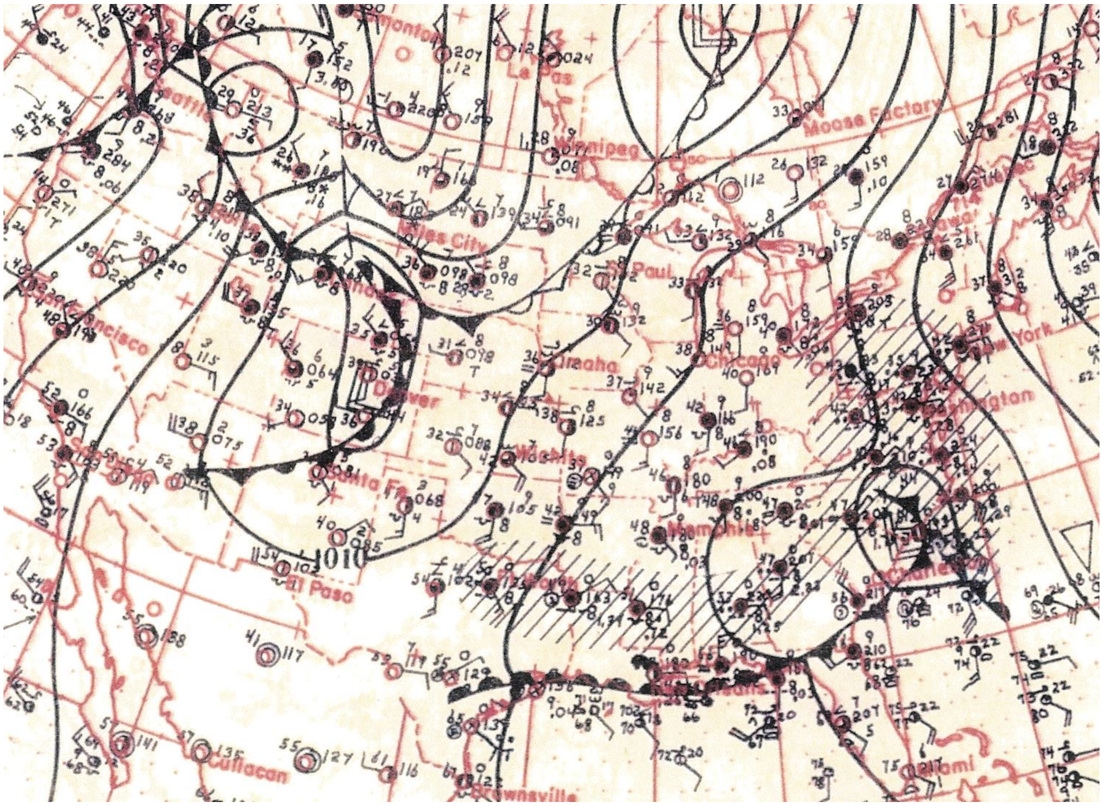


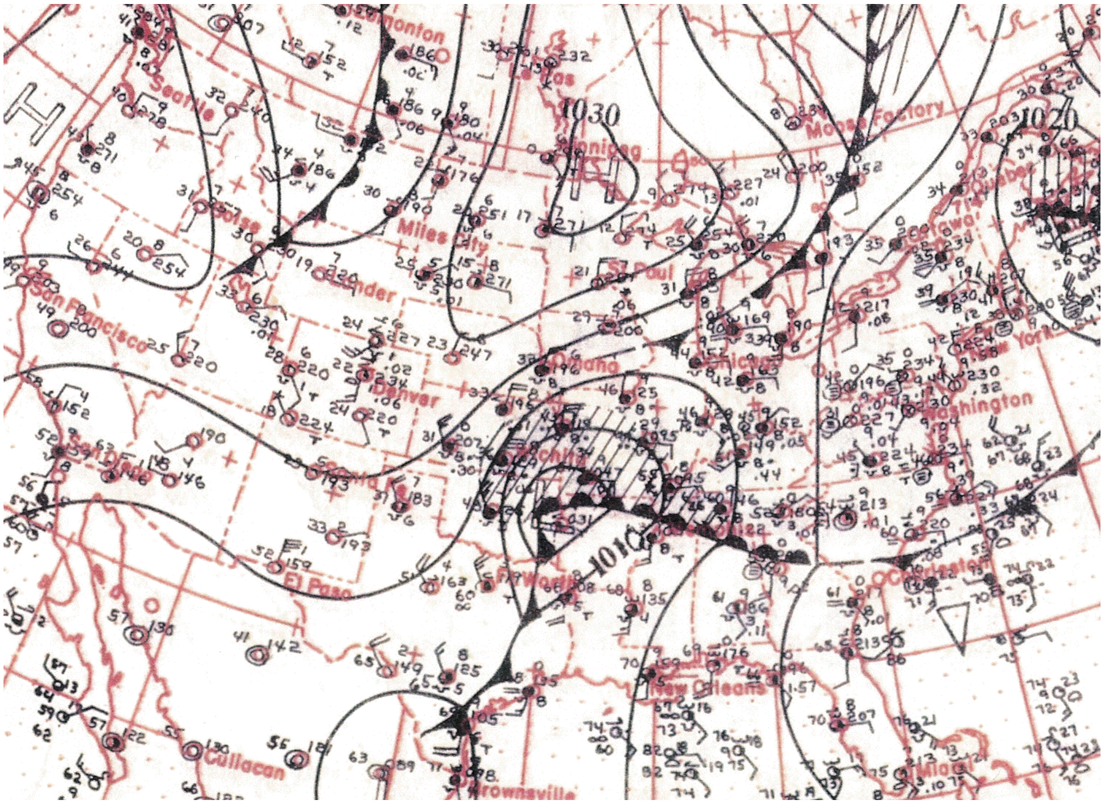
Figure 4: Tracks of surface cyclones for March 1925, from the March 1925 issue of *Monthly Weather Review*, as determined by the WB. The track of the cyclone associated with the Tri-State tornado has been highlighted in red. Pressures shown on this figure are in Hg and are missing the leading "2". Times in circles are: "A" for 0700 CST and "P" for 1900 CST. Meaning of the double circles is not known. Inset shows change in average monthly pressure (in Hg) from February to March 1925. *Click image to enlarge.*

Surface charts for 0700 CST, reanalyzed by the WB for this period, are presented in Fig. 5. The lowest pressure at 0700 CST on 17 March (Fig. 5a) was at Denver, CO, within a typical lee trough. No distinct cyclonic circulation was present in the observed surface winds, although cyclogenesis likely was occurring over southeastern Colorado. Occluded fronts were indicated from Hudson Bay southwestward across the northern Plains and within the lee trough. A warm front along the Gulf Coast lay south of a large area of damp, foggy, and showery weather that stretched from northern Texas to the Carolinas. Our surface analyses (not shown) indicated the presence of early-season, continental tropical (cT) air over western Texas and northern Mexico. At 1900 CST on the 17th El Paso, TX, reported a temperature of 73°F (23°C) and a dewpoint of 2°F (–17°C), while Abilene, TX, had 81°F (27°C) with a dewpoint of 6°F (–14°C). To the east and northeast of this hot, dry air mass, maritime tropical (mT) air was advected northward behind the warm front into eastern Oklahoma and northwestern Arkansas during the 17th. The surface low moved eastward during the night, passing just to the north of Oklahoma City, OK.

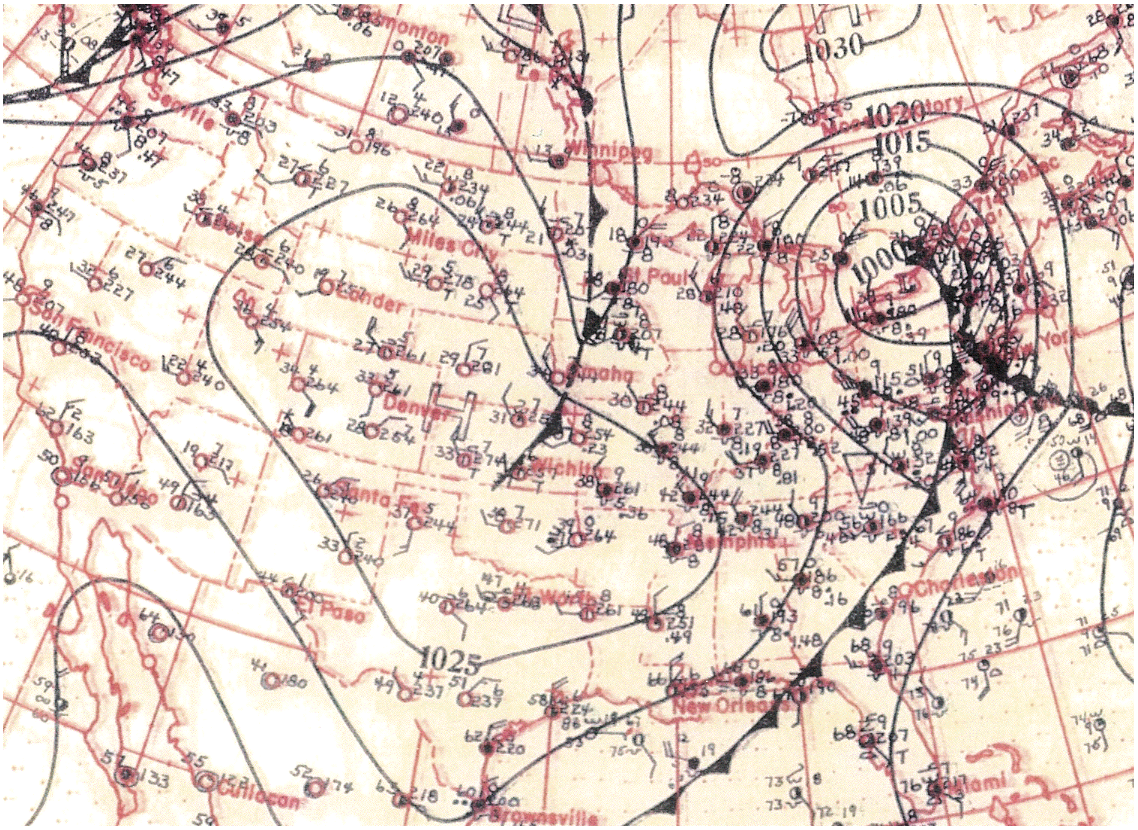
By 0700 CST 18 March, the surface low had moved to northeastern Oklahoma (Fig. 5b) and the warm front had moved northward into its circulation. The analysis indicates a Pacific cold front across eastern Texas; however, the actual frontal position is difficult to determine because of the presence of cT air (i.e., a dryline) ahead of the maritime Pacific (mP) air mass, a typical spring situation over the southern Plains. The synoptic situation was further complicated by the fact that the short-wave trough at 500 hPa, and the associated Pacific front, had traversed the mountain states from northwest to southeast.



(a) 17 March



(b) 18 March



(c) 19 March

Figure 5: Reanalyzed surface charts for 0700 CST on: a) 17, b) 18, and c) 19 March 1925. Frontal features are shown and isobars are in hPa. Copies of these WB maps were obtained from the Dept. of Commerce, Boulder Labs Library. *Click each image to enlarge.*

The mP air likely underwent considerable subsidence before it moved onto the southern Plains. The maritime mP air was not easily distinguished from the cT air by either temperature gradients or wind shifts. [Doswell (1982) and Sanders and Doswell (1995) discuss the problems of surface analysis when a dryline is involved.] To the northeast, the old occlusion had moved slowly southward across the Great Lakes region and extended southwestward toward the cyclone.

An area of early morning thunderstorms and rain had developed north of both the cyclone and the warm front from southeastern Kansas eastward to Kentucky and Indiana. Rain-cooled air north of the warm front would play an important role in the evolution of subsequent weather events. The first severe thunderstorms of 18 March already had occurred during the pre-dawn hours over southeastern Kansas, where several storms produced damaging hail and possibly a tornado. During the early morning hours, cooperative observers reported thunderstorms and hail (size unknown) over far northeastern Oklahoma. These nocturnal and early-morning storms likely occurred within a layer of lower-tropospheric warm advection north and northeast of the surface low.

By 0700 CST on the 19th (Fig. 5c) the surface low had deepened and moved rapidly northeastward into southern Canada. During the 18th, colder air from Canada and the western Great Lakes region advected southward into the cyclone's circulation, resulting in periods of snow and sleet from eastern Iowa into central Michigan. The WB positioning of the Pacific cold front was complicated by a squall line that had developed late on the 18th and moved eastward ahead of the front. It appears that the cold front indicated on this figure was actually the position of the prefrontal squall line.

The thunderstorm outbreak of 18 March was associated with a synoptic cyclone whose central pressure was around 998 hPa during the period of intense storms. The strength of this low pressure system was not similar to, for example, the surface lows associated with the Palm Sunday tornadoes of 1965 (U.S. Weather Bureau Survey Team 1965) and the 3–4 April 1974 tornado outbreak (Hoxit and Chappell 1975). These surface lows had central pressures of about 983 hPa, almost 15 hPa deeper than the low associated with the Tri-State tornado event. However, pressure gradients near the core of the Tri-State cyclone were strong from the morning of the 18th to the morning of the 19th. Surface winds on the afternoon of the 18th reached speeds (i.e., fastest mile) of 66 mph (30 m s^{-1}) at Cairo, IL, and Evansville, IN, as the low moved by to the north. Wind speeds at Buffalo, NY, reached an extreme, fastest mile of 84 mph (38 m s^{-1}) on the morning of the 19th.

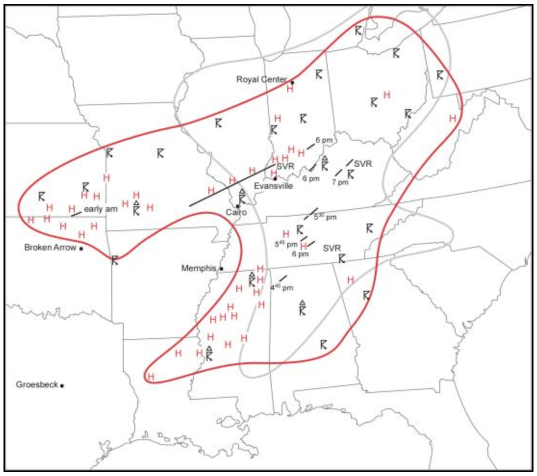


Figure 6: Area of thunderstorms and hail on 18 March 1925 (red line) from WB forms, *Monthly Climate Summaries* by state, and WB cooperative observer reports. Weather symbols indicate approximate locations of reported thunderstorms and hail. Known severe thunderstorms are marked "SVR". Black lines indicate tornado tracks with approximate times [as per Henry (1925), except that two new tornadoes, from Johns et al. (2013) and the Kansas *Climate Summary* for March 1925 have been added]. Tornado tracks have been modified slightly based on newspaper reports and Grazulis (1993). Several key WB stations are shown. The gray line indicates the extent of the 3–4 April 1974 outbreak. *Click image to enlarge.*

The Tri-State tornado has been the focus of attention over the years; however, a number of other destructive tornadoes occurred (Fig. 6). There were numerous reports of hail on this day and some thunderstorms produced high winds. The general area experiencing thunderstorms (many known to have been severe) and hail (sizes mostly unknown) extended from southeastern Kansas eastward to western Ohio and southward to portions of Louisiana, Mississippi, Alabama and Georgia. Had there been systematic documentation of severe thunderstorms in 1925, the overall Tri-State tornado and severe thunderstorm event would have been considered a widespread outbreak. The area of the 3–4 April 1974 tornado outbreak is indicated on Fig. 6 for comparison.

5. New analyses

Surface maps, plotted as described in Section 2, have been analyzed and are considered relative to the conditions and features associated with the long-track, Tri-State tornado. The synoptic cyclone, the supercell, and the tornado moved across a data-void region, complicating analysis efforts. Also considered in this section are barograph traces and detailed meteograms.

a. Surface charts

Seven members of our research team independently analyzed surface charts for the critical period from 1200–1700 CST. The spread of the individual results was fairly substantial and is discussed in Appendix B. The figures shown in this subsection represent one possible interpretation of the observations.

At 0700 CST (Fig. 7) the surface low, with central pressure ≈1003 hPa, was located in extreme northeastern Oklahoma. A dryline and cold front extended southward and southwestward from the low, but the exact positions are difficult to determine—a common situation as described by Doswell (1982). A warm front extended eastward from the low. An area of rain and thunderstorms was north of the surface low and the warm front. A mesoscale outflow boundary appeared to have moved slightly south of the warm front over northwestern Tennessee and northeastern Arkansas. The cool air sector over the north-central U.S. exhibited a number of weak pressure troughs, and the overall analysis was quite complicated. Moist mT air with surface dewpoints of 60–65°F (~16–18°C) extended northward to the warm frontal zone. The overall situation is typical of synoptic settings conducive to springtime severe thunderstorms (e.g., a synoptic type B pattern, as per Miller 1967).

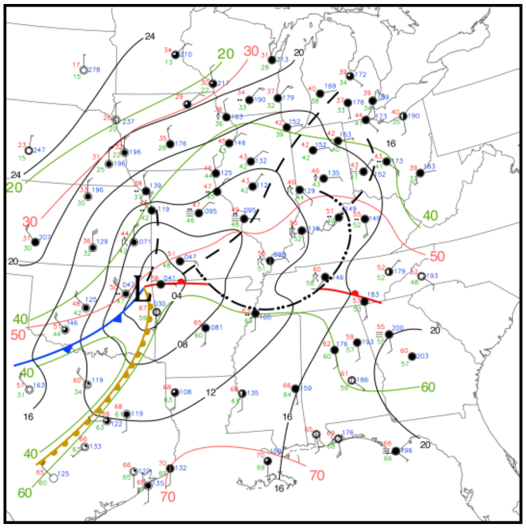


Figure 7: Newly analyzed 0700 CST surface map for 18 March 1925. Fronts and dryline are indicated by standard symbols, along with pressure troughs (dashed) and mesoscale outflow boundary (dash with double dots). Pressures and isobars are in hPa, winds are in mph and directions are to an eight-point compass, temperatures are in °F. Isotherms at 20°F intervals are red and isodrosotherms at 20°F intervals are green. *Click image to enlarge.*

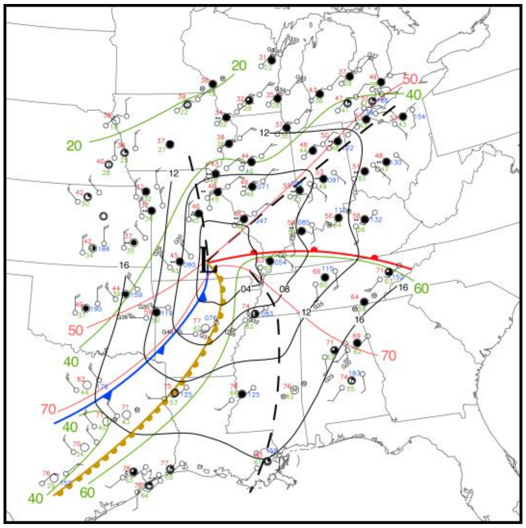


Figure 8: Newly analyzed local noon/1200 CST surface map. Details as in Fig. 7. The double wind plots are explained in the text. *Click image to enlarge.*

By 1200 CST (Fig. 8) the synoptic low had deepened and moved into the data void over southern Missouri. This surface plot combines special local-noon observations of temperature and dewpoint with the 1200 CST observations of SLP, winds and weather. The time offsets are not significant near the synoptic cyclone. The dryline was moving rapidly eastward immediately south of the surface low, while the cold front and dryline remained difficult to identify and position across Texas. The warm front, with dewpoints ≥60°F (~16°C) along and to its south, had moved northward, and extended directly eastward from the surface low. A pronounced pressure trough extended northeast of the low and indicated the general path the low would follow over the subsequent 12 h. The Tri-State tornado developed near the triple point at the surface low, dryline and warm front intersection—a favored position for tornadic storms (Moller 2001).

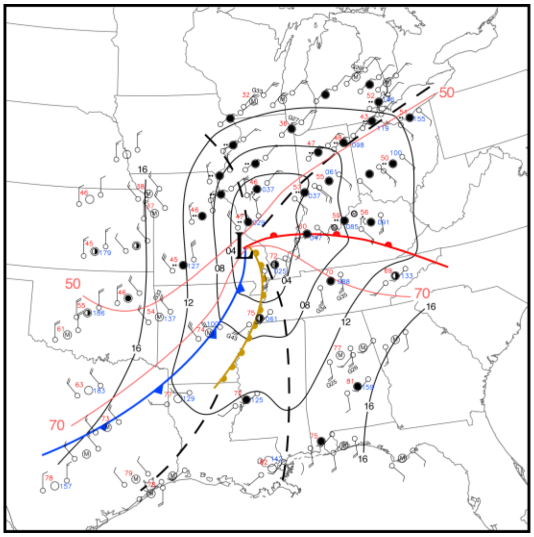


Figure 9: Newly analyzed 1400 CST surface map. Details as in Fig. 7, but double wind plots as in Fig. 8. *Click image to enlarge.*

The supercell was near the Mississippi River at 1400 CST (Fig. 9), and the tornado had just struck the small town of Biehle, MO (Fig. 1). As determined from continuity of the new surface analyses, the synoptic low was tracking about 15° to the left of the tornado track. The supercell and tornado moved toward the east-northeast (from ≈250°) at ≈59 mph (26 m s^{-1}), about 11 mph (5 m s^{-1}) faster than the synoptic low. The supercell was moving east-northeastward within the warm front's baroclinic zone; the temperature difference from St. Louis, MO, to Cairo, IL, was 25°F (14°C) across a distance of about 140 mi (225 km). Baroclinic zones have been shown to be favorable for strong tornadoes (Maddox et al. 1980; Markowski et al. 1998; Rasmussen et al. 2000).

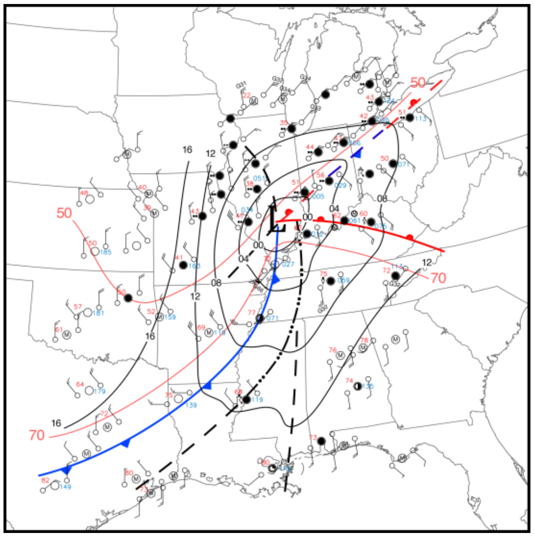


Figure 10: Newly analyzed 1600 CST surface map. Details as in Fig. 9. *Click image to enlarge.*

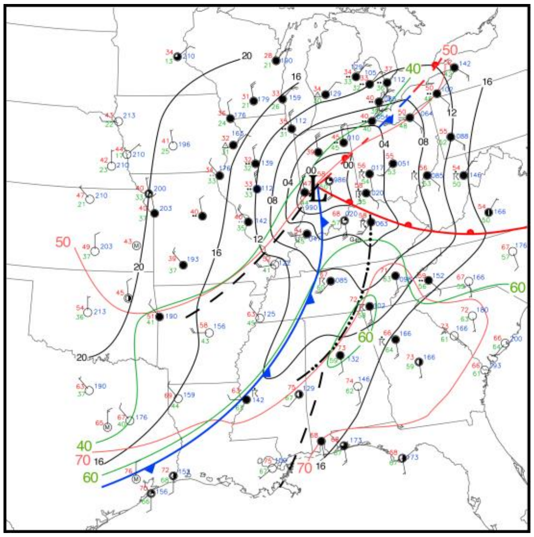


Figure 11: Newly analyzed 1900 CST surface map. Details as in Fig. 7. *Click image to enlarge.*

By 1600 CST (Fig. 10) the synoptic low had deepened to near 998 hPa and was over southern Illinois. The supercell and tornado had remained in the "sweet spot" along the baroclinic zone of the warm front and had just moved into Indiana. Strong thunderstorms had developed within the warm sector and the dryline was coincident with a line of severe thunderstorms. At 1900 CST (Fig. 11) the synoptic low was near Indianapolis, IN. Numerous thunderstorms were occurring east and south of the low center, and a line of storms was moving into the southeastern U. S.

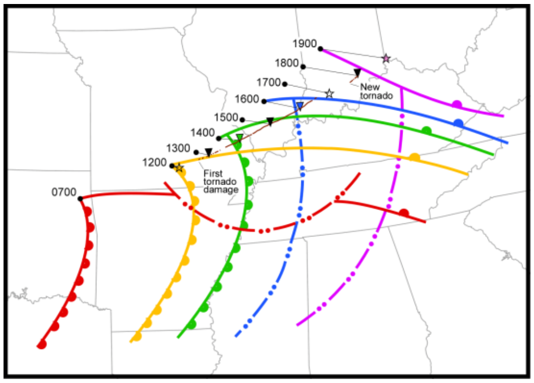


Figure 12: Positions of the synoptic low (black dots: 0700, 1200–1900 CST) and boundaries adjacent to the warm sector (dryline, warm front, and convective outflows) are shown. The Tri-State tornado (colored triangles) and extrapolated supercell positions (stars; 1200, 1700 and 1900 CST) are indicated. The tornado track, traced from the data points in Johns et al. (2013), is in dark brown. A thin black line connects the synoptic low pressure center and the tornado (or extrapolated supercell) position at each time. Supercell positions at 1200, 1700, and 1900 CST were estimated using the average speed of the tornado. Only a portion of the outflow boundary is shown for 0700 CST. *Click image to enlarge.*

A continuity chart, shown in Fig. 12, was constructed using the new surface analyses from 0700 CST through 1900 CST. The chart also shows estimated positions (at 1200, 1700, and 1900 CST) of the supercell associated with the tornado. Continuity indicates that the tornado, because of its different track and faster movement, advanced farther away from the synoptic low during the afternoon. However, the supercell, and associated tornado, remained very near the warm front through their lifetimes. An analysis of reported maximum temperatures on 18 March (Fig. 13) shows that the long-lived supercell and tornado had moved east-northeastward within a substantial baroclinic zone.

The pre-existing, mesoscale pool of rain-cooled air had slowed the northward motion of the synoptic-scale warm front, helping to maintain the strong temperature gradient. Maddox et al. (1980) noted that tornadoes moving along preexisting thermal boundaries tended to have longer tracks. Markowski et al (1998) reported that during the VORTEX field program, nearly 70% of the significant tornadoes

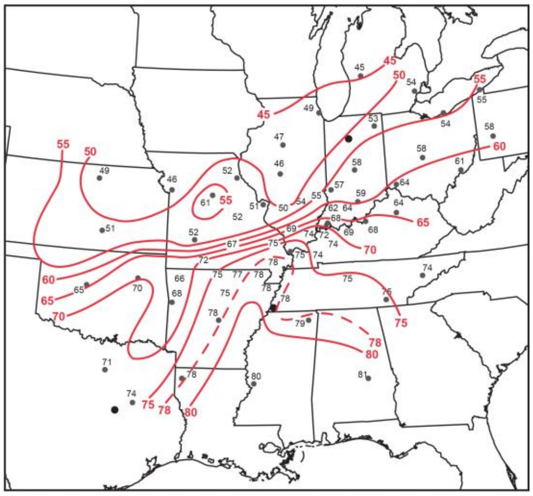


Figure 13: Maximum temperatures (°F) observed on 18 March 1925, contoured at 5°F intervals. Temperature reports from WB forms (small circles are WB stations, larger circles are WB aerological stations), *Monthly Climate Summaries* by state, and WB cooperative observer reports (plotted at approximate sites). *Click image to enlarge.*

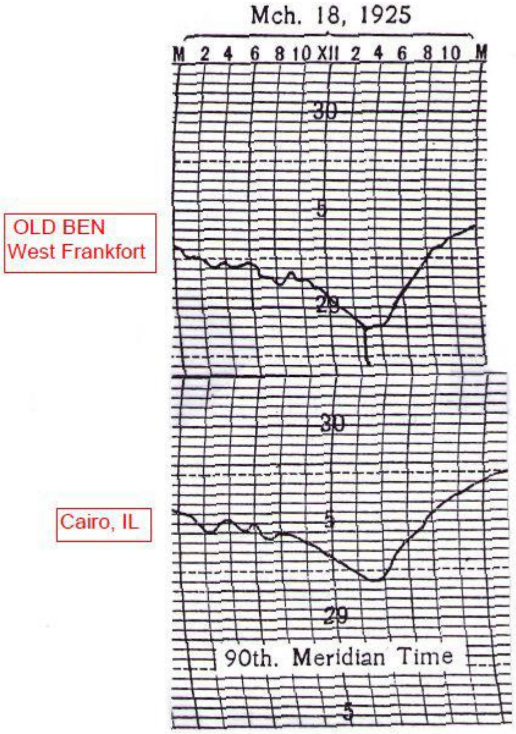


Figure 14: Old Ben and Cairo barographs from Henry (1925). Charts show in Hg. The Old Ben clock was running about 15 min slow. *Click image to enlarge.*

occurred near preexisting thermal boundaries, the majority on the cool side. The surface data are not adequate to determine precisely where the Tri-State tornado track was relative to the warm front.

b. Location of tornado relative to synoptic low

The WB obtained a barograph trace (Fig. 14), from the Old Ben Coal Corporation. The barometer was at a mine, on the south edge of West Frankfort, IL, about 1 mi (1.6 km) from the center of the tornado's damage track. There were no accompanying data to allow estimations of the SLP. However, on 18 March the pressure recorded at the mine was consistently about 0.30–0.35 in Hg (10–12 hPa) lower than was measured at the Cairo, IL, WB barometer (also shown in Fig. 14). Since the difference in elevation of the two instruments was probably only 50–100 ft (15–30 m), the Old Ben barograph was not well-calibrated. However, pressure falls from midnight to the time of lowest pressure on 18 March were similar on both traces. There was a low pressure spike measured by the Old Ben barometer, down to 28.70 in Hg (972 hPa), when the tornado passed by just to the north. The Old Ben clock was slow and the low-pressure spike associated directly with the tornado occurred very near 1500 CST (1458 CST; Johns et al. 2013).

Henry showed both of these barograph traces in his 1925 paper but did not comment on the data. The Old Ben trace shows the low-pressure spike occurred at the end of a long period of steadily falling pressure. The pressure then remained low and nearly constant for over an hour, before rising rapidly. Thus, the barograph trace from the coal mine indicated that the mesoscale cyclone directly associated with the tornado was located east [i.e., ahead, probably by 50–60 mi (80–97 km)—see Fig. 12] of the synoptic low at 1500 CST.

c. Presence of a dryline

The dryline is an interface, at the surface, between hot, dry cT air to the west and warm, moist mT air to the east (Schaefer 1974). Drylines occur most often over the southern and central Plains. Occasionally, very strong synoptic cyclones can advect cT air eastward across the Mississippi River, as in both the Palm Sunday (11 April 1965) and the 3–4 April 1974 outbreaks. Drylines typically slope, with height, to the east, resulting in a strong capping layer aloft. This dry layer suppresses development of thunderstorms (Lanicci and Warner 1991) except in regions of intense forcing for upward motion. For the Tri-State case it appears likely that an inversion aloft, ahead of the surface dryline, acted to suppress thunderstorm development across much of the warm sector until about 1500 CST. Thunderstorm development only occurred within the warm sector, near and east of the Mississippi River, where low-level air apparently was not as strongly capped by cT air aloft.

The best evidence for the presence of a strong dryline during the Tri-State event is provided by the surface data from Little Rock, AR, and secondarily from stations in northeastern Louisiana and eastern Texas (see analyses above in subsection *a*), as well as pibal data from Memphis, TN. A meteogram constructed for Little Rock (not shown) indicates that at 0700 CST the dewpoint was 62°F (17°C; RH = 85%) with southerly winds. At local noon the temperature was 77°F (25°C) and the dewpoint was 42°F (6°C; RH = 29%). Winds had become southwesterly shortly before 1000 CST, with speeds of around 35 mph (16 m s^{-1}). The cold front passed Little Rock around 1230 CST, with westerly winds that became northwesterly by 1330 CST. It is clear that a dryline indeed had passed Little Rock before noon. At local noon, Shreveport reported west to southwest winds at about 15 mph (7 m s^{-1}), and the relative humidity was 45% [dewpoint was 53°F (12°C)]. Thus, the dryline was less pronounced over northwestern Louisiana than at Little Rock.

The closest surface observations east-northeast of Little Rock were taken at Cairo, IL. A meteogram constructed from all the data available there is shown in Fig. 15. Cool, damp conditions prevailed at Cairo, where early morning storms kept temperatures in the upper 50s °F (around 14°C). Just before noon the temperature began a fairly rapid rise after a wind shift to the south.

The barograph trace was unsteady before 0800 CST, apparently due to elevated thunderstorms (i.e., thunderstorms whose updrafts were not rooted in the cool, stable surface layer). By 1500 CST winds had shifted to southwesterly, and skies cleared for a brief period. The average 5-min wind for the period beginning at 1455 CST was from the southwest at 40 mph (18 m s^{-1}). These rapid changes were associated with stronger winds aloft being mixed to the surface behind the dryline (Schaefer 1974). Pressure remained low until just before 1600 CST when it started a rapid rise, accompanied by falling temperatures, after passage of the cold front. The fastest mile of wind observed at Cairo on 18 March was 66 mph (30 m s^{-1}) at 1602 CST. The WB observer at Cairo noted:

"Second thunderstorm—Only one peal of thunder was heard—at 2:50 pm. The storm was north of the station. Though the wind reached a great velocity no deaths or material damage occurred in Cairo or its immediate vicinity. Hail up to as large as birds eggs occurred in upper Alexander and Pulaski Counties."

These remarks on the Form 1014 indicate that there was, at this time (1450 CST), at least one severe thunderstorm located well to the south of the Tri-State supercell [northern Alexander and Pulaski Counties are only about 20 mi (30–35 km) north of Cairo]. It is likely that this storm had formed along the dryline.

A brief, light shower was observed at Memphis, TN, around noon, and this may have indicated initial development of deep convection within the warm sector of the synoptic cyclone. Memphis (meteogram not shown) observed its fastest mile of wind [48 mph (21 m s^{-1}) from the southwest] around 1455 CST, indicating that the dryline passed Memphis about the same time as at Cairo. The temperature at Memphis remained above 70°F (21°C) until 1600 CST when its high temperature of 77°F (25°C) was observed. The temperature then fell rapidly.

Evansville, IN, was just south of the final portion of the track of the Tri-State tornado, and its meteogram is shown in Fig. 16. Conditions were similar to those at Cairo, with occasional rain and thunderstorms through the morning. Temperatures remained below 60°F (16°C) until after 1330 CST, when the warm front passed the station. There was a small dip in pressure when the tornado passed by 26 mi (42 km) to the north, striking Princeton, IN, at 1618 CST (Fig. 1). The pressure then continued to fall until 1700 CST, when it began to rise rapidly.

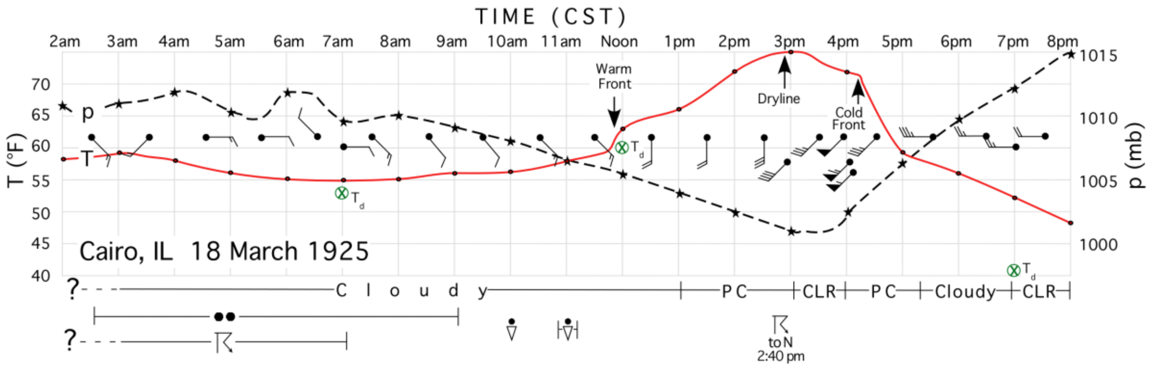


Figure 15: Meteogram for Cairo, IL, 18 March 1925. Pressures are in hPa; temperatures are in °F; dewpoints shown by small circles with "X"; winds are in mph; and time is CST. Clouds and weather conditions also are shown. Data are from WB Forms 1001 and 1014, as well as from the original barograph and thermograph traces. *Click image to enlarge.*

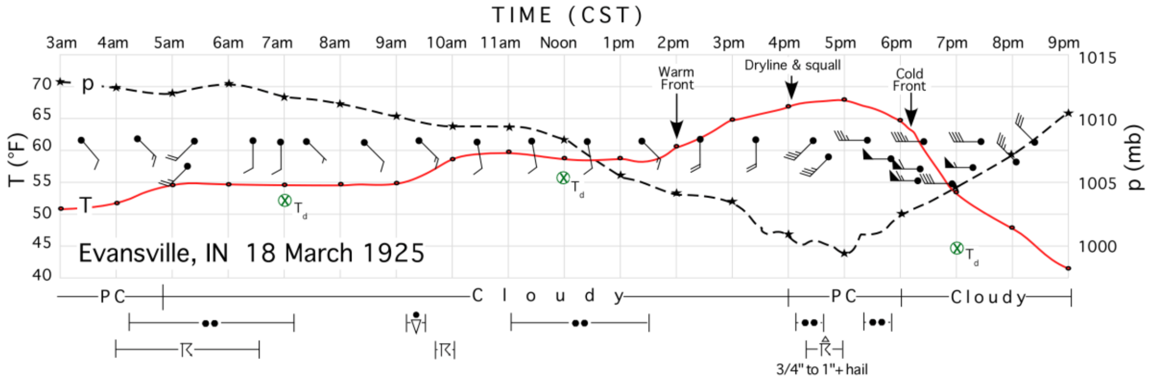


Figure 16: Meteogram for Evansville, IN, on 18 March 1925. Details as in Fig. 15. *Click image to enlarge.*

A thunderstorm was reported at the station from 1620–1700 CST; however, the Form 1014 also reports large hail over the southeast part of the city around 1615 CST. Thus, severe thunderstorms were continuing to the south of the Tri-State supercell. It is hard to determine whether the dryline was still present at Evansville. Surface winds there shifted to the southwest sometime after 1530 CST and were from this direction when the severe thunderstorms occurred. It is likely that the dryline was losing its identity as new thunderstorms developed along it, forming a north–south squall line in the warm sector. Winds shifted to the west around 1700 CST, and the cold front had westerly winds behind it for several hours. A 5-min average speed of 34 mph (15 m s^{-1}) was observed from the southwest, ending at 1648, and 48 mph (21 m s^{-1}) was observed from the west ending at 1800 CST. The fastest mile of wind, 66 mph (30 m s^{-1}), was westerly just after 1825 CST. The charts presented in Hoxit and Chappell (1975) indicate that during the 3–4 April 1974 outbreak, the dryline also reached east to around Evansville (their Fig. 39).

d. Character of the supercell

The Tri-State tornado was associated with a supercell thunderstorm that was long-lived and had a lengthy track. Bunkers et al. (2006a,b) defined a long-lived supercell as lasting at least 4 h. It is reasonable to assume that the Tri-State supercell developed around noon, about 40 min before first tornado reports. There was a final, previously undocumented tornado (Johns et al. 2013 and Fig. 12), apparently associated with the Tri-State supercell, based on timing and extrapolated track. We assume that the supercell decayed approximately an hour after the final tornado (i.e., around 1900 CST). These assumptions result in an estimate that the Tri-State supercell lasted about 7 h. The mean lifetime of long-lived supercells studied by Bunkers et al. (2006a,b) was 5.5 h. The duration of the Tri-State supercell ranks 32nd (top 15%) if added to the Bunkers sample. The estimated path of the Tri-State supercell was ≈413 mi (664 km). Because of its high speed of movement, the Tri-State supercell would have the 6th longest track (top 5%) in the Bunkers et al. sample (M. Bunkers 2012, personal communication). Compared to other long-lived supercells, the Tri-State storm was both unusually long-tracked and of relatively long duration.

Bunkers et al. (2006a) found that long-lived supercells tend to be discrete (68% of sample) and isolated (79% of sample). By discrete they mean identifiable thunderstorm cells that were distinct from one another, and by isolated they mean storms that were separated from others by at least one storm diameter. It is impossible to know the character of the Tri-State supercell, but observations suggest that it was the only severe thunderstorm on 18 March until around 1500 CST. At this time, observations from Cairo indicate another severe thunderstorm, considerably south of the Tri-State storm. It is likely that the Tri-State storm was isolated and discrete, similar to many of the long-lived supercells studied by Bunkers et al. (2006a). The Tri-State supercell also tracked near a surface baroclinic zone, as did 51% of the long-lived supercells studied by Bunkers et al.

e. Similar events

Long-track tornadoes are extremely rare, and the NOAA "ONETOR" database (available online from the Storm Prediction Center), lists only 60 tornadoes with path lengths >100 mi (161 km) since 1950. Since 1980 there have been only 12 such tornadoes. The authors briefly examined the synoptic settings of four significant events that occurred since 1980. Two events (28 March 1984 in the Carolinas, and 29 March 1998 in southern Minnesota) had tornadoes occurring along a warm front, but these produced series of tornadoes. Other long-track tornadoes occurred within the warm sector of two synoptic cyclones (24 April 2010 in Louisiana and Mississippi, and 27 April 2011 in the Southeast U. S.). The synoptic cyclones associated with these events all had considerably lower central pressures than did the Tri-State surface low. None of these events could be considered an analog to the Tri-State event.

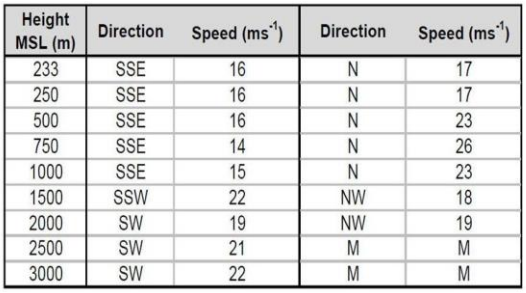
6. Upper-air data

During 1925 pibal observations of winds aloft were taken at some WB stations. We were able to obtain copies of March 1925 pibal data from three stations (refer to Fig. 6 for locations): Broken Arrow, OK (flights at 0700 and 1500 CST); Royal Center, IN (at 0700 and 1400 CST); and Memphis, TN (at 1500 CST). Some WB aerological stations used instrumented kites to measure upper-air conditions (including Groesbeck, TX; Broken Arrow, OK; and Royal Center, IN). Wind directions for upper-level wind data were determined for a 16-point compass and speeds were recorded in m s^{-1}. Data taken at these stations on 17 and 18 March are discussed below.

a. Pilot balloon winds

On 17 March at 0700 CST there was no flight at Broken Arrow because of low clouds, but there was a flight at 1500 CST (data for the two relevant Broken Arrow pibal flights on the 17th and 18th are shown in Table 1). The lower-tropospheric wind profile on the afternoon of the 17th indicated strong winds (>20 m s^{-1} at levels ≤3 km MSL) that veered with height. Such a wind profile would be expected ahead of the synoptic low, which was located over the Texas and Oklahoma Panhandles at the time of the flight. The veering winds at higher levels of the flight indicate warm advection aloft.

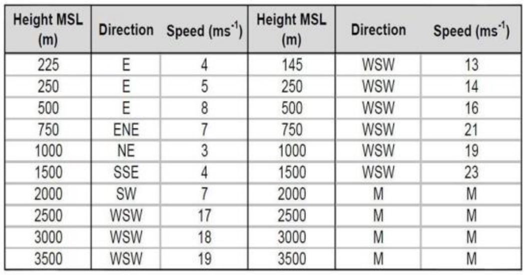
Table 1: Pibal data taken at Broken Arrow, OK. Data on left are from 1500 CST, 17 March 1925, and data on right are from 0700 CST 18 March 1925. "M" stands for missing data. *Click image to enlarge.*



Height MSL (m)	Direction	Speed (ms^{-1})	Direction	Speed (ms^{-1})
233	SSE	16	N	17
250	SSE	16	N	17
500	SSE	16	N	23
750	SSE	14	N	26
1000	SSE	15	N	23
1500	SSW	22	NW	18
2000	SW	19	NW	19
2500	SW	21	M	M
3000	SW	22	M	M

The flight the next morning at 0700 CST (Table 1) was taken just west of the synoptic low. Low-level winds were northerly to northwesterly and backed with height, indicating cold advection. The cold front had passed the kite station, and there was a pronounced northerly jet of 26 m s^{-1} below 1.0 km MSL. It is possible that wind speeds at Broken Arrow had been enhanced by outflows from an area of thunderstorms located over southeastern Kansas and northeastern Oklahoma, north of the station.

Table 2: Pibal data taken on 18 March 1925. Data on left are from Royal Center, IN, at 0700 CST. Data on right are from Memphis, TN, at 1500 CST. *Click image to enlarge.*



Height MSL (m)	Direction	Speed (ms^{-1})	Height MSL (m)	Direction	Speed (ms^{-1})
225	E	4	145	WSW	13
250	E	5	250	WSW	14
500	E	8	500	WSW	16
750	ENE	7	750	WSW	21
1000	NE	3	1000	WSW	19
1500	SSE	4	1500	WSW	23
2000	SW	7	2000	M	M
2500	WSW	17	2500	M	M
3000	WSW	18	3000	M	M
3500	WSW	19	3500	M	M

Royal Center, in northern Indiana, was located within the cold and rainy air mass north of the warm front. There was a pibal flight at 0700 CST on the 18th, but no flight was made at 1400 CST due to rain and low clouds. The morning flight (Table 2) indicated east to northeast winds above the surface, but the wind direction had veered to southwest by the time the balloon reached 2.0 km. From 2.5–3.5 km winds were west-southwest at 17–19 m s^{-1}, indicating strong west-southwest winds above the cold air mass.

A pibal was taken at Memphis at 1500 CST 18 March (Table 2). The flight was made just behind the dryline. The data indicated a deep boundary layer with winds from the WSW at all levels measured. The speed at 1.5 km MSL reached 23 m s^{-1}. This was the highest altitude for which a wind was obtained. The pibal data fit reasonably well with the surface analyses and the speed of surface winds immediately following dryline passage.

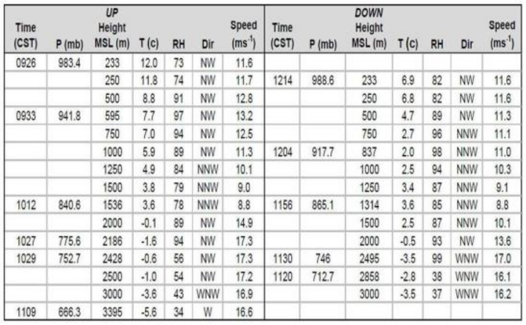
c. Kite-flight observations

We found limited upper-air data (not shown) from kite flights at Groesbeck (location on Fig. 6). At 1445 CST 17 March, there were veering winds, warm advection aloft, and moderately strong winds to the southeast of the developing cyclone. The air aloft was very dry, probably indicating a strong capping inversion above moist, low-level air. A morning kite flight at Groesbeck on 18 March indicated west-southwest winds aloft and low RH. The Groesbeck data support the hypothesis that the warm sector of the Tri-State synoptic cyclone was characterized by Type I severe thunderstorm soundings (Fawbush and Miller 1954).

At Broken Arrow, a kite was flown on the 18th from 0926–1214 CST (location shown on Fig. 6). The data for this flight, made in the cold air mass just behind the cyclone, are shown in Table 3. The flight reached 3395 m MSL (666 hPa) at 1109 CST, where winds were westerly at 16.6 m s^{-1} and the RH was 34%. The upper-air data were characterized by winds backing with height and strong cooling during the period of the flight. The layer from the surface to about 900 hPa cooled by 5°C during the flight.

The limited upper-air observations support the surface analyses presented in this paper, the presence of a distinct dryline, and the hypothesized strong, elevated capping inversion that suppressed storm development in the warm sector west of the Mississippi River.

Table 3: Kite-flight data taken at Broken Arrow, OK, on 18 March 1925. Data were taken while the kite was ascending (left side), and also while it was being brought down (right side). *Click image to enlarge.*



		UP							*DOWN*				
Time (CST)	P (mb)	Height MSL (m)	T (c)	RH	Dir	Speed (ms^{-1})	Time (CST)	P (mb)	Height MSL (m)	T (c)	RH	Dir	Speed (ms^{-1})
0926	983.4	233	12.0	73	NW	11.6							
		250	11.8	74	NW	11.7	1214	988.6	233	6.9	82	NW	11.6
		500	8.8	91	NW	12.8			250	6.8	82	NW	11.6
0933	941.8	595	7.7	97	NW	13.2			500	4.7	89	NW	11.3
		750	7.0	94	NW	12.5			750	2.7	96	NNW	11.1
		1000	5.9	89	NW	11.3	1204	917.7	837	2.0	98	NNW	11.0
		1250	4.9	84	NNW	10.1			1000	2.5	94	NNW	10.3
		1500	3.8	79	NNW	9.0			1250	3.4	87	NNW	9.1
1012	840.6	1536	3.6	78	NNW	8.8	1156	865.1	1314	3.6	85	NNW	8.8
		2000	-0.1	89	NW	14.9			1500	2.5	87	NNW	10.1
1027	775.6	2186	-1.6	94	NW	17.3			2000	-0.5	93	NW	13.6
1029	752.7	2428	-0.6	56	NW	17.3	1130	746	2495	-3.5	99	WNW	17.0
		2500	-1.0	54	NW	17.2	1120	712.7	2858	-2.8	38	WNW	16.1
		3000	-3.6	43	WNW	16.9			3000	-3.5	37	WNW	16.2
1109	666.3	3395	-5.6	34	W	16.6							

d. Estimated hodographs

The Tri-State supercell was long-lived and moved along a nearly straight-line path from ≈250 degrees at ≈59 mph (26 m s^{-1}) (Johns et al. 2013). Because of its nearly steady velocity, it is possible to estimate environmental hodographs near the storm. Bunkers et al. (2000) developed an empirical technique that uses the environmental hodograph to predict the velocity vector of supercell thunderstorms (see their Section 3*a*). Their procedure has been used to obtain estimates of the Tri-State hodograph. The velocity vector of the storm was well-documented and the nearby surface winds can be estimated from surface observations. Using these two fixed values, subjective iteration of estimated winds aloft can produce hodographs that yield the Tri-State storm's velocity, via the Bunkers et al. technique. Although there can be an infinite number of solutions, the actual spread of possible, physically realistic estimates is fairly constrained.

Results from this exercise are shown in Fig. 17. Two of the plots are subjectively estimated hodographs. Curve A uses the surface wind observed at Cairo, Illinois, and curve B uses an estimated surface wind north of Cairo, near the warm front. Curve C, for comparison, is the mean F5 tornado hodograph from Colquhoun and Riley (1996), rotated and magnified to match the Tri-State storm's velocity. Estimates A and C have the same general shape and wind velocities, with some differences from 5–6 km. Estimate B has a weaker, south-southeasterly surface wind with a pronounced low-level jet just below 1 km AGL. Naylor and Gilmore (2012) have found that longer durations and intensities of simulated tornadoes best relate to higher values of 0–3 km storm-relative environmental helicity (SREH). Values for 0–3 km SREH are: curve A, 232 $\mathrm{m^2\ s^{-2}}$; curve B, 340 $\mathrm{m^2\ s^{-2}}$; and curve C, 243 $\mathrm{m^2\ s^{-2}}$.

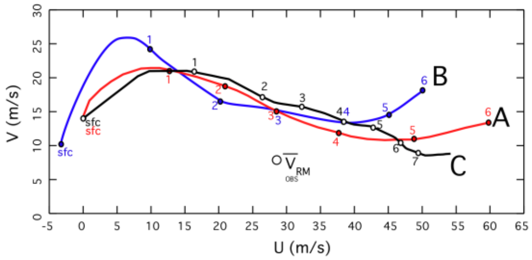


Figure 17: Estimated hodographs for about 1500 CST on 18 March 1925. Curves A and B were derived using the technique of Bunkers et al. (2000) and curve C was adapted from Colquhoun and Riley (1996). Circle is estimated velocity **V** of a right-moving (RM) supercell, which was the observed motion of the Tri-State supercell. Numbers along hodographs indicate height (km AGL). *Click image to enlarge.*

The estimated hodographs indicate that winds aloft in the lower half of the troposphere were very strong. The winds probably veered rapidly within the lowest 3 km, contributing to substantial SREH near the rapidly moving supercell. Winds above 3 km were probably west-southwesterly at about 30 $\mathrm{m\ s^{-1}}$ near 700 hPa and around 40–50 $\mathrm{m\ s^{-1}}$ near 500 hPa.

7. Final comments

A widespread thunderstorm outbreak affected much of the south-central U.S. on the afternoon of 18 March 1925. The deadly, long-track Tri-State tornado was the most severe storm event of the 18th. Past reports had inaccurate surface analyses and indicated, erroneously, that the tornado had formed in cold air west of a synoptic cyclone. However, the Tri-State tornado was directly associated with a fast-moving cyclone whose central pressure was not unusually low. Winds aloft appear to have been very strong. Although the synoptic pattern would indicate the likelihood of severe weather, there is no singular aspect of the setting that explains the long track and persistent, violent intensity of the Tri-State tornado. Indeed, the somewhat mundane character of the synoptic situation leads one to wonder why very long-track tornadoes do not occur more frequently. Mesoscale analyses along the track of the tornado reveal that:

- The tornadic supercell developed very near the center of the synoptic cyclone, possibly at the triple point intersection of the warm front and the dryline.
- The north–south temperature gradient near the triple point and north of the warm front remained strong during the afternoon due to air that had been cooled by earlier precipitation.
- The tornadic supercell moved east-northeastward at ≈59 mph (26 $\mathrm{m\ s^{-1}}$) away from the center of the slower-moving cyclone.
- The long-lived, tornadic supercell remained close to the surface warm front during most of its life.

These analyses indicate that, as the surface cyclone and dryline moved rapidly eastward, the northward movement of the warm front kept the Tri-State supercell within a very favorable storm environment for several hours. Apparently, this consistent time and space concatenation of the supercell, the warm front, and the dryline during most of the afternoon of 18 March 1925 was extremely unusual.

ACKNOWLEDGMENTS

The authors extend their thanks to the following people who assisted us during this decade-long project. Matthew Bunkers, NWS Rapid City, read a draft manuscript and provided comments and suggestions to the lead author. Gil Compo, Tom Hamill, and Jeff Whitaker, all of NOAA ESRL, provided access to special upper-air reanalyses for March 1925. Reviewers Kevin Goebbert, John Lewis, and Ernest Ostuno provided useful advice for how to improve the manuscript. We appreciate their efforts on our behalf. We thank Roger Edwards and Amos Magliocco, EJSSM editors, for their comments and suggestions. Patrick Marsh, Univ. of Oklahoma CIMMS/NSSL, helped the authors identify other long-track tornadoes. J. J. Gourley, NOAA NSSL, helped the authors obtain some of the surface data used during the project. Gary Grice, NWS retired, helped the lead author document 1925 WB procedures. Katie Hirschboeck of the University of Arizona helped the lead author interact with the widely dispersed team. She also read the draft manuscript and provided comments and suggestions. Steve Kahn of WGN-TV, Chicago, steered the lead author to information regarding A. J. Henry. National Science Foundation grants ATM-0003869, ATM-0339519, ATM-0449753, and AGS-0843269 funded portions of Matthew Gilmore's efforts on this project and AGS-0843269 helped fund data digitizing efforts by Univ. of North Dakota students: Melissa Becker, Jason Naylor, Marc Provencher, and Justin Weber. The other seven authors received no formal support and accomplished this project on their own time, using personal resources.

The following people and/or organizations helped the authors locate 1925 WB Forms:

Allen County Public Library (Ft. Wayne, IN)
Judy Bolton (Louisiana State Univ. at Baton Rouge)
Chris Buonnano (NWS, Little Rock, AR)
John Distefano (NWS, retired)
Steve Doty (NCDC, retired)
Ken Falk (NWS, Shreveport, LA)
Stuart Foster (Kentucky Climate Center)
David Gaede (NWS, Springfield, MO)
Bob Graham (Jerome Library, Bowling Green State Univ., OH)
Randy Gray (NWS, Pueblo, CO)
Pat Guinan (Missouri State Climatologist)
Steve Hodanish (NWS, Pueblo, CO)
Daniel Huckaby (NWS, Ft. Worth, TX)
Donald Hughes (NWS, Cincinnati, OH)
Logan Johnson (NWS, Indianapolis, IN)
Troy Kimmel (Univ. of Texas at Austin)
Mary Knapp (Kansas State Climatologist)
Louisiana State Univ. at Shreveport Library
Bill Marshall (Univ. of Kentucky at Lexington)
Jim Moore (St. Louis Univ., MO)
Nashville, TN, Public Library
Felix Navejar (NWS, Lake Charles, LA)
Dev Niyogi (Indiana State Climatologist)
Gregory Patrick (NWS, Ft. Worth, TX)
Peoria, IL, Public Library
Ron Przbylinski (NWS, St. Louis, MO)
Brian Raitz (Parkersburg & Wood County Public Library, WV)
Bill Read (NWS, retired)
Marilyn Schuster (Atkins Library, Univ. of North Carolina at Charlotte)
Patricia Sides (Willard Library, Evansville, IN)
Monica Smith (Cairo, IL, Public Library)
Univ. of Texas at San Antonio Library, Special Collections
Paul Wolyn (NWS, Pueblo, CO)
Richard Wynne (NWS, Amarillo, TX)
Jon Zeitler (NWS, Austin/San Antonio, TX)

APPENDIX A

We have examined recent upper-air reanalyses based upon only surface data (Whitaker et al. 2004; Compo et al. 2006). A surface-based, reanalysis 500-hPa chart (Fig. A.1) indicates that the short-wave trough associated with the Tri-State event remained a fast-moving, open wave, with some degree of negative tilt likely, during the period of interest. Figure A.1 was constructed by choosing 10 of 100 reanalysis ensemble members (J. Whitaker 2006 personal communication) and averaging the 500-hPa height fields. The ten reanalyses were chosen subjectively from the 100 members because they had the most accurate positioning and central pressure for the surface low at 1200 CST 18 March 1925. The reconstructed 500-hPa charts for 18 March depict an evolution of the large-scale setting that is in general agreement with the discussions and hypotheses of this paper.

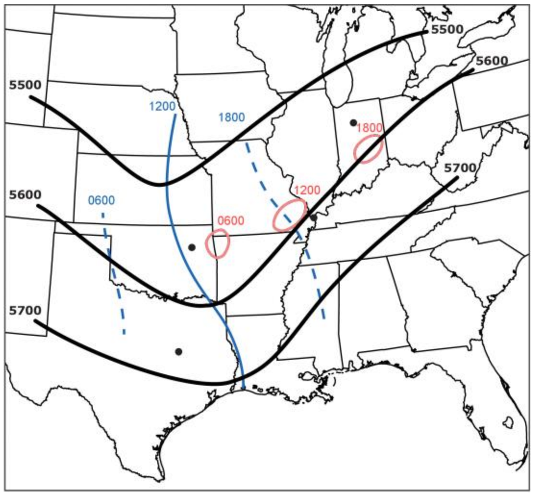


Figure A1: Surface-based reanalysis for 1200 CST 500-hPa chart. Heights (black) are in m. Solid blue line shows short-wave trough position at 1200 CST, and trough positions at ±6 h shown by dashed blue lines. Red ovals enclose surface lows of the ten reanalysis members used to construct this figure, with times shown. Black dots show locations of several key WB stations. *Click image to enlarge.*

APPENDIX B

The synoptic situation of 18 March 1925 was complicated, particularly to the south and west of the surface cyclone because of mP and cT air masses that had only slightly different characteristics. Subjective analyses are known to present challenges, since multiple analysts produce solutions that differ, sometimes very slightly and sometimes substantially. Everyone on our team was sent a series of unanalyzed surface plots for every other hour from noon through 1800 CST and asked to do surface analyses without consulting with the other team members. They returned their completed charts to the lead author. Only the lead author had access to all of the hardcopy charts, graphs, and forms that we had obtained.

Seven different results are shown in Fig. B.1. The analyses are for 1200 CST/local noon, since this is when the surface cyclone was “hidden” within the southern Missouri data void. The results are clustered fairly tightly, except for two outliers to the north (cold front and warm front) and one (warm front) to the south. One analyst indicated a trough to the east of the low pressure center. The trough and stationary front northeast of the cyclone are very tightly clustered in the results; whereas, the dryline spread is about half the width of Arkansas [i. e., about 125 mi (200 km)]. The large spread in analyzed positions of the dryline is not surprising, since there were few observations available to delineate its position precisely.

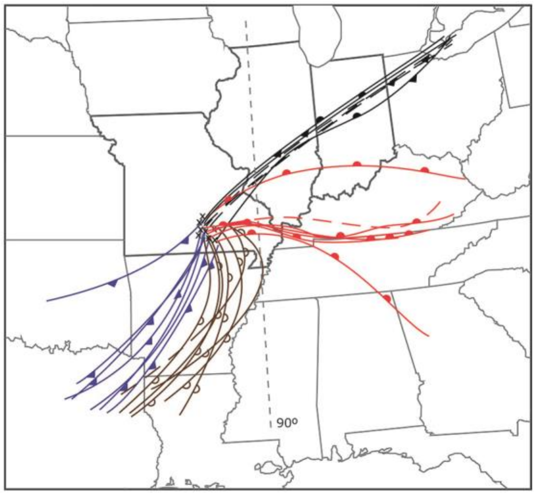


Figure B1: Spaghetti chart of surface analyses by seven of our team members for noon/1200 CST 18 March 1925. Shown are the various frontal, dryline, and trough positions identified by the team members. *Click image to enlarge.*

In March 1991 a Surface Analysis Workshop was held at the National Meteorological Center. During this workshop the participants were asked to analyze independently a surface plot for the central and eastern U.S. The synoptic situation (13 February 1991) used at the workshop was quite similar to that of 18 March 1925. The workshop participants had to analyze their surface maps under operational time constraints but also benefited from more precise and more numerous surface observations. The results of their exercise were very similar to the results of the current Tri-State exercise [compare Fig. 2 in Uccellini et al. (1992) with Fig. B1]. The new surface charts in the paper herein present one possible solution to the surface analyses. They were finalized considering each team members’ charts and using all observational data available.

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REVIEWER COMMENTS

[Authors' responses in *blue italics*.]

REVIEWER A (Ernest J. Ostuno):

Initial Review:

Recommendation: Accept with minor revisions.

Substantive comments: This is a well-written paper and there is little in the way of substantive changes that I feel need to be made to what is already here. I do believe that a few more things could be added to enhance the text and illustrations, which I describe below.

1 - I feel the main question to be answered is why this tornado remains unique in terms of path length and intensity. The paper answers this by stating:

"There appear to be no outstanding aspects of the meteorological setting that would explain the extreme character of the Tri-State tornado."

Then goes on to say:

"As the supercell and dryline moved rapidly eastward, the northward movement of the warm front kept the tornadic supercell within a very favorable storm environment for several hours. Apparently, this consistent, time and space concatenation of the supercell, the warm front, and the dryline for more than three hours was extremely unusual."

We have done the following to correct this inconsistency—the Abstract and the Summary have been rewritten to state that there were no singular features or synoptic aspects apparent for the Tri-State event. We have emphasized the time and space concatenation of important features. We have also emphasized the likelihood that the Tri-State supercell remained isolated from other storms during its life.

2 - I would like to see at least a brief discussion added about whether similar synoptic conditions were present in other long track tornadoes or tornado families, such as the 9 April 1947 Woodward tornado family and the 5 February 2008 long track tornado in Arkansas. Were there any analogues to this event in terms of a long track destructive tornado that evolved in a similar way?

We have examined a number of events that produced significant tornadoes and/or long-track tornadoes. These have been from the 1980s and later, since basic documentation was relatively easy to find. Some events produced long-track tornadoes within the warm sector while other events produced supercells moving along warm fronts, but with a series of tornadoes. We have found no events that are very similar, in all aspects, to the Tri-State tornado event. A short subsection has been added to the paper describing the extreme rarity of long-track tornadoes and several of the other events we considered.

3 - It would be helpful to have an illustration showing the path of the tornado and surface low during the course of this event. Ideally, I would like to see an animated sequence showing the positions of the low and tornado in one or two hour increments along with their path tracks overlaid on Fig. 12.

We have added a new figure that shows the continuity of selected surface features from 0700–1900 CST. The approximate position of the tornado and its parent supercell are also shown.

[Minor comments omitted...]

Second Review:

Recommendation: Accept with minor revisions.

Substantive comments: The re-organization of the paper looks good, although I thought the first draft flowed smoothly as it was.

All the modifications have sufficiently addressed the first draft concerns I had. I appreciate the inclusion of Fig. 12a since this really helps illustrate the location of the supercell/tornado with respect to the track of the surface low and positions/evolution of the surface features. Section 5c briefly describes some other long-track tornado events. The final sentence is:

"The only common feature of the Tri-State tornado and the events examined was that the hodographs indicated very strong winds aloft."

I would only ask if it were possible to quantify how strong the winds aloft were for the 1925 event and compare them to winds aloft in the vicinity of the long-track tornadoes in the events mentioned (28 Mar 1984, 29 Mar 1998, 24 Apr 2010, 27 Apr 2011).

It is important to note that there were only very limited observational data available for the Tri-State event from aloft. The hodographs we presented for the event were estimates developed subjectively. Comparing Fig. 16 with modern, observed hodographs would not be a direct comparison. We prefer not to use the Bunkers et al. technique to develop subjective estimates of hodographs for these modern events, since the purpose of the added paragraph was to point out that we had found no analogs for the Tri-State synoptic setting and its evolution in time.

In response to Reviewer A's question we have done the following: In Section 5e—Similar events—we have deleted the final sentence ("The only common feature of the Tri-State…") and moved the sentence ("None of these events could be considered an analog to the Tri-State event.") to the end of the section.

REVIEWER B (John M. Lewis)

Recommendation: Accept.

Overview: This contribution represents a supreme effort to understand the mechanisms that produced the infamous long-tracked tri-state (Missouri, Illinois, Indiana) tornado of 1925. Eight severe-storm meteorologists with a wealth of experience constitute the team of authors. The study is commendable for its access and interpretation of surface data and upper-air observations (from kite stations). The paper is most appropriate for publication in Electronic Journal of Severe Storms Meteorology (EJSSM). Comments and suggestions are basically aimed at: 1) re-organization issues, 2) pedagogical issues—summarizing limited knowledge about tornadoes in 1925 compared to the current age, and 3) guidance to the weather forecaster.

Comments and Suggestions:

1. Reorganization issues/pedagogy

The Introduction includes significant discussion of earlier results from Henry (1925) and Changnon and Semonin (1966). It would seem appropriate to have a concise Introduction where re-examination of the tri-state tornado is justified based on incomplete earlier work and the continued interest to understand long-tracked tornadoes. A second section could then summarize results from the two papers mentioned above including mention of state-of-knowledge about tornadoes in 1925 (citing information in Joseph Galway's seminal papers on the history of severe storm forecasting including the review of J. P. Finley's work at the end of the 19th century).

We have done as suggested above. The Introduction was rewritten as two short paragraphs. Section 2 now starts with some background on the "state-of-art" knowledge back in 1925. Galway's three papers have been cited, and some information regarding Finley and tornado forecasting in the Signal Corps has been included.

Although the paper includes two appendices, I believe much of the material in section 2 (Observations and Methodology) could be relegated to an appendix. This section threw me off my quest to keep track of the paper's main theme. I think Appendix B could be included in the main body of the paper as a subsection in "New Analysis". This was one of the most interesting parts of the paper for me and it reminded me of the Fred Sanders/Bob Burpee contribution (Sanders and Burpee, 1968, *JAM*) where five teams of students in the synoptic meteorology class were required to produce initial fields for barotropic track forecasts of Hurricane Donna (September 1960). It was the outlier forecast, not the consensus forecast, which most-closely matched the actual track!

This suggestion is interesting, since early versions of the paper were structured just as suggested. We found that the information in Section 2 was not as effective when it was set off in an appendix. The information in this section is critical if synoptic meteorologists and forecasters are to follow what we've had to do because of the much different observing procedures used in 1925. Indeed, we feel that our unraveling of the observing procedures and figuring out how best to plot and analyze the data were important accomplishments during this lengthy study. We also ended up deciding that the analysis exercise was not a good "fit" when it was part of the body of the paper.

2. Pedagogical issues

With a little effort, this contribution can serve as a stimulating article for the novice as well as the experienced meteorologist. To serve the novice or meteorologist outside the severe storm community, it would be valuable to review our current state of knowledge regarding tornadoes before discussion in "New Analyses" and "Upper Air" sections. Some of this information is scattered throughout the paper, but I think it more valuable to primarily include at a single place. For example, characteristics of a supercell and the crucial importance of helicity (and the associated display on a hodograph) could be included in such a summary.

We certainly understand what the reviewer is suggesting here; however, it leads to several dilemmas. First we have written the paper essentially for the primary readership of the EJSSM, i.e., the severe storm research and forecasting community. Second, the paper is already quite long and adding background and review section(s) would make the paper far too lengthy. What we have done instead is to add references to monographs that would provide the interested reader access to important background information on tornadoes and supercells. Additionally, several of our authors are planning, or already working on, additional articles or books for the broader community.

3. Guidance

With the great effort that has gone into this study and with the team's knowledge of earlier work, the readers would benefit from an itemization of key "signatures" in meteorological fields that portend long-tracked tornadoes. Of course, this also allows the authors to highlight the weaknesses in our current understanding of synoptic/mesoscale circulations and linkages to the supercell and the tornado.

This suggestion essentially recommends new research. Long-track tornadoes are extremely rare and "key signatures that portend long-track tornadoes" are not known. We have added information about the rarity of such events and have emphasized more the information cited about the character of long-track supercells.

Second Review:

Recommendation: Accept.

Substantive comments: The paper meets with my approval. My suggestion for re-organization was one that would fit my approach to the study but it's certainly not the only way to handle it.

REVIEWER C (Kevin Goebbert):

Initial Review:

Reviewer recommendation: Accept.

General Comments: This paper re-analyzes the synoptic weather pattern surrounding the 18 March 1925 Tri-State tornado event. They accomplish this through the integration of all known available data from the remaining records and do a thorough job presenting a new coherent and justified surface synoptic pattern. Even with the limitations in available surface and upper-air data the authors go to great lengths to indicate that their analyses are consistent in both space and time. This paper also rectifies a misconception about this specific case that has persisted for over 40 years. The new analysis is presented clearly and is well justified. This paper is an excellent contribution for this journal and will be widely read by those who are interested in famous tornado events.

Review Criteria Comments:

Based on the review criteria the authors do a fine job of referencing the appropriate work, especially with the sources of old Weather Bureau analyses and the state of the bureau in 1925. The scientific arguments that they make in the paper are well justified and their procedures are sufficiently detailed to allow others to independently verify their results.

The paper has high quality figures that are easy to read and link to larger versions. The paper is well written, following a clear and logical order. Their explanations and descriptions are clear and straightforward while addressing the important issues of the limitations of the available data.

Thank you, we appreciate your comments.

[Minor comments omitted…]

Second Review:

Recommendation: Accept.

General Comments: Finally had a chance to read through the manuscript. Looks good to me. No further comments and I'm excited to see this paper published. I think there will be great interest from many people for this work.