

Another Look at the 11 April 1965 Palm Sunday Outbreak

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ABSTRACT

The 11 April 1965 tornado outbreak was one of the most devastating tornado outbreaks in recorded history, affecting six Midwestern states with significant loss of life and property. This storm system was particularly interesting for the number of discrete tornadic supercells in the southern Great Lakes, especially given the number of F3+ tornadoes. In addition, many supercells were observed to contain multiple funnels and multiple tornado cyclones (some occurring simultaneously). Dr. Theodore Fujita performed a comprehensive analysis of this event in the late 1960s, featuring a detailed analysis of both the meteorology and tornado damage paths. However, technology and science have progressed much between 1970 and 2015, with new forecast parameters and techniques available to forecasters. The Palm Sunday Outbreak of 1965 was re-examined using modern-day severe weather forecast parameters derived from observational data to help understand why this storm system produced such violent thunderstorms, particularly across extreme northern Indiana. In order to do this, approximately 200 handwritten surface observations were obtained from the National Climatic Data Center's Electronic Digital Archive Data System web interface. Once these observations were put into a database, several surface weather maps, synthetic soundings, hodographs, and upper-level analyses were constructed. These data, along with archived upper-air data, were used to calculate several severe weather forecast parameters, which truly revealed the magnitude of the event.

1. Introduction

The 11 April 1965 tornado outbreak was one of the most devastating tornado outbreaks in recorded history. It is ranked number three in the top 25 severe weather outbreaks according to the multivariate outbreak index (Shafer and Doswell 2010). The outbreak affected six Midwestern states (Iowa, Wisconsin, Illinois, Indiana, Michigan, and Ohio), and lasted approximately 12 hours (Fig.1). At

least 37 tornadoes were confirmed, with one study indicating as many as 47¹. At least 3100 people were injured, with 258 confirmed dead. The estimated economic loss in 1965 was at least \$238 million, with the worst tornado damage being across northern Indiana (Fig. 1) (Fujita et al. 1970). What makes this event both interesting and unique was the strength of the environmental wind, the number of F3+ tornadoes, and the sheer number of assumed discrete tornadic supercell thunderstorms; this is something quite unusual for the Great Lakes region, as most tornadoes in this area are produced from squall lines (Smith et al. 2012). Evidence shared by Dr. Fujita's research (Fujita et al. 1970), eyewitness accounts, and photographic evidence, indicates that many of the thunderstorms, particularly across northern Indiana, were long-lived cyclic supercells (Adlerman and Droegemeier 2005; Bunkers et al. 2006). Photographic, damage path, and radar evidence also indicate that at least two of these storms had simultaneous-producing tornado cyclones, with at least two confirmed twin funnel tornadoes (possibly more as suggested by Fujita et al. 1970). In fact, one of the most famous tornado pictures was captured by Paul Huffman (a news reporter for the *Elkhart Truth* at the time) just south of Dunlap, Indiana (Fig. 2). Interestingly, this particular storm was trailed by another destructive tornado-producing supercell by 30-40 minutes, with the second storm producing a tornado over or very near the same tornado damage path as the previous supercell. It was these aforementioned unique attributes of this storm system that prompted this reanalysis, the goal of which was to explore what sort of environmental variables would support such a destructive severe weather outbreak in this region, especially one that supported several violent cyclic supercells, some which possessed dual tornado formation. The research of this event was further spurred by recent reanalysis of historic tornado outbreaks (Corfidi et al. 2010 and Maddox et al. 2013). Corfidi et al. (2010) re-examined the Super Outbreak of 1974, adding new analysis of several fields (including an Eta model simulation) and looking at mean synoptic conditions a month leading up to the event. Maddox et al. (2013) also produced new analysis data that were much more reliable and thorough than previous reports for the historic Tri-State Tornado event of 1925. More stations were

¹ Aerial surveys by Dr. Theodore Fujita indicated the possibility of more tracks although no further investigation was performed (Fujita et al. 1970).

included in the new analysis and data were thoroughly checked for inconsistencies and errors, leading to a more sound scientific understanding of the synoptic and meso-scales of the event. Both of these case studies provided a look at events through the eyes of current forecasting techniques and research, helping present and future forecasters better understand the conditions that lead to such significant tornado outbreaks. The goal of this paper is similar to that of Corfidi and Maddox, namely, to provide a better understanding of the historic 1965 Palm Sunday Outbreak.

2. Data and methods

The region of northern Indiana is the focus of this paper, as this was where some of the most violent storms occurred. Calculating several severe weather variables based on a high-density network of surface observations and available upper-air data constitutes the bulk of this analysis. However, the lack of surface weather observations was a substantial hurdle. Digitized archived surface weather observations for this event were limited to synoptic stations at the standard 3-hourly observation times (0000, 0300, 0600, 0900, 1200, 1500, 1800, 2100 UTC), which was much too sparse in both time and space for mesoscale analysis. Fortunately, the author was able to obtain digitized versions of archived Weather Bureau Army Navy (WBAN) Form 10A for all active stations in the Midwest. These data were obtained from the National Climatic Data Center's (NCDC) Electronic Digital Archive Data System (EDADS) web interface (<https://www.ncdc.noaa.gov/EdadsV2>), which then led to the time-consuming task of data entry for several hundred observations. Perhaps one of the most difficult data issues was that nearly all station reports were based on local standard time (LST) and the local time zone was absent from some forms. Hence, research of the local time zone was performed, which was convoluted for the state of Indiana given the state's frequent changes in time zone boundaries during the 1960s (<http://www.indianalawblog.com/documents/Timezone.pdf>). Once data input was complete, the surface data were analyzed using the Digital Atmosphere software (www.weathergraphics.com/da/).

Upper-air data were collected from 11 April 1965 0000 UTC to 12 April 1965 0000 UTC, plotted, and analyzed. Upper-air data from the National Center for Environmental Prediction (NCEP)–National Center for Environmental Research (NCAR) reanalysis data (Kalnay et al. 1996) also were analyzed, which provided smooth upper-level contours of height and wind speed. The NCEP–NCAR reanalysis data also were used to make mean and anomaly composites of temperature and moisture for the month leading up to the event.

Given the occurrence of severe thunderstorms in between upper-air observation sites, the Universal Rawinsonde Observation program (RAOB) software (www.raob.com/) was used to create a synthetic sounding at South Bend, Indiana (KSBN), incorporating data from the KSBN airport. This synthetic sounding was needed in order to estimate severe weather variables in northern Indiana. The sounding data for Peoria, Illinois (KPIA) were merged with Flint, Michigan (KFNT). The merged data were then blended with NCEP–NCAR reanalysis data (50% each) at available levels to help further improve the sounding data.

Storm reports were gathered from NCDC. However, owing to the limitation of storm report gathering in the 1960s, coupled with lack of tornado track details from NCDC, additional tornado track information was gleaned from Fujita et al. (1970) and Grazulis (1993), both which provide exceptionally detailed track information. This information was used to create Google Earth keyhole markup language (KML) files of storm reports and tornado tracks. Additional items such as radar photographs, satellite photographs, tornado photographs, and damage pictures were obtained from Fujita et al. (1970) for analysis. Several additional photographs also were obtained from local newspapers and through the courteous donation of local residents who lived through the event.

3. Event Overview

An abnormally strong low pressure was in place on the morning of 11 April 1965, with a central pressure anomaly of about –25 mb (as compared to 1981–2010 climatology, not shown). A broad upper-

level trough was located over much of the western United States on the morning of 11 April 1965, with a strong short-wave trough and jet streak over the central Plains (Fig. 3). The northern Plains trough had a midlevel jet maximum in excess of 50 m s^{-1} (100 kt) located on its southern periphery, over the southwestern United States into the central Plains region. This jet was facilitating lower-level heat and moisture advection, with 25 m s^{-1} (50 kt) southerly winds ahead of the 850-mb trough (not shown). Of importance was an elevated mixed layer (EML) from observed soundings over the southern and central Plains (not shown), and also indicated by a swath of low relative humidity (5-20%) at 500 mb, extending from the southwestern United States into the central Plains (Fig. 4). This layer of well-mixed dry air and associated steep midlevel lapse rates was in the process of advecting over increasing low-level heat and moisture, decreasing the static stability of the atmosphere downstream over the Midwest. One way to illustrate the decreased static stability and the potential for deep convection is by plotting the difference of equivalent potential temperature (θ_e) at the surface from the equivalent potential temperature near the top of the troposphere (Fig. 5). It can be seen that a minimum of this variable (red dashed lines) was in place at 1200 UTC, extending from the Gulf Coast northward into portions of the Midwest, indicating the potential for deep convection. At the surface, low pressure was centered over eastern South Dakota, with associated cold and warm fronts to the south-southeast (Fig. 6). Showers and thunderstorms were reported north of the warm front in an area of positive low-level θ_e advection, likely being produced by a system-generated low-level jet (not shown). Mostly clear skies were reported in the warm sector, which eventually would lead to 80-90% insolation by late morning and early afternoon.

The upper trough and associated surface low pressure had moved east into the western Great Lakes by 0000 UTC 12 April. The most important features at this time were (1) the intensity of the midlevel jet and its location relative to the surface cold front and (2) the strong diffluent signal noted in the upper troposphere (Fig. 7). A maximum wind speed of 69 m s^{-1} (135 kt) was reported in the core of the jet by KPIA. This is an exceptional value given that it was an anomaly of 33 m s^{-1} (64 kt) faster than the 1981-2010 climatological average per reanalysis data. The nose of the jet was located over southern

Michigan and northern Indiana, which is a highly favored location for severe convective storms and tornadoes (Clark et al. 2009). Upper-level diffluence at 500 mb as shown in Figure 7 was maximized over southern Lake Michigan, which also was very near the triple point or mesolow along the warm front at the surface (shown later). Low-level heat and moisture advection were ongoing ahead of the upper trough over portions of northern Ohio and eastern Michigan as inferred from the 850-mb analysis, which indicated southerly flow of at least 20 m s^{-1} (40 kt) over western Ohio in the warm sector (not shown). This has been only a brief synoptic overview, mainly highlighting the favorable upper-level conditions for severe convection. For a more complete synoptic overview, refer to Fujita et al. (1970).

4. Surface synoptic-to-mesoscale overview

Low pressure was located over central Iowa at 1500 UTC 11 April, with a warm front extending east-southeast across northern Indiana (Fig. 8). Convection was ongoing north of the warm front, with low-level moisture being advected north as manifest by rising θ_e values of approximately 11 K per 3 hours. The cold front (south of the low) was a pseudo-dryline considering the substantial dewpoint decline across the front [i.e., $\sim 15^\circ\text{C}$ (25°F)]. In addition, temperatures actually rose with frontal passage at some locations across Missouri and Illinois as the day progressed. Strong and dry westerly winds were found to the west of the cold front because of the well-mixed boundary layer and near 100% insolation. The surface low moved east into the western Great Lakes from 1500 to 2200 UTC, with the relatively very warm and moist boundary layer advecting north per strong southerly winds (Fig. 9). Temperatures were in the lower 20s $^\circ\text{C}$ (70s $^\circ\text{F}$) with dewpoints of 16-19 $^\circ\text{C}$ (lower to middle 60s $^\circ\text{F}$) ahead of the cold front. Winds were gusting over 25 m s^{-1} (50 kt) at times west of the front, with blowing dust being reported further upstream across the central and southern Plains—an indication of deep boundary layer mixing. An important feature was the development of a mesolow center, which developed adjacent to the synoptic low pressure over Wisconsin, and moved east along the warm front, with a trough extending northwest into the main synoptic low. This area of enhanced convergence created a triple point between three relatively different air masses, which is a favorable location for tornado development (Moller 2001).

Several supercell thunderstorms and tornadoes developed across the Midwest (e.g., Illinois, Iowa, and Wisconsin) during this time. However, the focus area of this paper is the local environment over northern Indiana, southern Michigan, and northwestern Ohio. A surface θ_e ridge was located across western Indiana by 2300 UTC, with sustained southerly flow of $7\text{--}13\text{ m s}^{-1}$ (15–25 kt), slightly backed to the southeast nearer the warm front across southern Michigan (Fig.10). It was at this time that at least three supercell thunderstorms were located across northern Indiana (evidenced by photos, storm track data, and radar data), with at least two over extreme northern Indiana (Fig.11). The observation at KSBN, near the southern tip of Lake Michigan on the surface charts, indicated that one of these storms (storm J in Fujita et al. 1970) was near the airport at this time. Conveniently, this was at the time upper-air observations were taken, thus a proximity sounding was created for KSBN, which was used to analyze several important severe weather variables. A 2300 UTC sounding was constructed using available upper-air data (from KFNT and KPIA) and the KSBN surface observation (Fig. 12). The sounding exhibited convective available potential energy (CAPE) of 1170 J kg^{-1} [using a 50-mb mean layer (ML)], with 0–6-km bulk wind difference of 53 m s^{-1} (103 kt), an exceptional value given the CAPE. When combined, these two parameters produce a significant severe value of $62,000\text{ m}^3\text{ s}^{-3}$, a value that is at the extreme high side of Craven and Brooks's (2004) box-and-whiskers plot for significant severe values. Bulk layer shear in the 0–8-km layer was approximately 57 m s^{-1} (110 kt), a value that is above the maximum value when comparing it to the Bunkers et al. (2006) long-lived supercell study, and helps to explain the longevity of supercell thunderstorms that day (individual storm cells lasted up to 4.5 h) when coupled with a bulk Richardson number (BRN) of 4. When examining the potential for long-lived tornadoes, Garner (2007) found that 0–8-km layer bulk shear, BRN shear, and midlevel wind speed proved useful in distinguishing short-lived and long-lived tornadoes. Comparing these parameters from the Palm Sunday case to Garner's work is revealing as the 0–8-km shear and midlevel wind speed (at ~500 mb) were both outside the extreme end of both box-and-whisker plots (Fig. 13), with BRN shear being near the middle or median. It can be seen that the longest tornado tracks were across the Indiana, Michigan, and Ohio region (Fig. 1). Two cyclic supercell thunderstorms produced all the tornado tracks across extreme northern Indiana and

extreme southern Michigan (Fujita et al. 1970). Using the merged KSBN sounding and all local available soundings at 0000 UTC April 12, plain-view graphics of important tornado-producing severe weather variables were created. These graphics included MLCAPE, 0–6-km bulk shear, 0–1-km SRH, 0–3-km vorticity generation (VGP), 0–1-km energy helicity index (EHI), and MLCIN (Fig. 14). In viewing these graphics, it can be seen that thunderstorms across northern Indiana, southern Michigan, and northwestern Ohio were on the northern gradient of appreciable MLCAPE and centered in very strong deep-layer and low-level shear, a location that is highly favorable for severe thunderstorms (Cohen 2010). When coupled with their proximity to large-scale ascent from the advecting/propagating upper trough and the position of the upper-level jet, it can be argued that the two northern Indiana supercell thunderstorms were in a highly favorable location for storm development and maintenance: near the triple-point area, at the nose of the midlevel jet, and under strong upper-level diffluence at peak heating. Simply put, these two thunderstorms were in a prime location for long-lived violent tornadoes. Another factor that was likely important to the isolated nature of warm sector thunderstorms that day and lack of upscale growth into a squall line was the presence of very strong capping, likely due to the presence of an EML. The EML has been associated with a number of significant severe weather outbreaks in the Great Lakes and northeast United States (Banacos and Ekster 2010). The weakest part of the capping inversion was located over Indiana at that time (Fig. 14b). The cap was weak enough to allow the formation of scattered to isolated supercells south of the warm front, but strong enough to limit the areal extent of convection, leading to less storm competition. As the system pushed east that evening, isolated supercells continued to produce tornadoes across Ohio and Michigan, with the last tornado report near Cleveland, Ohio, around midnight.

5. Discussion

Perhaps one of the most interesting and unique aspects of this storm system was the prevalence of dual mesocyclones and multiple tornadoes from a single tornado cyclone (MTSTC), the most famous being the Dunlap, Indiana twin funnel (Fig. 2). MTSTCs were reported with thunderstorms in Indiana and Ohio that day, and damage suggests possibly over Illinois, too (Fujita et al. 1970). The presence of

MTSTCs and multiple mesocyclones points to the possible presence of vortex upscale growth or vortex breakdown (Agee et al. 1976; Wurman and Kosiba 2013). Track evidence across Indiana confirms that supercells were cyclic and contained long occlusion cycles (occluding cyclic mesocyclogenesis; OCM) to nearly steady non-cycling phases based on some of the very long tornado path lengths (Adlerman et al. 2005). Adlerman et al. found that when lower tropospheric shear is increased for given hodographs that support OCM, a slowing or a cease in mesocyclone cycling typically can result, especially in environments that contain high values of shear. Hence, the incredibly strong ambient shear (particularly in the 0–6-km layer) during the Palm Sunday event may in fact explain the plethora of long cycles observed that day (1–3 hours), perhaps similar to the Tri-State tornado of 1925 (Maddox et al. 2013). In some instances, as with storms J and K (Fujita et al. 1970), separate tornadoes from separate parent low-level mesocyclones (tornado cyclones) were evidenced occurring simultaneously (being inferred from double hook structures in radar data combined with tornado track data, Figs. 1 & 15). One hypothesis for the prevalence of MTSTC and multiple low-level mesocyclones during this event could be related to the speed of the storms, which also was hinted at in Adlerman et al. (2005). Storm motions in the KSBN pseudo-sounding were very fast. Using the Bunkers et al. (2000) right-moving method, supercell speeds were around 31 m s^{-1} (60 kt). Perusal of Weather Bureau statements from that day indicates storm speed estimates of 18–22 m s^{-1} (40–50 mph). However, using tornado start/end times from NCDC’s storm report data puts some storm speeds at about 27 m s^{-1} (60 mph). Perhaps Weather Bureau meteorologists were hesitant to use faster speeds given their uncommon occurrence. Regardless, the fast storm motions could have allowed thunderstorm tornado cyclones to remain in a sort of steady-state growth phase, with low-level mesocyclones and associated tornadoes able to “grow upscale” given the lack of rear-flank downdraft or other environmental interference (mesocyclone cycling), similar to Burgess (1982). Environments that contain very fast storm motions (as observed during the Palm Sunday event) also typically contain high shear values. Perhaps as environmental wind shear is increased (due to increasing flow) and storm speeds increase for a given hodograph shape, supercell mesocyclones may reach a quasi-steady state with the gust front, remaining in the ideal location for uninterrupted inflow and leading to potential long-track

tornadoes, for a given set of environmental conditions. The environment was certainly ideal for long-lived tornadic supercells, and perhaps this “storm-relative near steady state” allowed for slower/longer mesocyclone cycling times and a chance for tornado vortices to undergo vortex breakdown into multiple funnels (Agee et al. 1976; Wurman and Kosiba 2013).

As shown above, the 11 April 1965 tornado outbreak had several key tornado-producing ingredients in place, which were able to work synergistically to produce a violent and destructive tornado event. A strongly sheared environment to the degree of the Palm Sunday outbreak is unusual, but certainly not rare. Perhaps the most uncommon aspect of this event was the fact that extremely strong shear and abundant deep low-level moisture were coincident under an EML, this far north for the time of year. Although rare, it has happened before and led to other significant tornado outbreaks in the Great Lakes (8 March 1920, 2 April 1956, and 3 April 1974). Typically, it is very hard to get abundant low-level moisture very far north in the early spring, as Gulf of Mexico moisture gets diluted by cold frontal intrusions. However, a composite analysis of the flow and moisture pattern the previous month leading up to the outbreak illustrates that flow over the southern United States was generally zonal with a positive height anomaly noted over the southeastern United States (Fig. 16), similar to what Corfidi et al. (2010) found for the 1974 Super Outbreak. This type of flow pattern would limit southward extent of cold fronts into the southern United States and especially into the Gulf of Mexico, allowing the boundary layer over the Gulf of Mexico to remain moisture laden for most, if not all of the month leading up to the Palm Sunday event. A significant precipitable water anomaly was also evident along the Gulf Coast and southern United States in the month leading up to the outbreak per composite data (Fig.17). Thus, the deep meridional trough and associated surface cyclone of the Palm Sunday outbreak was able to advect a very moist and warm boundary layer far north with very little depletion, to where favorable vertical wind shear and large-scale ascent were in place for violent, long-lived tornadoes. The intensity of the deep-layer and low-level shear, when coupled with available low-level moisture and capping, allowed storms to

remain scattered to isolated, and produce long-lived supercell thunderstorms across the southern Great Lakes, some with multiple tornado cyclones and multiple tornadoes under one tornado cyclone.

The science of forecasting has progressed much since 1965 and now forecasters can anticipate outbreaks like this one several days in advance. Although nothing new in terms of tornado forecasting techniques have been presented, the intention herein was to use modern-day forecasting techniques and variables to illustrate quantitatively the intensity of this event using observed data. This will allow present and future forecasters to understand how and why the Palm Sunday event became one of the most devastating tornado outbreaks in the Midwest, and perhaps give insight to future tornado outbreaks in this region.

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TABLES AND FIGURES

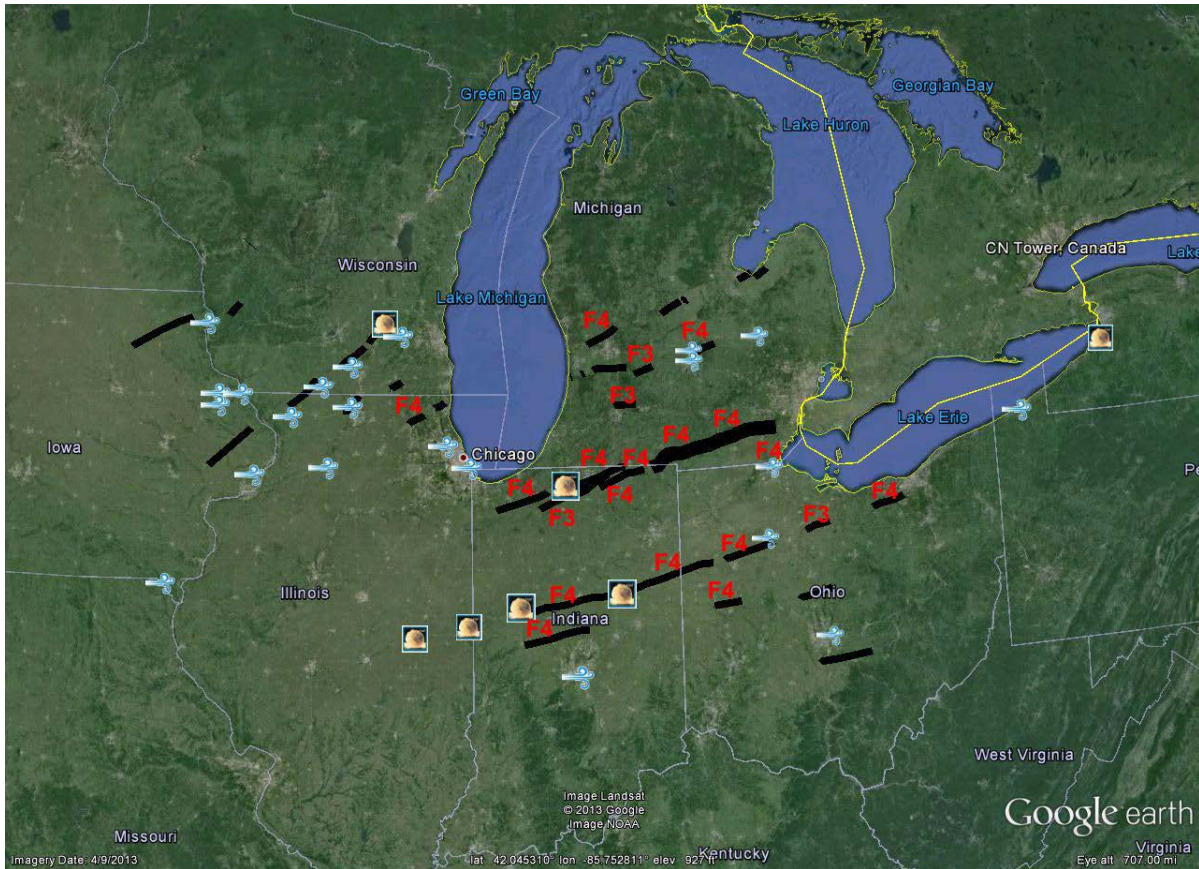
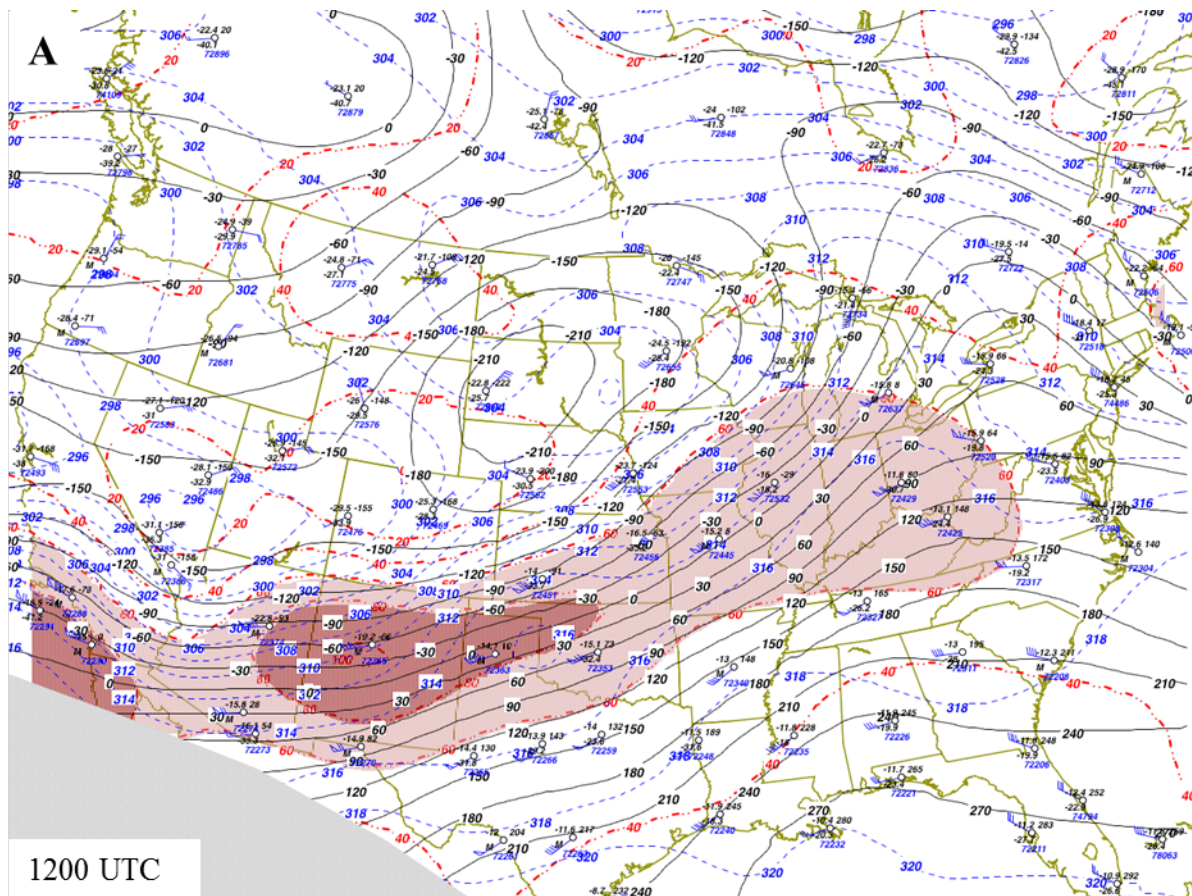


Fig. 1. Storm reports for 11 April 1965. Black lines are individual tornado tracks, with F3 and F4 tornadoes annotated by red text. Wind damage reports are indicated with light blue icons and hail reports are indicated with white hail icons.



Fig. 2. Photograph of the “twin tornado” just south of Dunlap, IN. Photo was taken by Paul Huffman and is property of the *Elkhart Truth*.



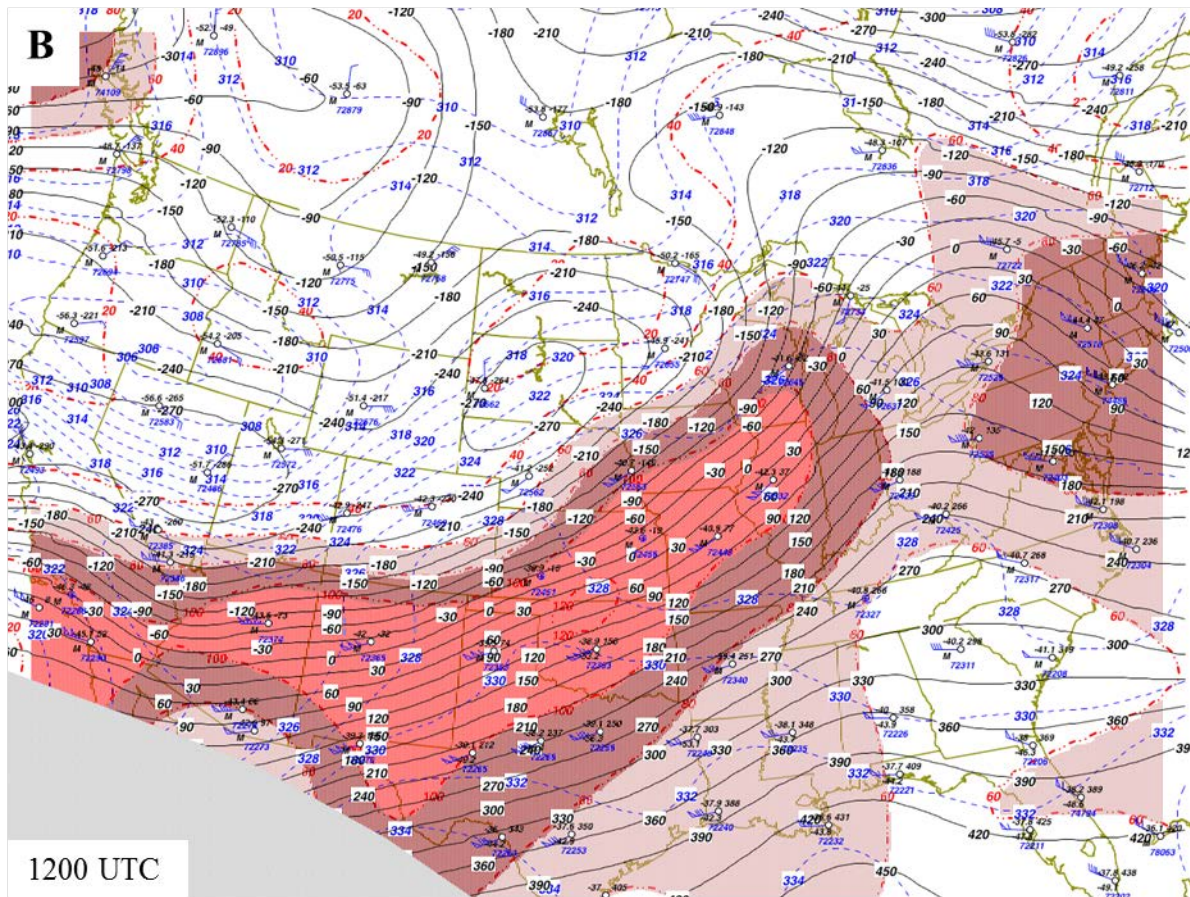


Fig. 3. Upper-level analysis of D value (departure from standard atmosphere height in meters, black lines), theta (K, dashed blue lines), and wind speeds (kt, stippled red lines) at 1200 UTC April 11 for (a) 500 mb and (b) 300 mb. Wind speeds are shaded at 60, 80, and 100 kt. Standard upper-air station plots also are given.

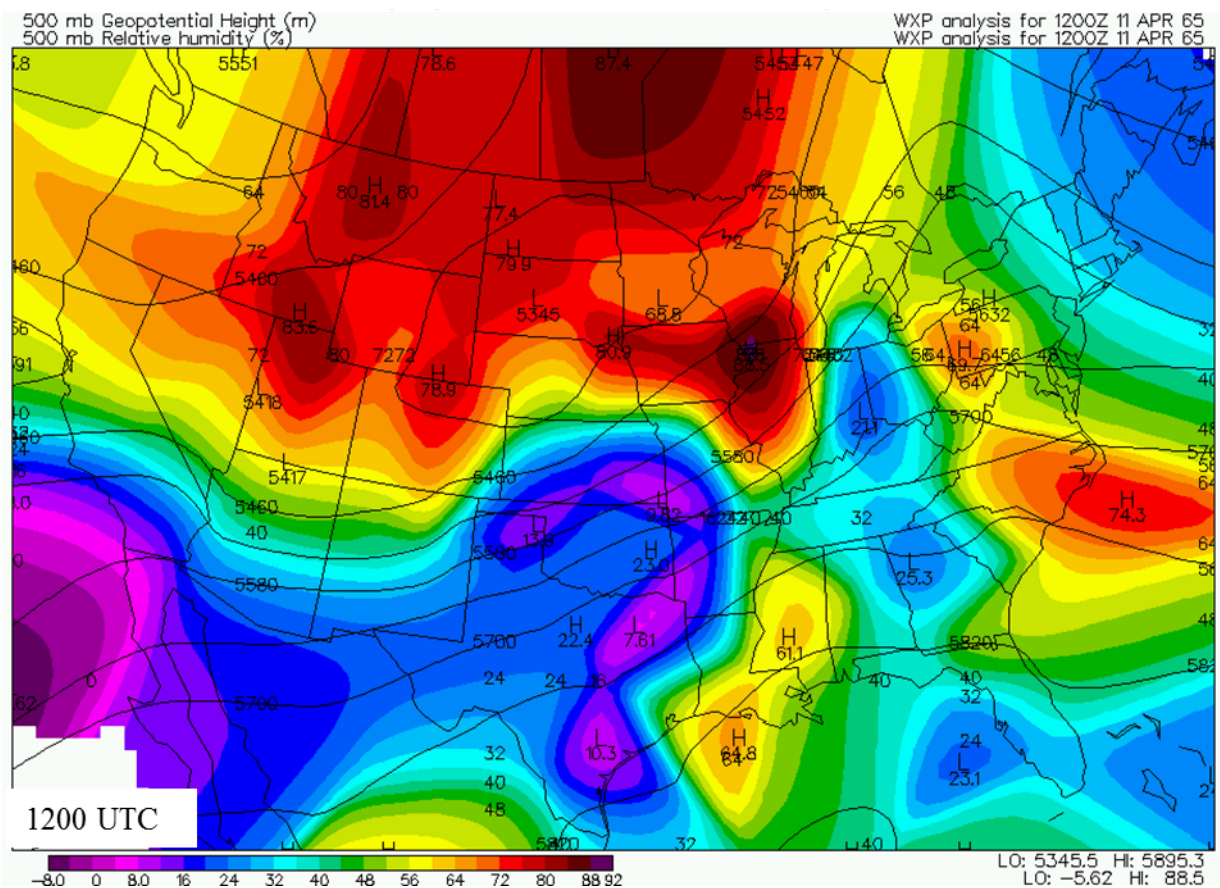


Fig. 4. Analysis of relative humidity (percent shaded, scale at bottom) and geopotential height (solid black) at 500 mb for 1200 UTC April 11. Image courtesy of Plymouth State University.

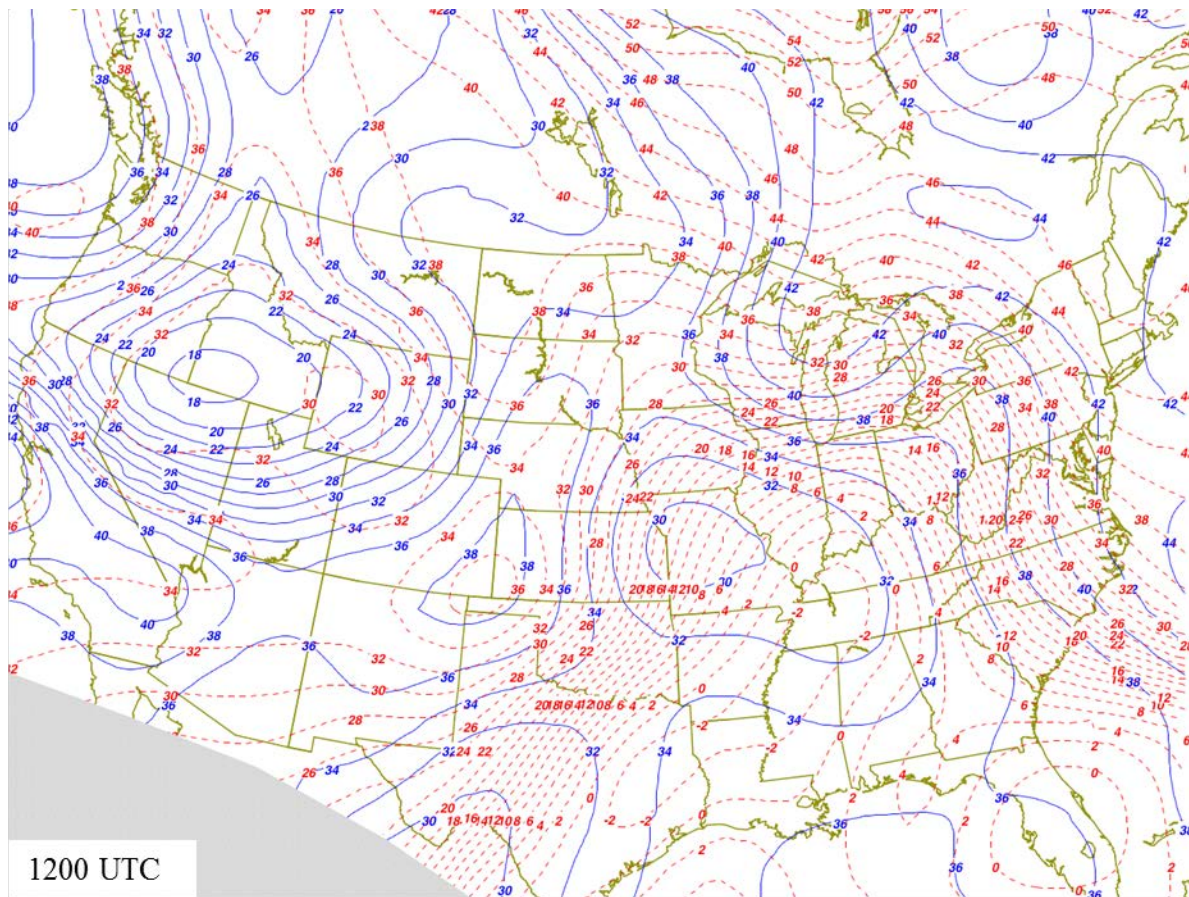


Fig. 5. Blue contours are the difference between the mean theta in the lowest hundred mb of the atmosphere to the level of this map, which is 300 mb. The red contours show the same function but for equivalent potential temperature (theta-e). Valid time is 1200 UTC April 11.

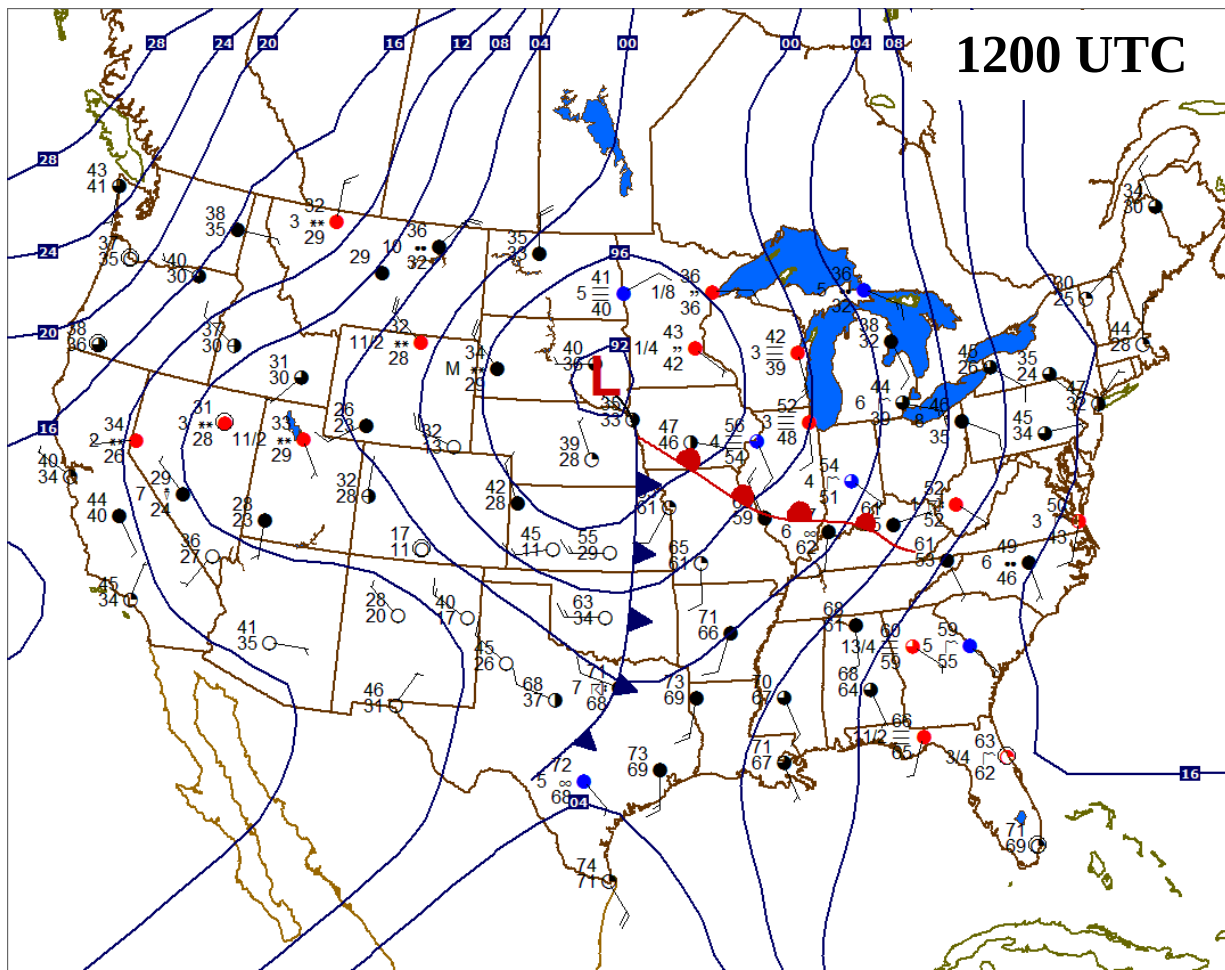
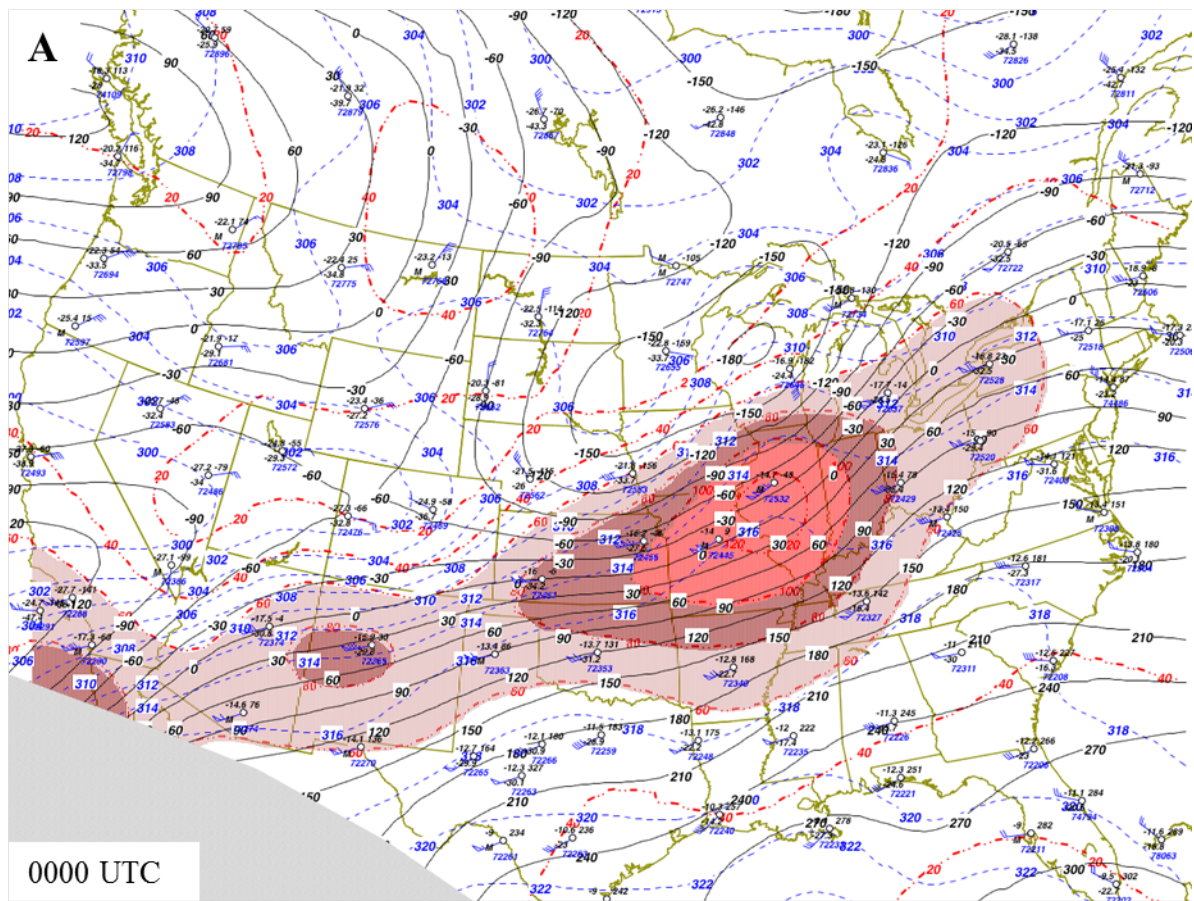


Fig. 6. Surface chart for 1200 UTC 11 April 1965 indicating frontal positions with mean sea level pressure contours (blue). Station plots (°F and kt) of present weather are included as well.



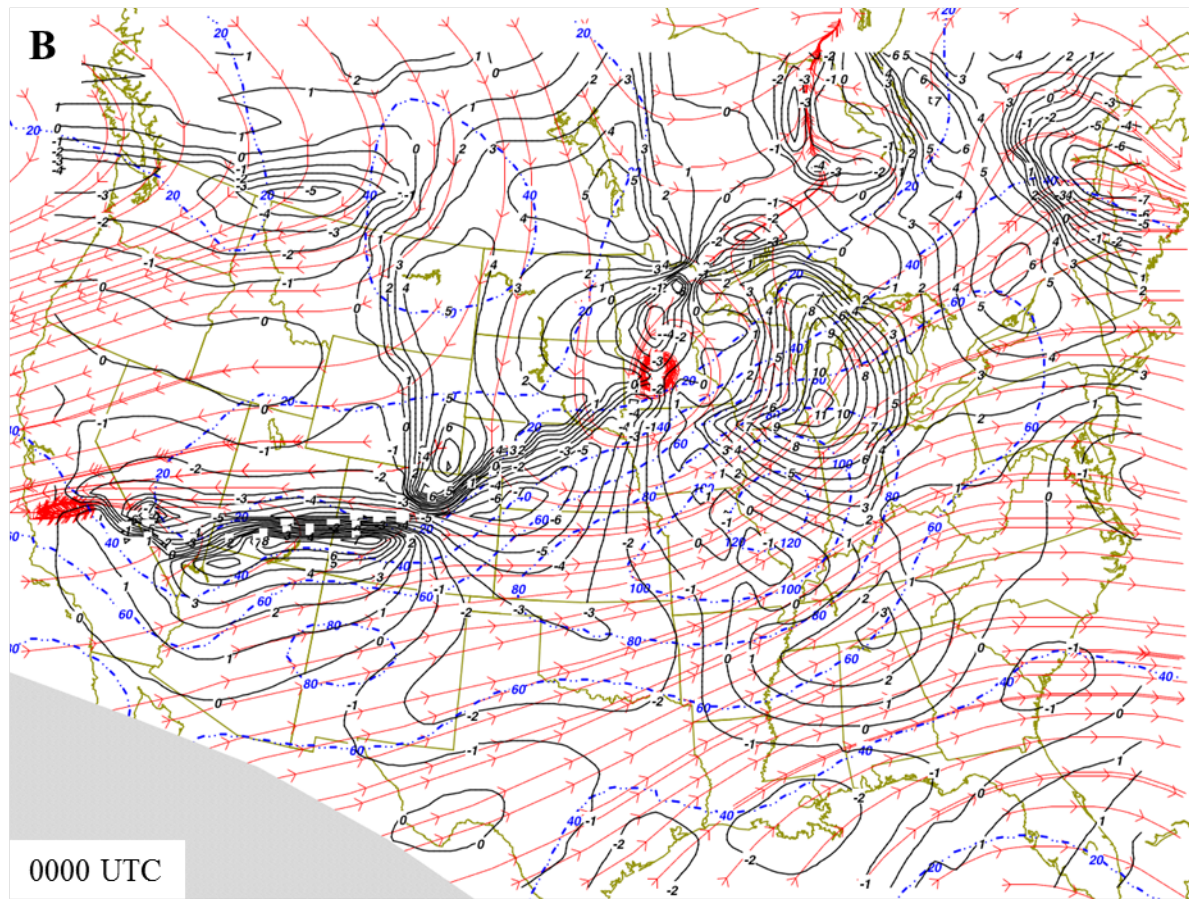


Fig. 7. (a) Same as Fig. 3b except for 0000 UTC 12 April. (b) Upper level analysis of diffuence (black lines), wind streamlines (red), and contours of wind speeds (60, 80, and 100 kt, blue stippled lines) at 0000 UTC April 12 for 500 mb.

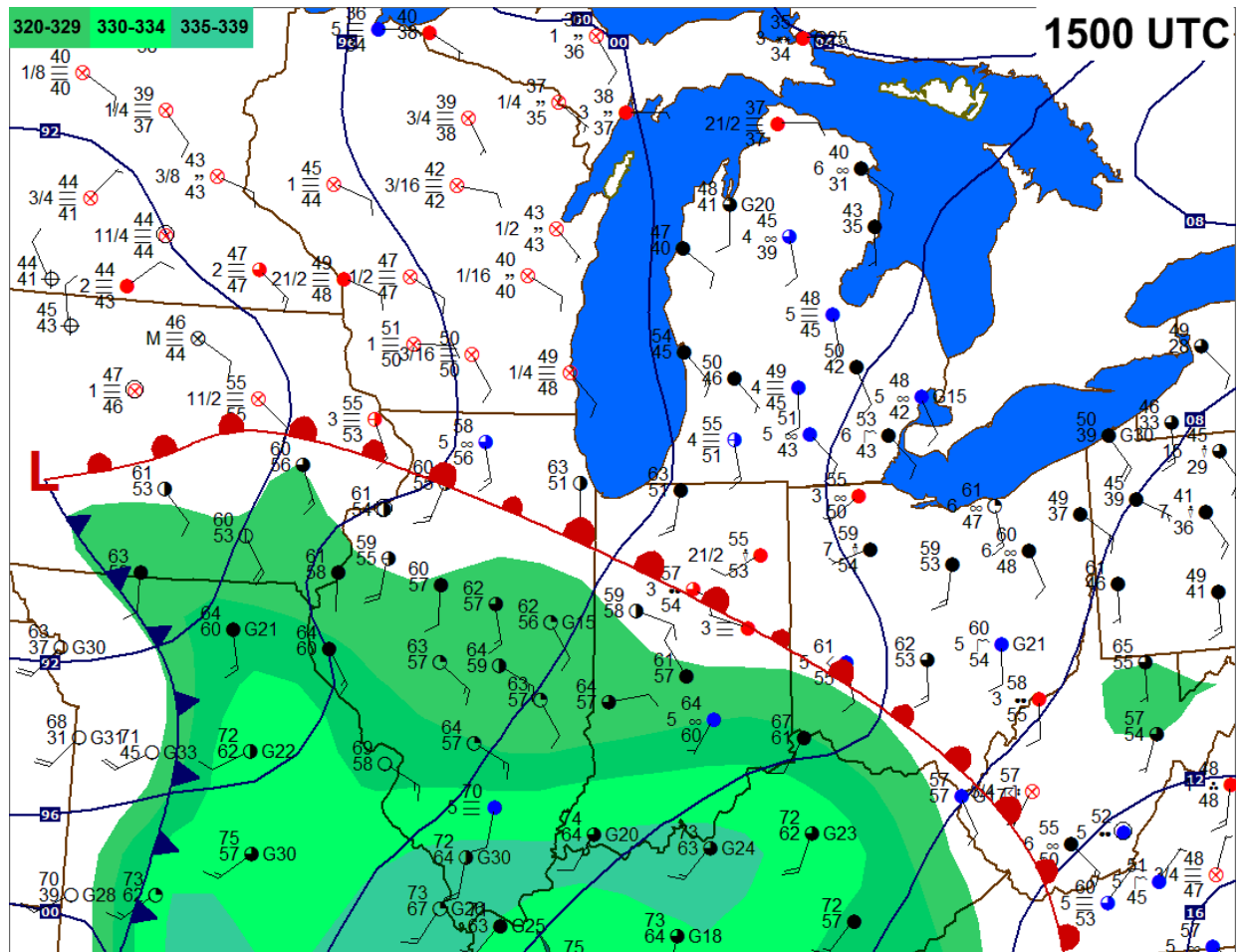


Fig. 8. Same as Fig. 6 except for 1500 UTC 11 April. Surface θ_e values are shaded (K, scale at upper left).

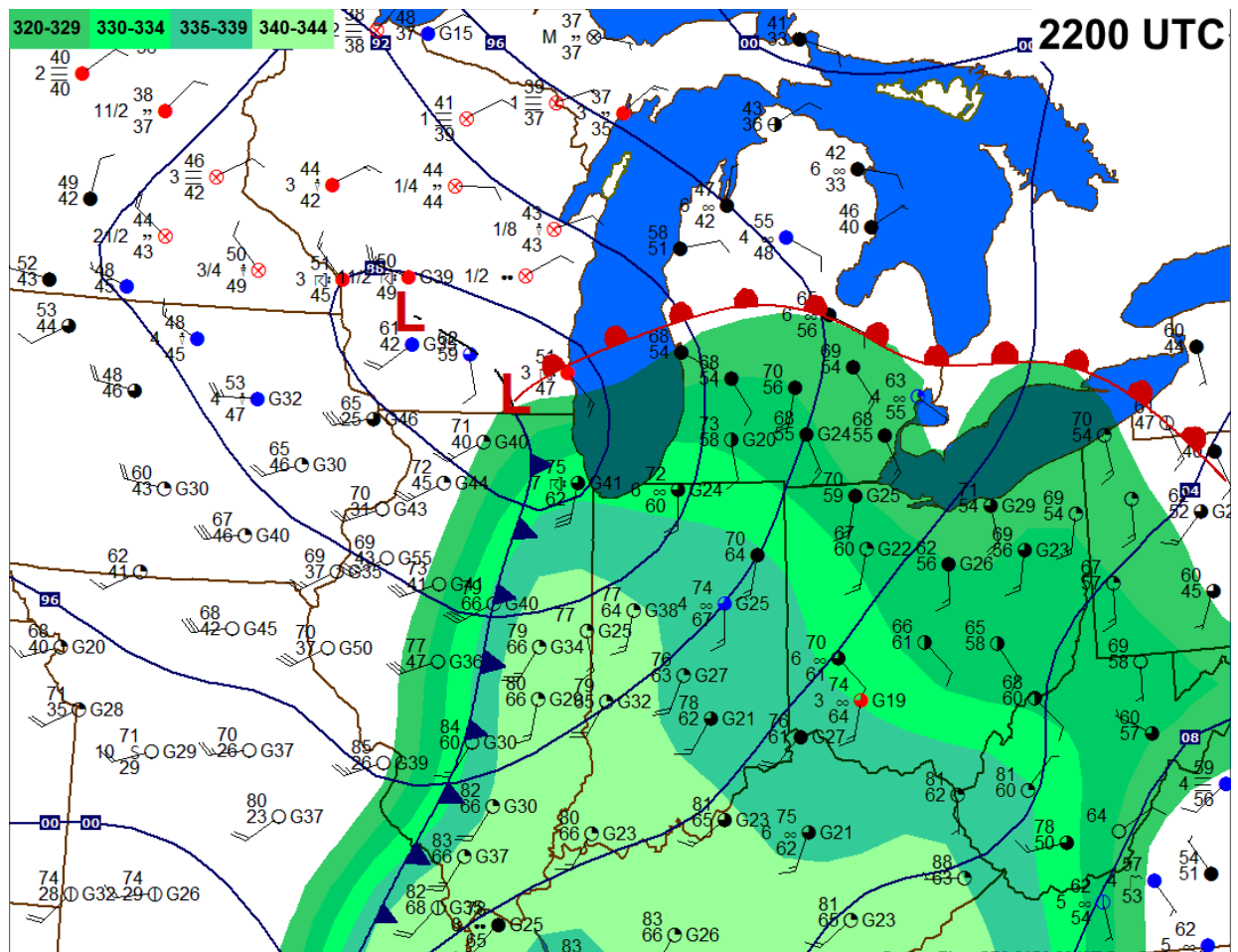


Fig. 9. Same as Fig. 8, except at 2200 UTC 11 April.

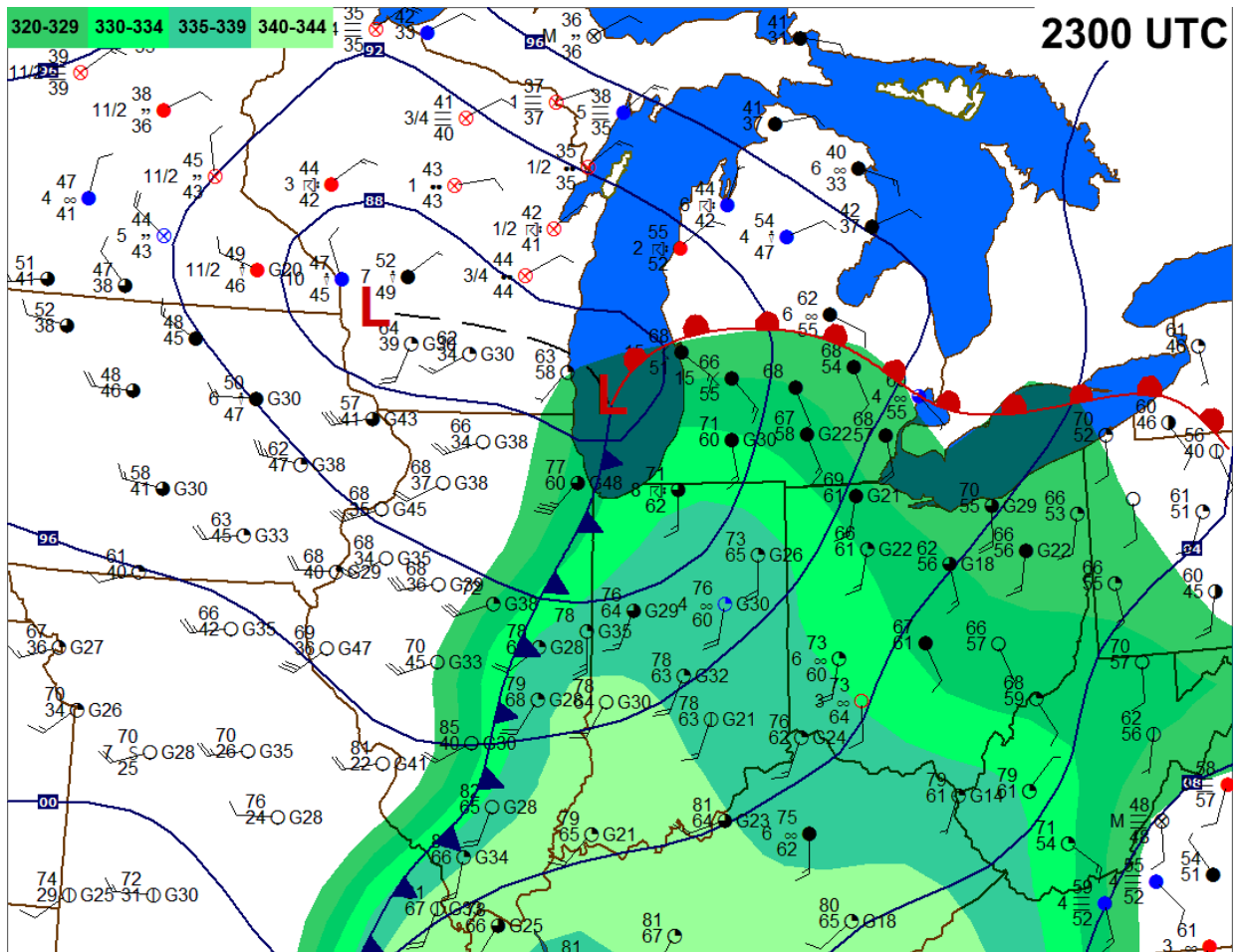


Fig. 10. Same as Fig.8, except at 2300 UTC April 11.

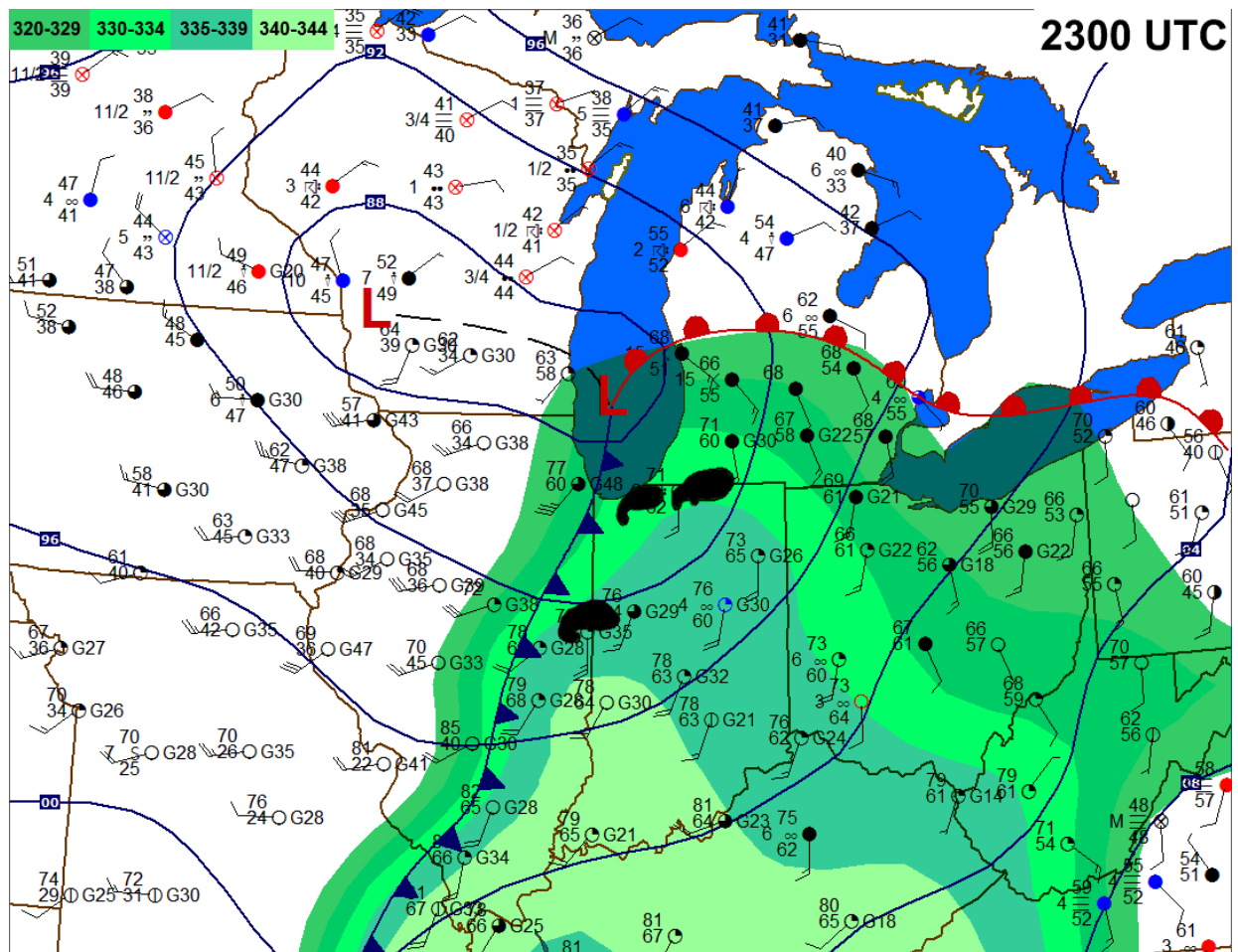


Fig. 11. Same as Fig.8, except approximate locations of observed supercell thunderstorms were added (not drawn to scale, black shading). Eastern supercell (near the Indiana–Michigan border) was drawn to contain a double hook structure, a feature that was confirmed per the Weather Surveillance Radar 1957 (WSR-57) radar image included in Fujita et al. (1970).

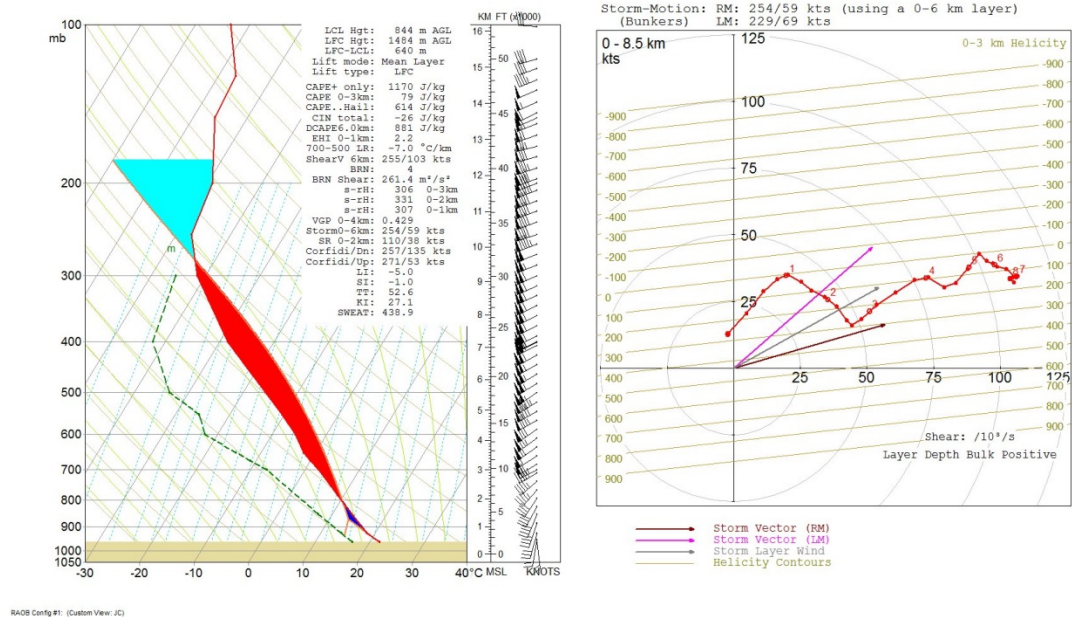
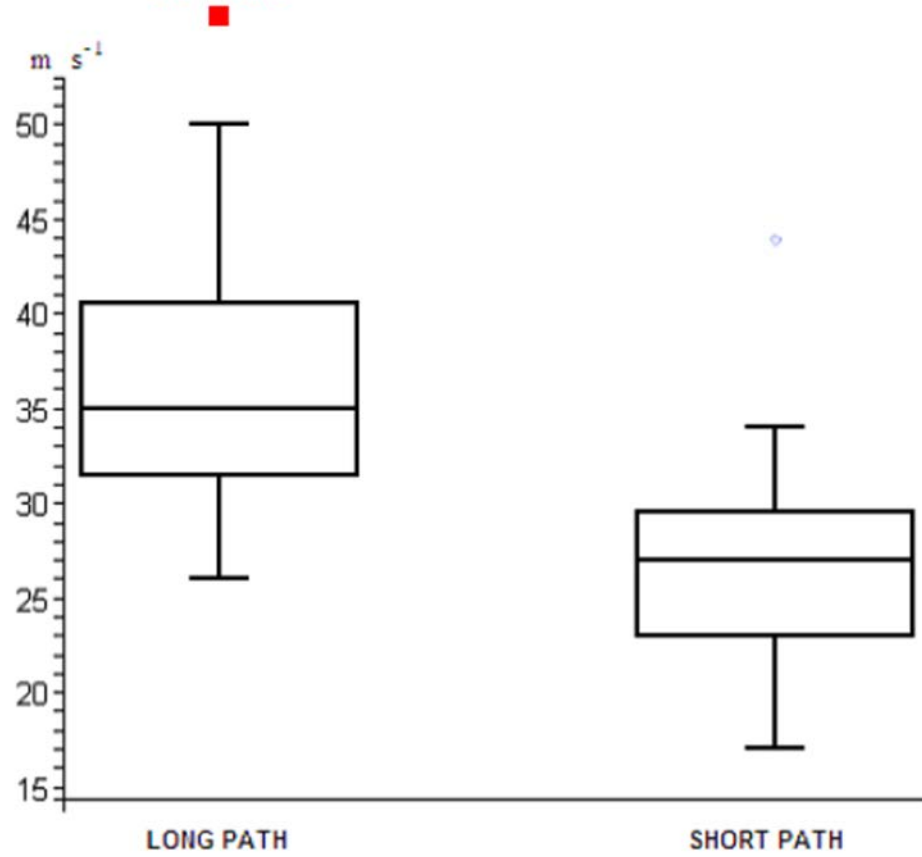


Fig. 12. Synthetic sounding and hodograph constructed using Peoria, Illinois (KPIA), and Flint, Michigan (KFNT) observations. Red filled area on the sounding is positive CAPE, dark blue (toward the bottom of the sounding) indicates convective inhibition (CIN), and light blue is above the equilibrium level.

A **57 m/s** 0-8 KM BULK SHEAR



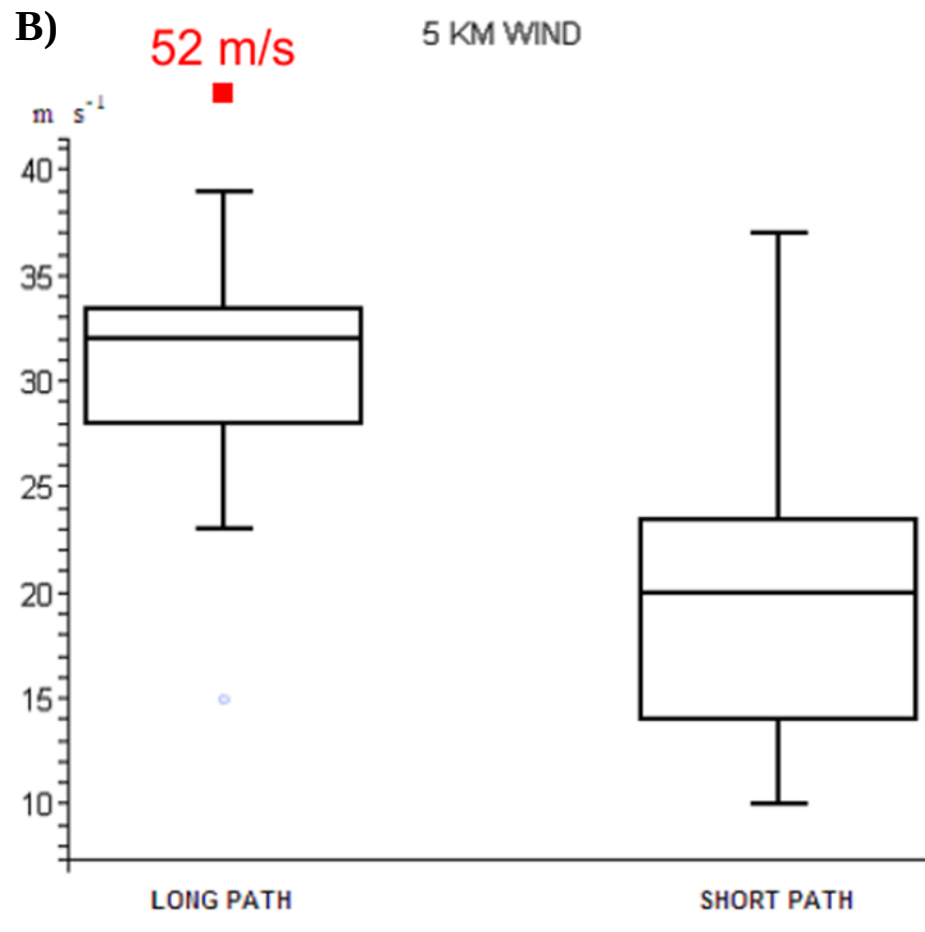


Fig. 13. Comparison of 8-km bulk shear (a) and 5-km wind (b) from synthetic KSBN sounding to Garner (2007) results for long-path and short-path tornadoes. Values derived from KSBN synthetic sounding are plotted in red.

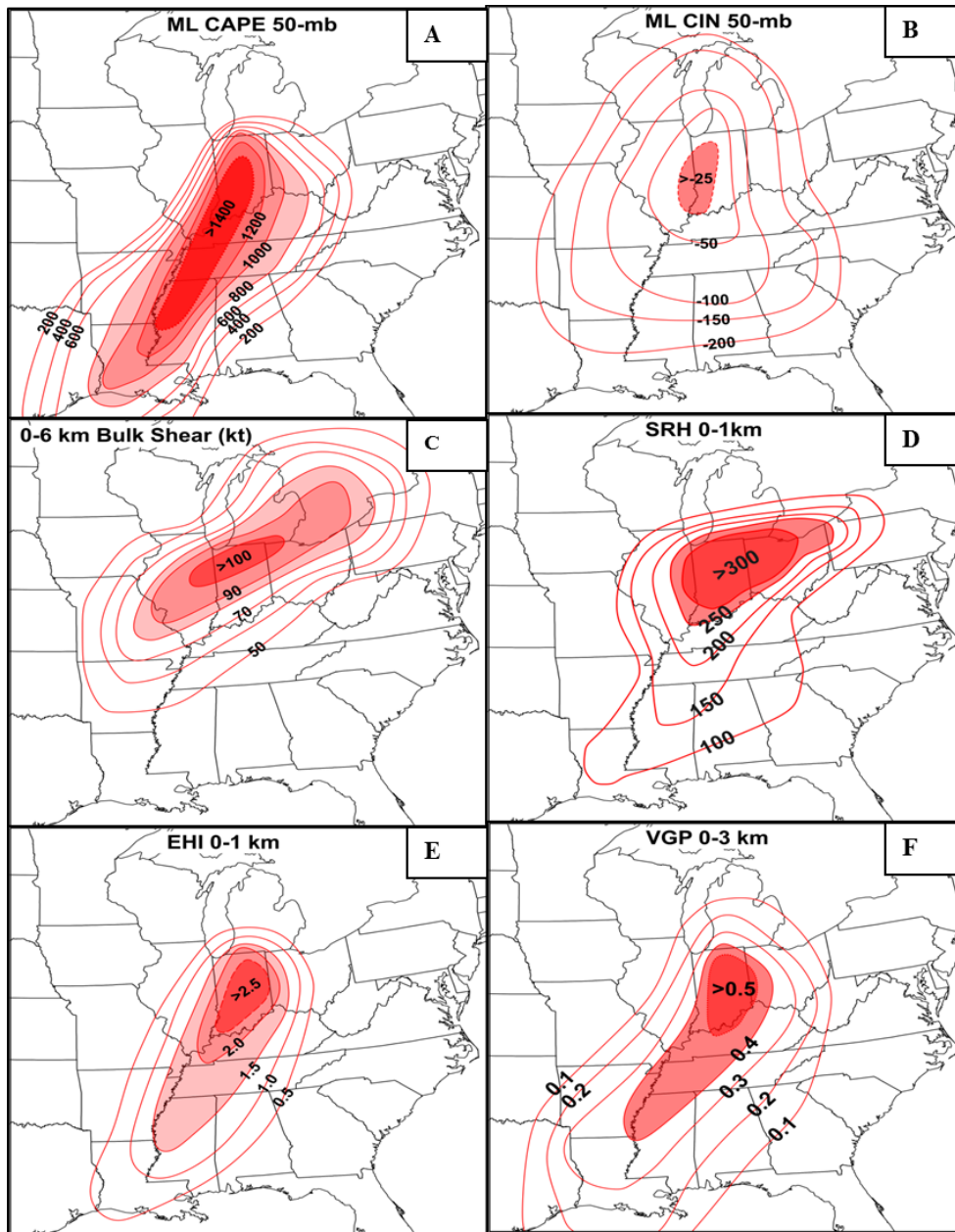


Fig. 14. Forecast variables important to the formation of severe thunderstorms and tornadoes valid 0000 UTC 12 April 1965. Values below first contour were not included. (a) Lowest 50-mb average layer parcel lift CAPE contoured every 200 J kg^{-1} , red fill area includes values 800 J kg^{-1} and above. (b) Lowest 50-mb average layer lift CIN, contoured every 50 J kg^{-1} , red fill area includes values -25 J kg^{-1} or greater. (c) 0–6-km bulk shear in knots contoured every 10 knots, red fill area includes values 80 knots and higher. (d) Storm-relative helicity (SRH) in the 0–1-km layer contoured every 50 $\text{m}^2 \text{s}^{-2}$ red filled area is 250 $\text{m}^2 \text{s}^{-2}$ or higher. (e) Energy helicity index in the 0–1-km layer, contoured every 0.5, red fill area includes values 1.5 or higher. (f) Vorticity generation parameter (VGP) contoured every 0.1 m s^{-2} , red fill area contains values 0.4 or higher.

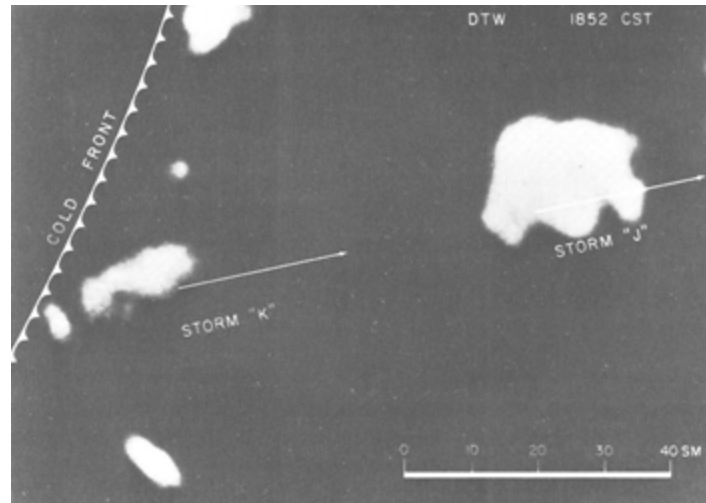


Fig. 15. WSR-57 radar image of storms K and J taken at 0052 UTC 12 April with cold front superimposed. From Fujita et al. (1970), ©American Meteorological Society. Used with permission.

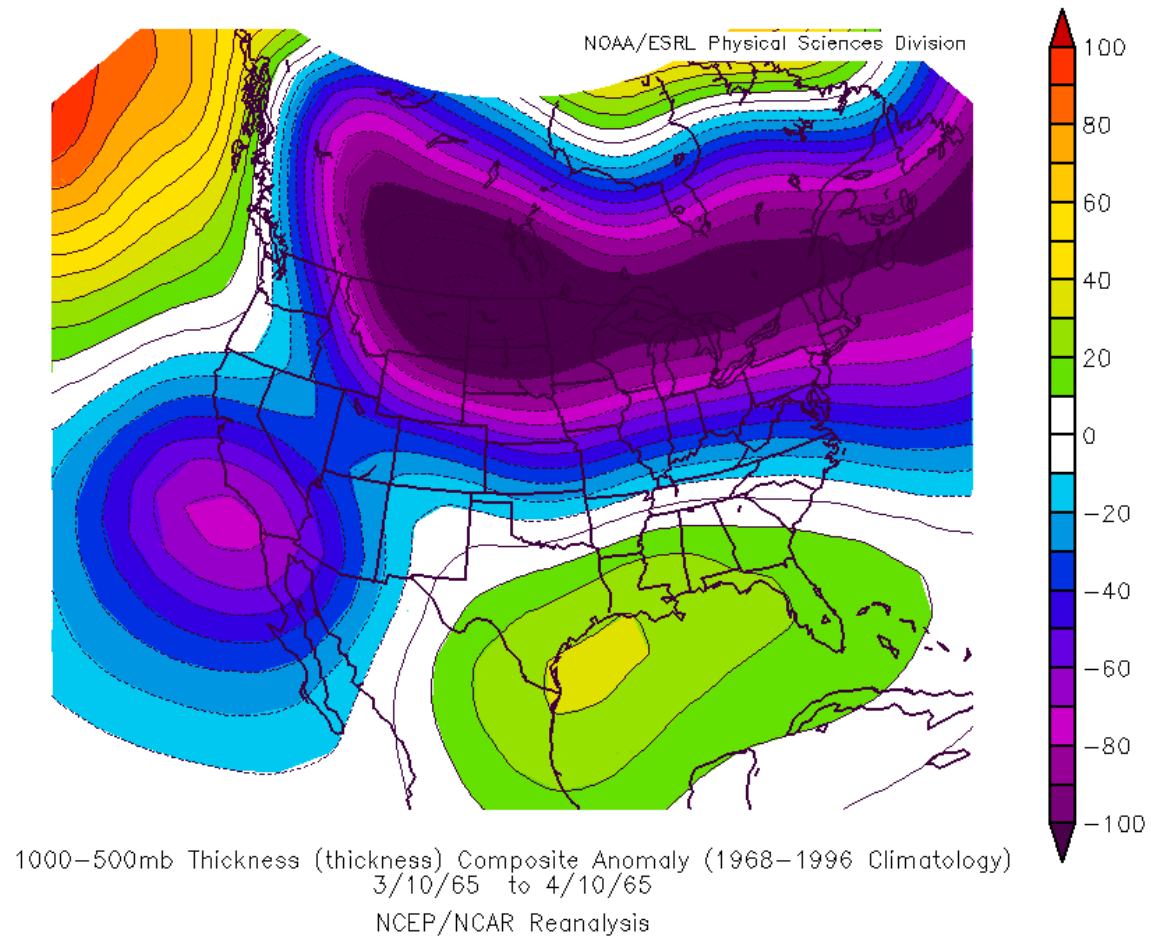
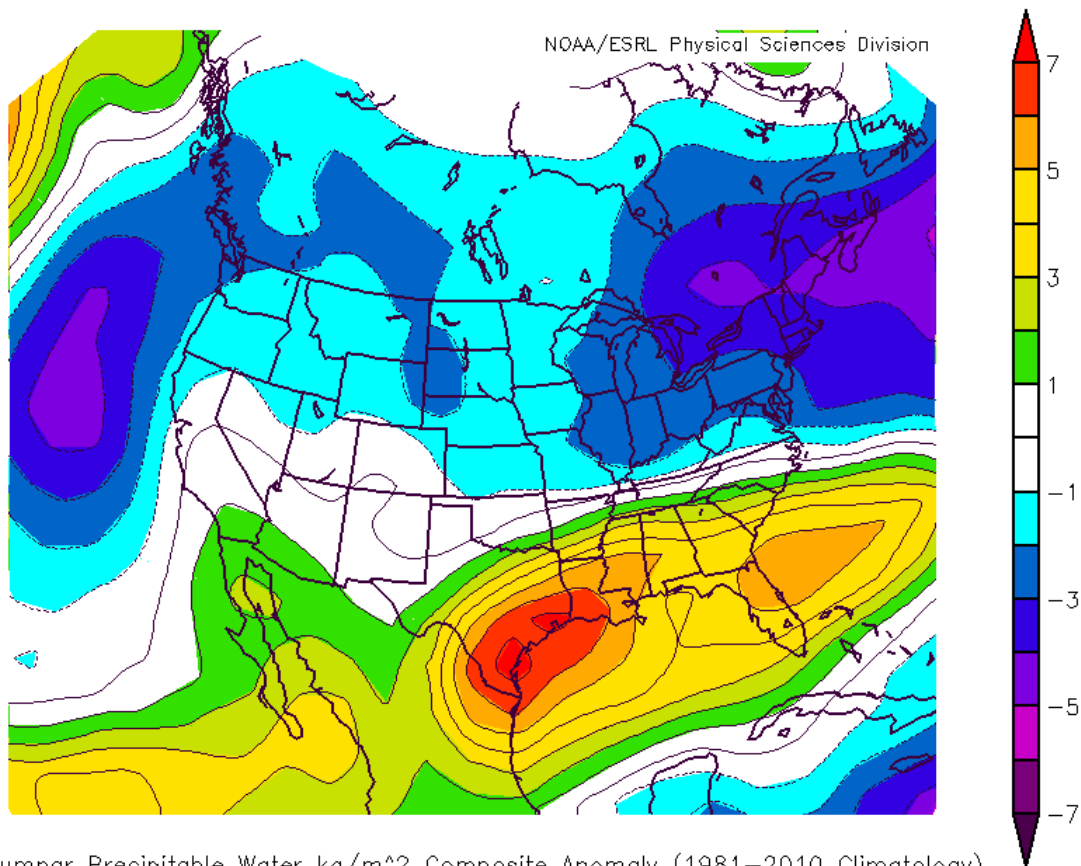


Fig. 16. Mean 1000–500-mb thickness anomaly, 10 March–April 10 1965 (m, scale at right); anomaly based on 1968–96. Image courtesy of Earth Systems Research Laboratory.



Columnar Precipitable Water kg/m^2 Composite Anomaly (1981–2010 Climatology)
 3/10/65 to 4/10/65
 NCEP/NCAR Reanalysis

Fig. 17. Mean columnar precipitable water anomaly, 10 March–April 10 1965 (kg m^{-2} , scale at right); anomaly based on 1968–96. Image courtesy of Earth Systems Research Laboratory.