THE MAY 2003 EXTENDED TORNADO OUTBREAK

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1. Introduction

In May 2003 there was a very destructive extended outbreak of tornadoes across the central and eastern United States (US). More than a dozen tornadoes struck each day from 3 May to 11 May 2003 (Table 1**,** Fig. 1, and online supplement A), with one or more tornadoes in 26 different states. This outbreak caused 41 fatalities, 642 injuries, and approximately $829 million dollars of property damage. More than 2300 homes and businesses were destroyed, and 11,200 sustained damage.

This extended outbreak was unusual in several aspects. First, the outbreak set a record for most tornadoes ever reported in a week[1] (334 between 4-10 May) and contributed to the month of May 2003 recording more tornadoes than any previous month in history, totaling 559, 361 of which occurred during the 9-day extended outbreak. Second, strong tornadoes (F2+, i.e., F2 or greater on the Fujita scale; Fujita 1971) occurred in an unbroken sequence of *nine straight days*. Third, tornadoes hit similar regions of the US on different days of the outbreak, even on successive days. Last, the center of the area of greatest tornado frequency during the 3 to 11 May period was located north and east of the average highest frequency position for strong tornadoes in May (Fig. 2 and Concannon et al. 2000). Fortunately, despite this being one of the largest extended outbreaks of tornadoes on record, it did not cause as many fatalities as in the few comparable past outbreaks, due in large measure to the warning efforts of National Weather Service, television, and private-company forecasters and the smaller number of violent (F4-F5) tornadoes.

We attempt to answer several questions in the rest of the paper. First, in section 2

[1] Such statistics, however, are somewhat misleading, as weaker tornadoes were underreported in previous decades. See Section 3 and Fig. 5.

we explore the unusual and persistent tornado-favorable conditions that fostered this outbreak. In section 3 we look back at past outbreaks and reanalysis data and attempt to determine just how unusual this outbreak was. In section 4 we explore the extent to which this event was forecastable, and we present conclusions in section 5.

2. What weather conditions fostered the extended outbreak?

The development of supercells that are the parent of most strong tornadoes requires two simultaneous factors: (1) an unstable thermodynamic environment that supports strong thunderstorm updrafts (e.g., Miller 1972), and (2) vertical wind shear (horizontal vorticity) that the thunderstorm updrafts can tilt and stretch to generate supercell rotation (e.g., Rotunno and Klemp 1985). Why some supercells produce tornadoes and others don't is still not well understood. Field experiments (Rassmussen et al. 1994) indicated that the production of a strong mesocyclone at low levels, a common feature in mature supercells, is not in itself a sufficient condition for tornadogenesis (Wakimoto and Atkins 1996, Wakimoto et al. 1998, Wakimoto and Liu 1998, Trapp 1999, Ziegler et al 2001, Dowell and Bluestein 2002a,b, Wakimoto et al. 2004). More recently, several studies have indicated that several other environmental factors such as low lifted condensation levels (e.g., Rasmussen and Blanchard 1998, Markowski et al. 2002) and large vertical shear and moisture near the surface (Thompson et al. 2003) are often associated with the formation of strong tornadoes. Enhanced buoyancy and shear low to the ground may be especially important contributors to the formation of low-level vertical vorticity through stretching and tilting.

Figure 3 illustrates a conceptual model of the stereotypical synoptic features and the region where instability and shear may be ample enough to support the development of supercells; similar models were proposed in Miller (1972) and Barnes and Newton (1983). In this model, a southerly low-level jet in advance of a strong surface low-pressure system transports warm, moist air from the Gulf of Mexico ahead of a dryline and cold front. Aloft, strong southwesterly winds prevail ahead of an approaching upper-level trough with very cold air. This configuration may superpose colder air aloft overtop of the warm, moist air, creating instability. A triangular region between the dryline and the warm front typically contains the most favorable combination of instability and wind shear necessary for supercell and tornado formation (though favorable shear and instability may occur even in the absence of this particular pattern).

Large tornado outbreaks require the presence of sufficient instability and favorable wind shear over a wide geographic region. Typically, several times during a month in spring such a pattern may exist for one or two consecutive days as a low-pressure system moves east from the Rocky Mountains. What was remarkable about early May 2003 was that the tornado-favorable pattern was present for so many days in a row in the same part of the central US.

A pattern quite similar to the idealized one of Fig. 3 occurred each day from 3 May through 11 May 2003. In fact, the time-average atmospheric features for this nine-day period were very similar to this ideal pattern (individual daily maps are presented in online supplement A). Figure 4a shows the 925 hPa winds averaged from 0000 UTC 4 to 11 May 2003. These winds flow northward from southeast Texas towards Missouri; during this period, boundary-layer mixing ratios were anomalously large in the warm sector, commonly exceeding 16 g kg^{-1}. This persistent flow controlled the location of the warm, moist, unstable air needed for severe thunderstorms, and, consequently, the location of greatest tornado incidence, which was centered slightly north and east of the climatological maximum for tornado activity during early May (Fig. 2). The moist flow at times reached farther inland from the Gulf of Mexico than shown in the average pattern (see online supplement A for daily maps). Another significant feature in Fig. 4a is the absence of northerly winds coming from Canada. During this period, no strong cold fronts entered the US, which would have displaced the unstable air mass from the region and terminated the outbreak. This factor played a key role in the longevity of this event.

Figure 4b shows the average upper-level jet stream at 250 hPa. The highest wind speeds in the jet sweep in an arc from southern California to Arizona and New Mexico, then across Oklahoma, Kansas, and Missouri. As in Fig. 3, the upper-level jet crosses over the low-level jet over Oklahoma, Kansas, and Missouri. Figure 4c shows that strong vertical wind shear was present over Oklahoma, central and east Kansas, Missouri, and western portions of Illinois, Kentucky, and Tennessee, where most of the tornadoes occurred. Strong shear was also present over parts of Texas and northern Arkansas, but other unfavorable weather factors inhibited thunderstorms from forming or tapping this rotation source there.

Figure 4d shows the average lifted indices[2] (LI; Galway 1956, Bluestein 1993, p. 447) for the period. The area of exceptionally low LI's, in red, covers the Central and Southern Plains and the Gulf Coast states. Most of the extended outbreak tornadoes fell

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[2] CAPE, or Convective Available Potential Energy (Bluestein 1993, p. 444), is a more common diagnostic of instability. For the renanalysis and forecast data used in this study, CAPE was not available, so instability was diagnosed instead from LI.

within these bounds, but even areas farther northeast had tornadoes on a day or two when warm, moist air reached farther inland from the Gulf of Mexico. Because of the averaging of some unstable and some stable days in these regions, the average LI shows up as more moderate.

This persistence of the patterns illustrated in Fig. 3 was key to the longevity of the outbreak. Nevertheless, through this period the jet stream also contained a series of short-wave troughs (online supplement A). As one trough moved east, which normally would have carried the tornado threat east as well, another trough moved in from the eastern Pacific. This succession helped to regenerate tornadoes in the same region. What caused this repeated series of short waves is unclear, but they appeared within a slowly evolving long-wave pattern that was very favorable for tornadoes in the US.

3. How unusual was this extended outbreak?

The frequent occurrence of strong tornadoes for nine straight days was clearly unusual, but just how unusual was it? The most straightforward way to examine this is to look to the climatological record of tornadoes to see how frequently similar events occurred. Comparisons of recent with historic tornado records are complicated by significant shortcomings in earlier records. The National Weather Service did not begin collecting data on weaker tornadoes until 1950, and rigorous day-to-day tornado reporting did not begin until the late 1970s. Population increases, new radar technology, an improved storm-spotting network, and a number of other factors now result in the detection and reporting of a much greater number of weak tornadoes (F0 and F1) than in the past (Fig. 5). Conversely, historic reports of "strong" (F2+) tornadoes were based on a variety of sources and are of comparatively high quality back to 1916 (Grazulis 1993). Figure 5 shows no long-term upward trend in the frequency of F2+ tornado occurrence. Hence we will compare only the strong tornado statistics from this outbreak to the similar statistics from past outbreaks.

Outbreaks with at least 50 strong tornadoes were examined back to 1916. Table 2 includes the five other such events that were roughly comparable to May 2003. Three events (1917, 1930, 1949) were qualitatively of the same scale in terms of duration and number of strong tornadoes as the 2003 extended outbreak, although only the 1949 extended outbreak matches 2003 with having strong tornadoes on each day somewhere in the country. There were also fewer "violent" (F4-F5) tornadoes and deaths in the May 2003 event than in the other events.

The 2003 extended outbreak was geographically displaced to the east of the 1930 and 1949 extended outbreaks (Fig. 6). The 1917 event, which had devastating tornadoes in central Illinois and western Tennessee, covered much of the same area as the May 2003 outbreak.

Other than May 2003, there have been no recorded long (1 week or longer) outbreak sequences with at least 50 strong tornadoes since 1949. However, there are two notable events with over 50 strong tornadoes that occurred over a shorter period of only a few days (Table 2). In particular, the single 24-hour period of 3-4 April 1974 actually produced more strong tornadoes and deaths than the whole May 2003 extended outbreak. Hence, a better way of gauging outbreak severity is to consider tornado counts over a given period of time, regardless of whether the tornadoes were spread uniformly over a week or concentrated in a day or two. Figure 7 shows the maximum number of strong tornadoes recorded during any consecutive 9-day period for each year from 1916 to 2003. The six highest values were actually associated with the six sequences in Table 2. The 1917, 1930, 1949, and 2003 peaks were extended outbreak sequences while the 1965 and 1974 outbreaks were shorter sequences.

The nine consecutive days in May 2003 with an F2+ tornado was the longest consecutive sequence of days since record keeping began in 1916. Is it possible to estimate the likelihood of such an unusually extended sequence of days with severe tornadoes? Evaluating the statistical likelihood of events that have occurred once or twice in the period of record is problematic. However, a return frequency can be estimated from related but less rare events. Figure 8 provides evidence that events like this occur roughly from once a decade to once a century. On this figure, the green dots indicate the frequency of occurrence per century of 5 or more F2+ tornadoes each day in a 9-day period (estimated from a 74-year tornado record). There were approximately 330 days with more than 5 F2+ tornadoes for at least one day during the 9-day period, approximately 72 instances where 2 out of the 9 days had at least 5 F2+ tornadoes, 33 instances with 3 of the 9 days, 8 instances with 4 of the 9 days, and approximately 2.66 days per century with 5 out of the 9 days. The green line provides a regression line of best fit to this data. Using the data in column 3 of Table 1, for the 2003 outbreak we can see that 5 of the 9 days had at least 5 F2+ tornadoes, thus indicating such an event would be expected to recur only 2.7 times a century (plotted with green double circle). A similar analysis can be repeated for the occurrence of 8 tornadoes per day over a 7-day period (data in red), and 10 tornadoes per day in a 7-day period (blue). The 2003 outbreak had 3 days with at least 10 tornadoes during a 7-day period, with the fitted regression indicating about 4 occurrences per century. There were 4 days in 2003 with at least 8 tornadoes in a 7-day period, which is estimated from the regression equation to occur only slightly more than once a century. Hence, generalizing from all of these results, similar events occur from once a decade to once a century, depending on the metric. These results are consistent with the previous finding of six roughly comparable outbreaks from the past 88 years.

Three of the four extended outbreak sequences occurred between 1917 and 1949, followed thereafter by an absence of such sequences until 2003. We believe this is most likely explained by the underlying event rarity and randomness rather than some long-term decreasing trend in the frequency of extended outbreaks.

As opposed to examining the tornado record, we could also evaluate the event rarity by determining how unusual it was for tornado-favorable conditions to exist for many days over the same region. To do this, we examined the instability and wind parameters similar to those described above for each day in April and May for the period 1979 through 2003 and developed a quantitative model for tornado risk based on this and observational data (see description of this technique in online supplement B). Figure 9 shows the resulting daily time series for each year of the fraction of an area in the central and eastern US at elevated risk for tornadoes based on this analysis. Peaks on the diagrams indicate times when large areas were at elevated risk of tornadoes based on stability and shear conditions. The broad peak in early May 2003 shows that weather conditions on these days were more persistently favorable for tornadoes over a large area than they were during any other April or May during the last 25 years. It is important to note that while this simple measure helps to identify conditions favorable for supercell thunderstorms, such conditions do *not* always result in large tornado outbreaks because other factors are also involved (e.g., the peak in April 2001 was not accompanied by a major outbreak).

4. How predictable was this outbreak?

Did the National Weather Service (NWS) Storm Prediction Center (SPC) do a creditable job of providing advanced warnings many days in advance of the outbreak and more specific, accurate forecasts as the outbreak drew closer? Yes.

Consider the official NWS forecasts for the start of this extended outbreak; specifically May 4, 2003 in particular, the day with the most strong tornadoes and fatalities. Five days in advance, forecasters noted that severe weather was possible over a large area of the central and eastern US over a several-day period (Fig. 10a). As this target day approached, forecasters were able to narrow their predictions of where the severe weather was likely (Figs. 10b-c). On May 4, they issued watches (see Fig. 10d)[3] with an average of over 2 hours lead time before the incidence of the first tornado (US Dept. of Commerce, 2004, p. 11). The Weather Forecast Office warnings (Fig. 10e) were issued with an average of 19 minutes lead time, and all fatalities occurred within watch and warning regions (ibid, p. 2). And of course, though terribly destructive, the actual tornado paths covered only a relatively small geographic area (Fig. 10e).

The skillful severe weather outlook area 5 days in advance reflects the improving skill of National Weather Service numerical forecasts. Figure 11 presents the analyzed

[3] Several regions outside the region plotted in Figures 10d-e also were covered by watches and warnings.

conditions as well as the 2-day and 5-day National Centers for Environmental Prediction (NCEP) medium-range forecast (MRF) model ensemble-mean forecasts (Toth and Kalnay 1997) valid on 0000 UTC 5 May 2003. As indicated, even the 5-day forecasts provided reasonably accurate guidance on the potential for tornado-favorable conditions in the central US, in this case similar in accuracy to the 2-day forecast. Similar maps for other days during the outbreak as well as the daily tornado tracks are available in online Supplement A.

Figure 12 shows the NCEP medium-range ensemble-mean forecast wind and instability fields corresponding to those observed in Fig. 4, averaged for 4-11 May 2003 and started from a forecast on 28 April (a 6- to 13-day forecast). The forecasts showed a very strong upper-level jet streak (see Fig. 12b) entering Texas and large low-level wind shear centered over Texas (Fig. 12c). Ensemble mean forecast instability was not as pronounced as was observed, but a broad area of unstable conditions was forecast from the Rockies to the east coast of the US (Fig. 12d). Comparing forecasts against observed values shows that forecast instability was lower than observed and was located about 200 to 500 km southwest of the observed peak. While the subsynoptic details were not correctly forecast, this longer-lead forecast still indicated a favorable jet stream configuration, suggesting that the potential for severe weather in the central US was significantly higher than average.

5. Summary

In May 2003 there was an unusual extended tornado outbreak, with multiple F2+ tornadoes on each day from 3 to 11 May. This outbreak was destructive, deadly, and costly in terms of property damage. Yet the loss of life was smaller when compared to the few similar prior outbreaks, probably a result of useful tornado warnings and response and a somewhat smaller percentage of F4 and F5 tornadoes than in the few comparable outbreaks.

The unusual string of successive days with tornadoes was the result of a quasi-stationary weather pattern that was conducive to tornadoes. This pattern produced a continual flow of low-level, warm, moist air off the Gulf of Mexico up the Mississippi valley, overridden by stronger, west-southwest winds aloft. No cold fronts from Canada intruded into the central US during this period, which would have stabilized the atmosphere and terminated the outbreak.

An analysis of the outbreak showed that events of similar severity tallied over a 9-day period have occurred 5 other times in the last 88 years. None of these prior outbreaks had strong tornadoes each of the 9 days, and no time within the last 25 years had such a long sequence of tornado-favorable conditions over a large fraction of the US.

While it is not possible to fully mitigate the damage from strong tornadoes, with adequate warning and training, loss of life can be minimized. The reduced loss of life during this outbreak can in part be attributed to the good weather forecasts. These in turn reflect efforts of the meteorology community: the researchers providing an improved understanding of severe weather dynamics; the numerical modelers, producing relatively accurate numerical guidance many days in advance; instrument developers, permitting the real-time monitoring of the dangerous weather; and especially the nation's severe weather forecasters, who worked diligently and nearly nonstop for nine straight days through the extended outbreak.

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Figure 8: Observed (colored symbols) and fitted regression lines for different series of large number of daily F2+ tornadoes occurring on several days during a short period of time. Green symbols and lines associated with having at least 5 tornadoes on a day in 9 day period, red for having at least 8 tornadoes in 7 day period, and blue associated with at least 10 tornadoes in 7 day period. Double circles represent estimated recurrence frequency for observed reports in May 2003, in events per century. Raw data from Grazulis (1993) for period 1921-1993.

Figure 9. Time series of the fraction of the area within central and southeastern US with conditions favorable for tornado outbreaks as obtained from large-scale meteorological analyses. Data is plotted for April and May from 1979 to 2003 (See online supplement B). Favorable areas are established by the presence of sufficient wind shear and instability. A larger fraction indicates a larger area with tornado-favorable conditions. Days with greater than 20 percent coverage are highlighted with red.

Figure 10. (a) NOAA hazards assessment issued 30 Apr 2003 for increased risk of severe thunderstorms for the period 02-06 May 2003. (b) NOAA forecast probability of

severe weather (within 25 miles of any location) issued 1200 UTC 02 May for the period 1200 UTC 04 May to 1200 UTC 05 May 2003. (c) NOAA forecast probability of tornadoes (10% probability of strong tornadoes shaded) issued 1600 UTC on 04 May 2003 for the period 1630 UTC 04 May to 1200 UTC 05 May 2003. (d) NOAA severe thunderstorm (purple) and tornado (red) watch boxes issued on 04 May 2003, (e) NOAA tornado warnings issued on 04 May 2003 with observed tornado tracks.

Figure 11. Analyses (top row), 2-day forecasts (middle row) and 5-day forecasts (bottom row) all valid at 0000 UTC 5 May 2003. The maps depict sea-level pressure (hPa), 500 hPa geopotential height (m), Lifted Indices (LI; degrees C), and surface to 500 hPa wind shear (ms^{-1}). The top panels determined from NCEP-NCAR reanalyses and the middle and bottom panels the NCEP MRF ensemble mean forecasts. Color tables apply to all three panels in the column.

Figure 12. As in Figure 4, but here for a 15-member ensemble-mean forecast started at 0000 UTC 28 April 2003, valid for the period 0000 UTC 4 May 2003 – 0000 UTC 11 May 2003, (a 6- to 13-day forecast). (a) Wind direction and magnitude at 925 hPa. (b) wind direction and magnitude at 250 hPa, (c) wind shear, the vector difference between surface winds and winds at 500 hPa, (d) lifted index (deg C).

Date	Total number of tornadoes	Number of F2-F5 tornadoes	Number of F4-F5 tornadoes	Number of Fatalities
May 3	13	1	0	0
May 4	81	26	5	38
May 5	25	1	0	0
May 6	75	8	1	2
May 7	29	1	0	0
May 8	45	10	0	0
May 9	28	2	0	0
May 10	51	11	1	0
May 11	14	5	0	1
Total	361	65	7	41

Table 1 – Number of tornadoes and tornado fatalities per day between 3 and 11 May 2003, and the numbers of strong (F2-F5) and violent (F4-F5) tornadoes, rated using the Fujita Scale (Fujita 1971). Data from National Weather Service Storm Prediction Center.

Year	Number of "strong" (F2-F5) tornadoes	Number of "violent" (F4-F5) tornadoes	Number of Fatalities
1917 (7 of 8)	63	15	383
1930 (7 of 9)	67	13	110
1949 (8 of 8)	73	9	66
1965 (5 of 5)	51	21	256
1974 (4 of 4)	103	30	309
2003 (9 of 9)	65	7	41

Table 2. Summary of four long-sequence outbreaks and two short-sequence outbreaks. Parenthetical values after year are number of days with at least one strong tornado out of total days in sequence.

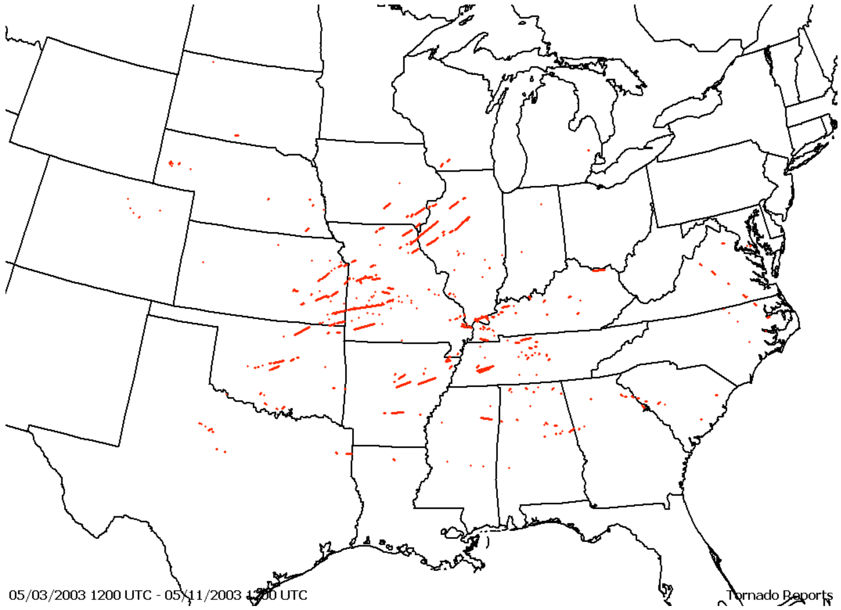

Figure 1. Tornado tracks arising from the May 2003 outbreak from 1801 UTC 03 May 2003 (12:01 CST) through 1759 UTC 11 May 2003 (11:59 CST), comprising eight 24-hr periods.

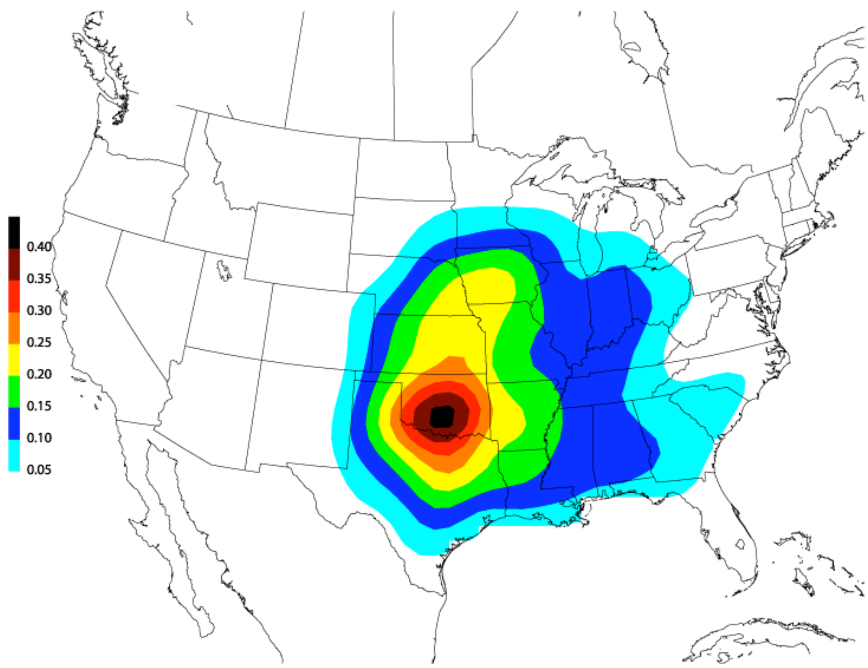

Figure 2. Relative climatological threat in percent of F2 or stronger tornadoes within 40 km of given location for the week centered on 6 May, analyzed from tornado data from 1980 to 2002.

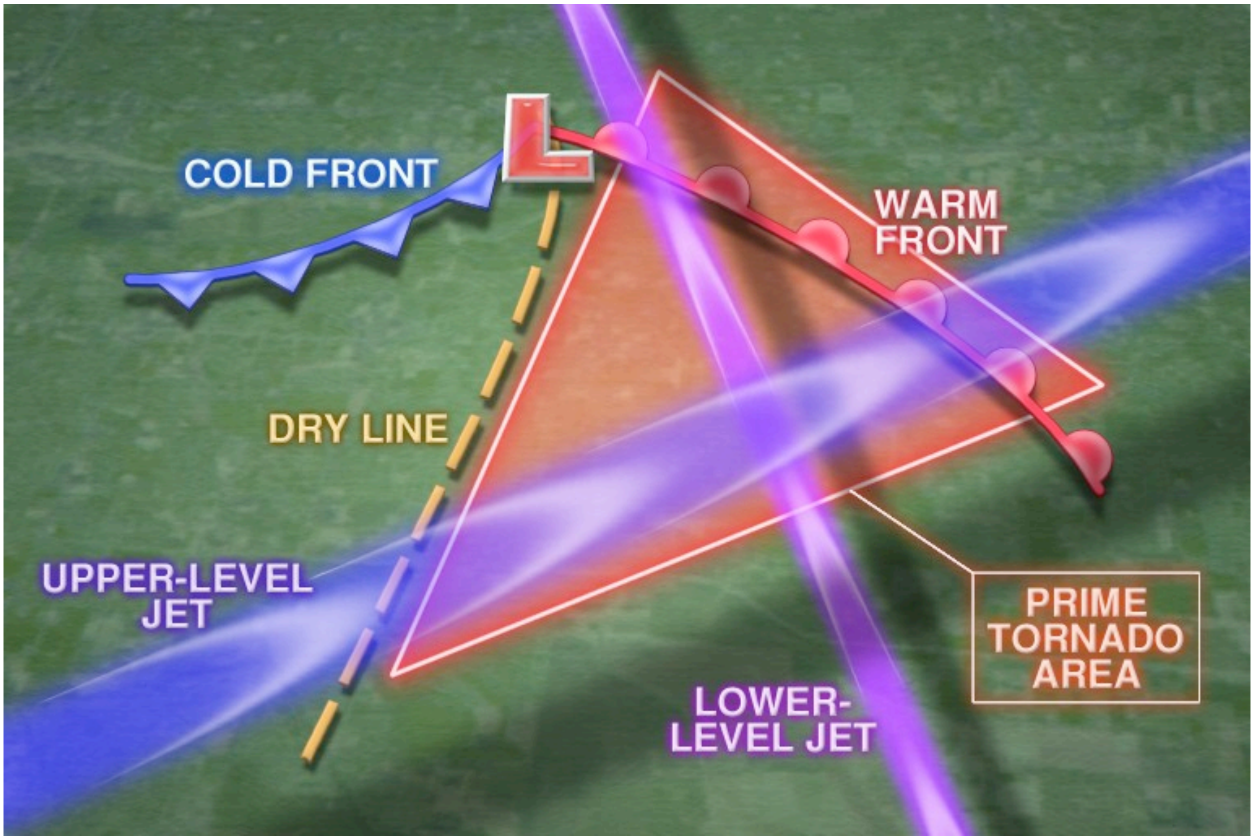

Figure 3. Synoptic conditions typically associated with a large tornado outbreak. Red area indicates region of expected tornadoes. [Courtesy of AccuWeather, Inc.]

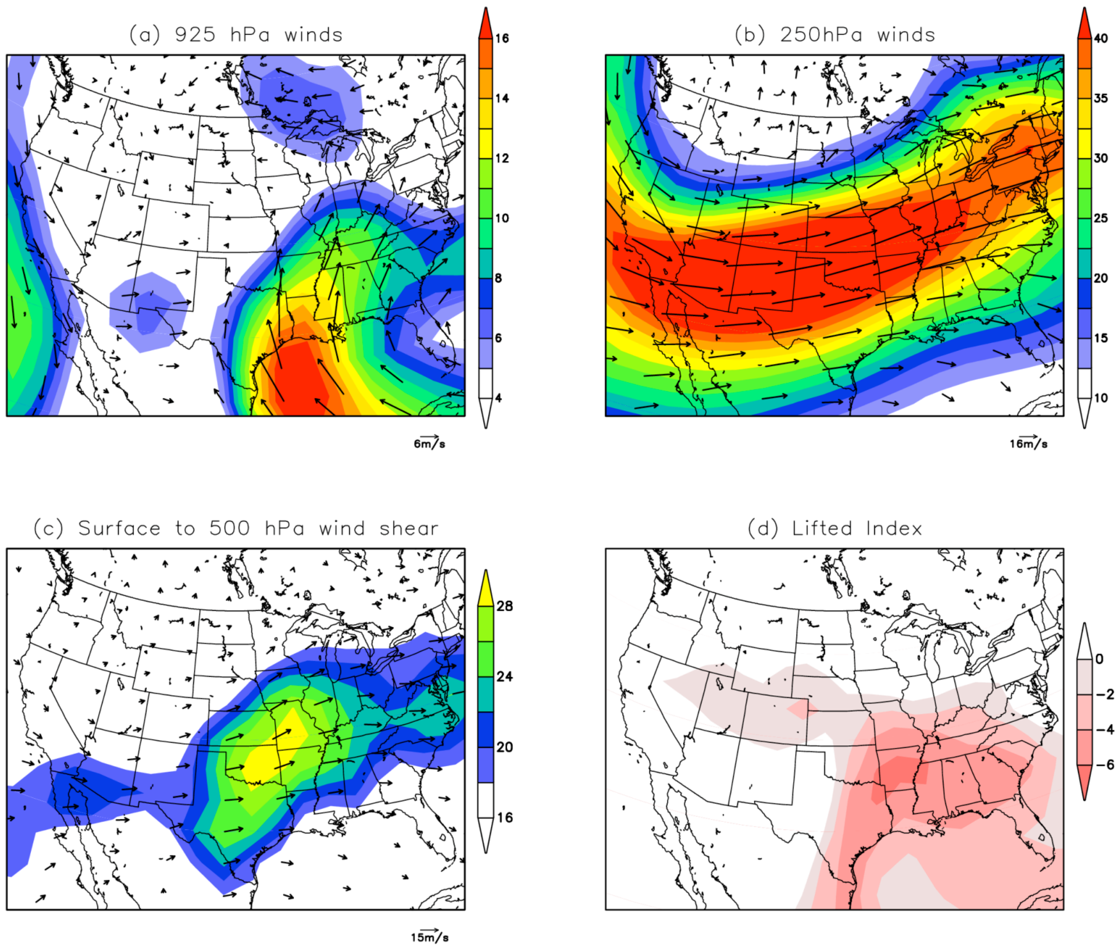

Figure 4. Average analyzed (true) wind and lifted indices from 0000 UTC 4 May 2003 – 0000 UTC 11 May 2003 using only 0000 UTC data. (a) Wind direction and magnitude at 925 hPa, (b) wind direction and magnitude at 250 hPa, (c) wind shear, the vector difference between surface winds and winds at 500 hPa, (d) lifted index (deg C).

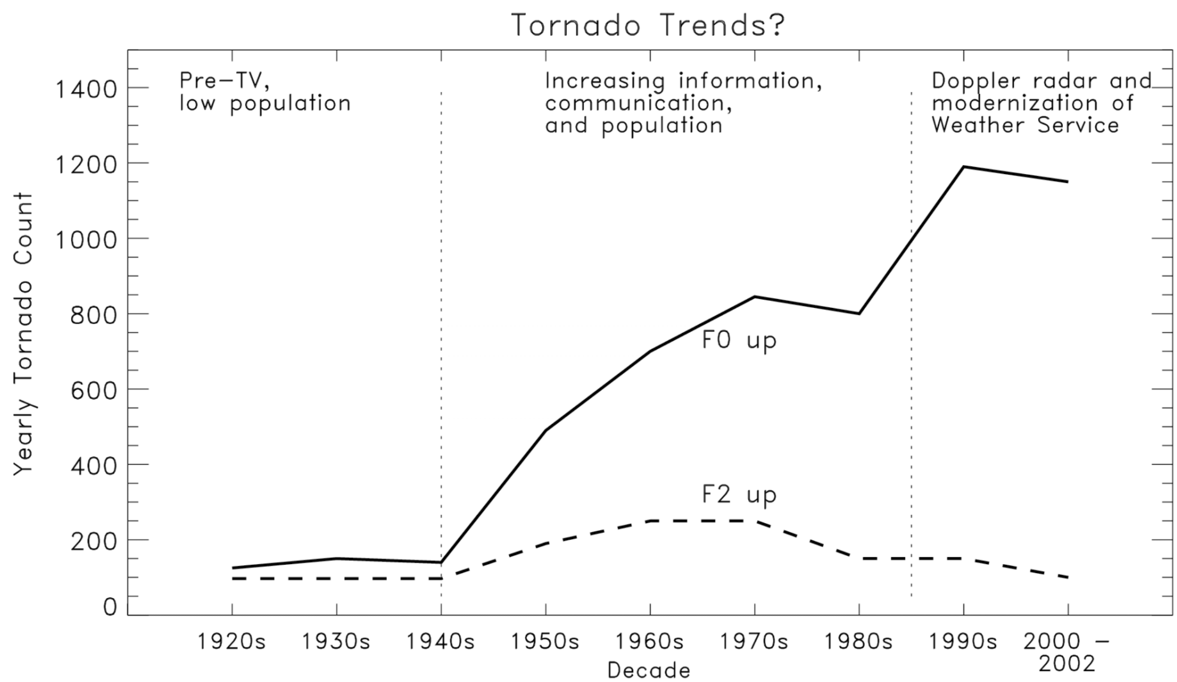

Figure 5: Yearly count of tornadoes by decade. Strong tornadoes (F2 and higher) are shown in dashed curve. Yearly total count of all tornadoes is shown in solid curve.

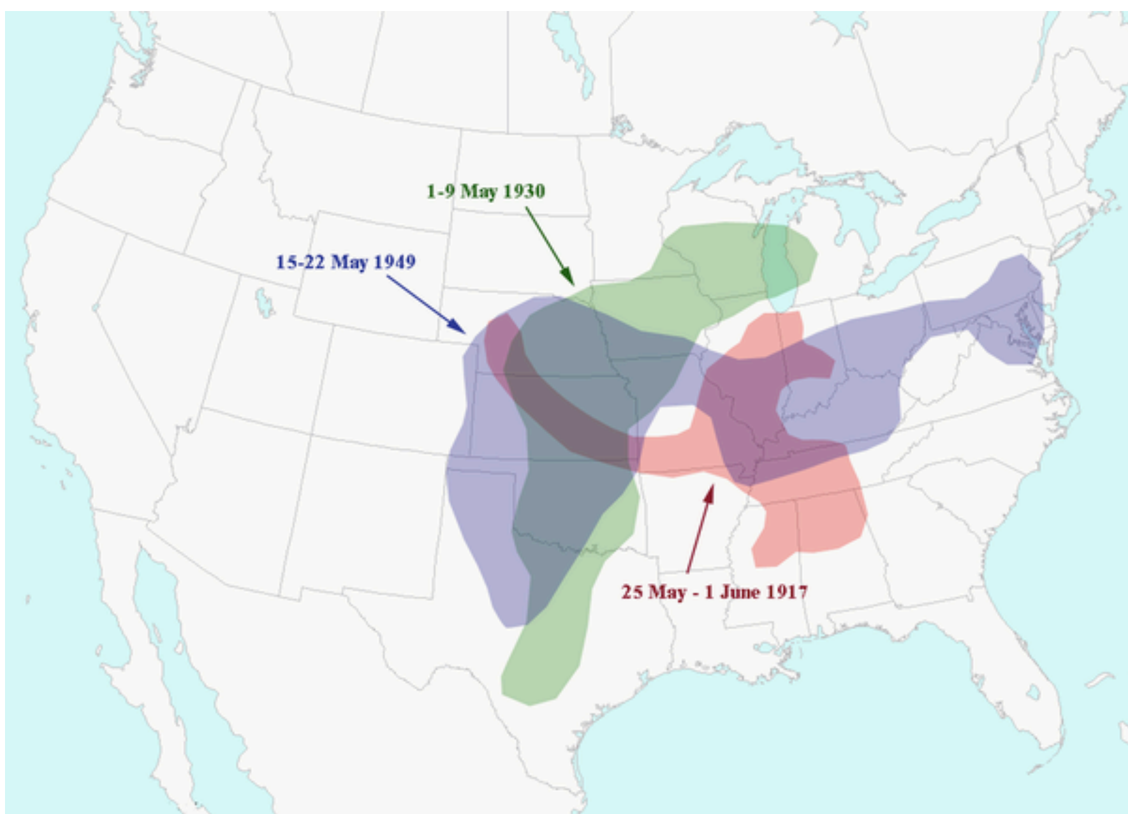

Figure 6: Map of areas affected by outbreak sequences in 1917, 1930, and 1949.

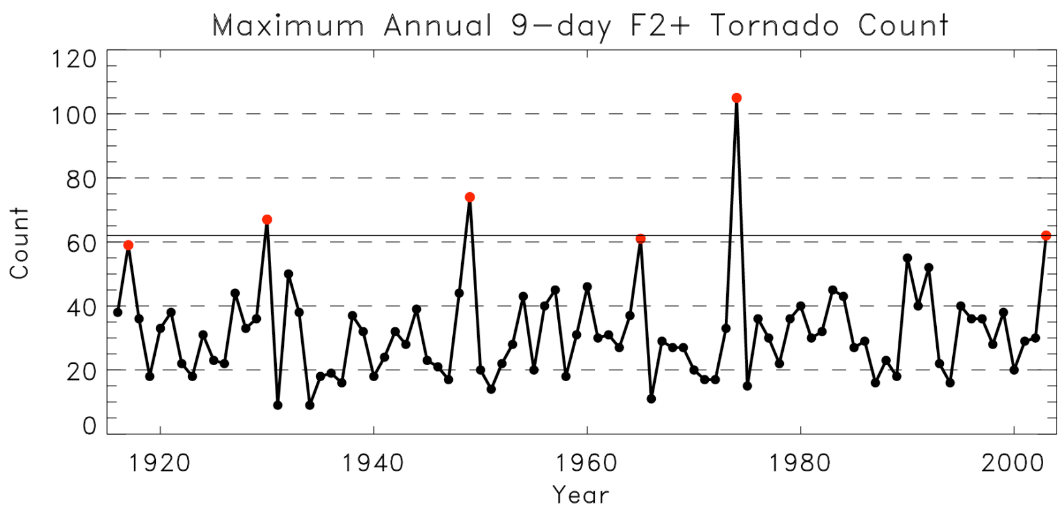

Figure 7. Maximum number of strong tornadoes during any nine-day period each year from 1916-2003 (through May). Horizontal solid black line represents number of F2+ tornadoes in the May 2003 sequence. Note that the 2003 number was exceeded in several prior years and approached in many others; the six dates in Table 2 are denoted by red dots.

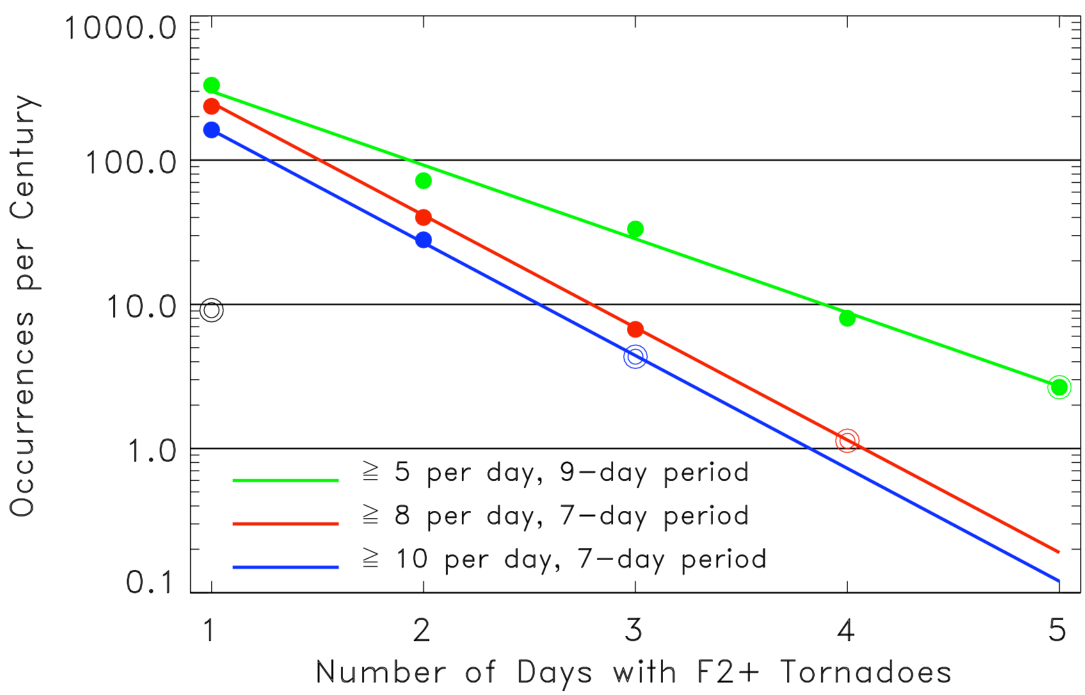

Figure 8: Observed (colored symbols) and fitted regression lines for different series of large number of daily F2+ tornadoes occurring on several days during a short period of time. Green symbols and lines associated with having at least 5 tornadoes on a day in 9 day period, red for having at least 8 tornadoes in 7 day period, and blue associated with at least 10 tornadoes in 7 day period. Double circles represent estimated recurrence frequency for observed reports in May 2003, in events per century. Raw data from Grazulis (1993) for period 1921-1993.

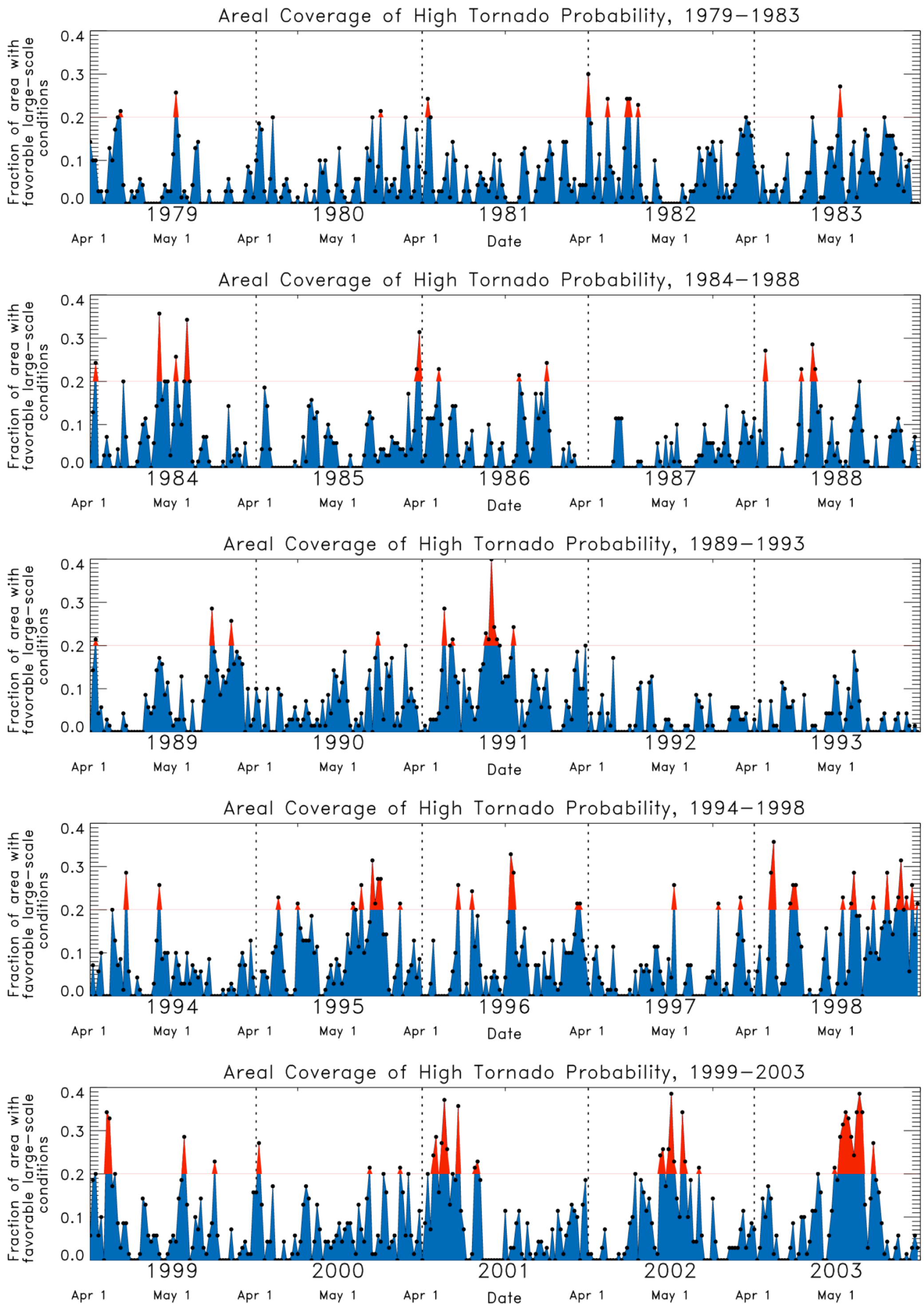

Figure 9. Time series of the fraction of the area within central and southeastern US with conditions favorable for tornado outbreaks as obtained from large-scale meteorological analyses. Data is plotted for April and May from 1979 to 2003 (See online supplement B). Favorable areas are established by the presence of sufficient wind shear and instability. A larger fraction indicates a larger area with tornado-favorable conditions. Days with greater than 20 percent coverage are highlighted with red.

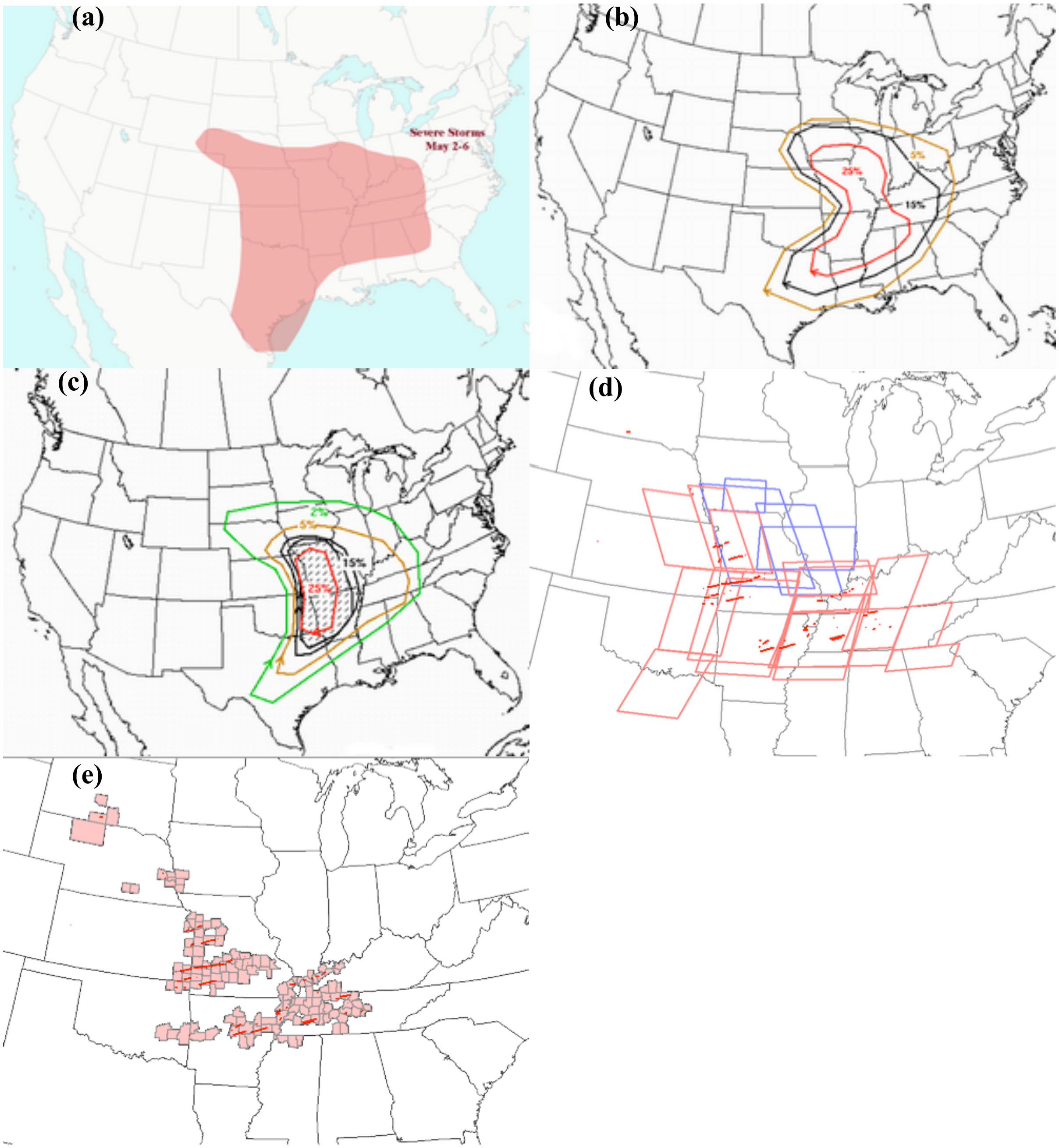

Figure 10. (a) NOAA hazards assessment issued 30 Apr 2003 for increased risk of severe thunderstorms for the period 02-06 May 2003. (b) NOAA forecast probability of severe weather (within 25 miles of any location) issued 1200 UTC 02 May for the period 1200 UTC 04 May to 1200 UTC 05 May 2003. (c) NOAA forecast probability of tornadoes (10% probability of strong tornadoes shaded) issued 1600 UTC on 04 May 2003 for the period 1630 UTC 04 May to 1200 UTC 05 May 2003. (d) NOAA severe thunderstorm (purple) and tornado (red) watch boxes issued on 04 May 2003, (e) NOAA tornado warnings issued on 04 May 2003 with observed tornado tracks.

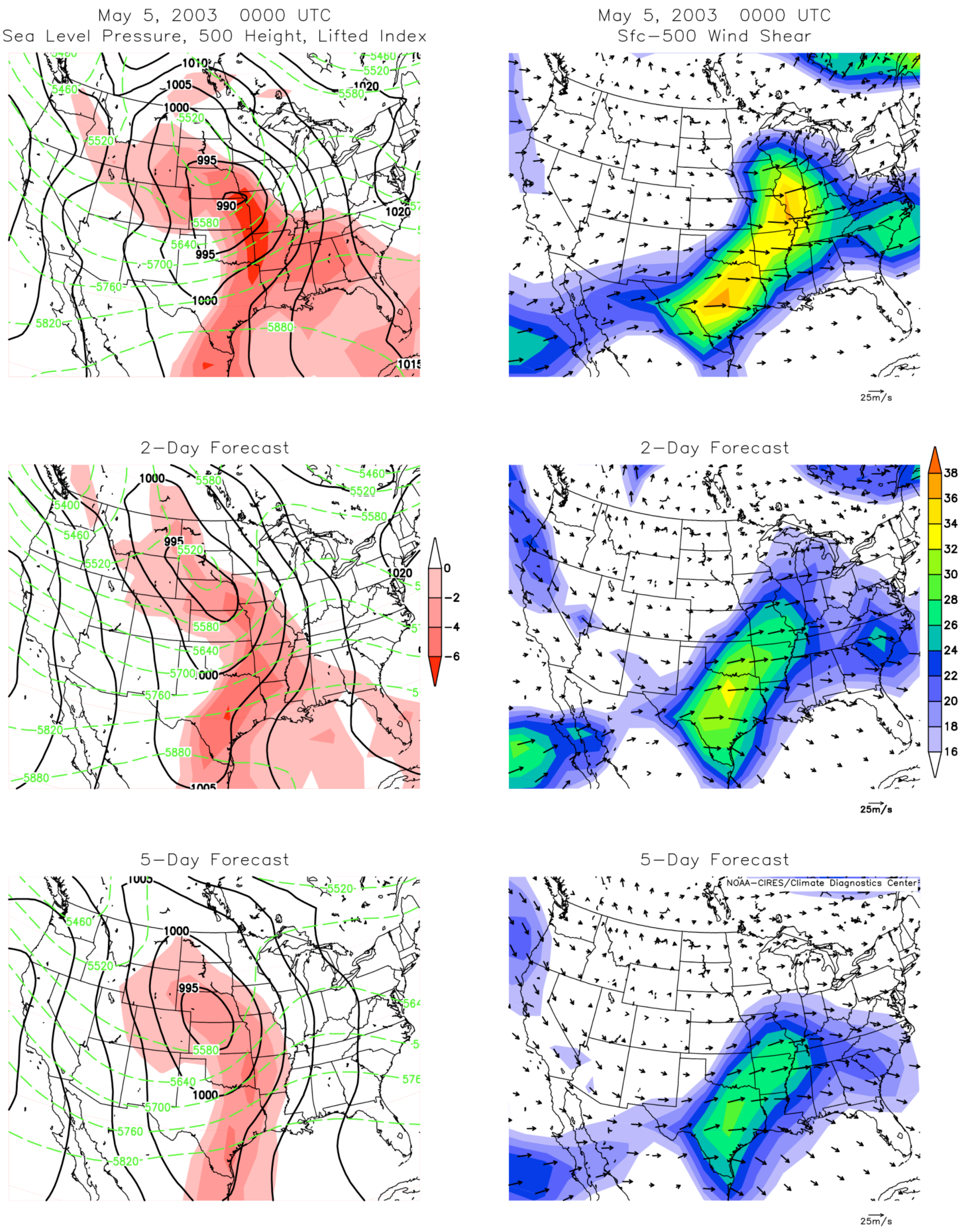

Figure 11. Analyses (top row), 2-day forecasts (middle row) and 5-day forecasts (bottom row) all valid at 0000 UTC 5 May 2003. The maps depict sea-level pressure (hPa), 500 hPa geopotential height (m), Lifted Indices (LI; degrees C), and surface to 500 hPa wind shear (ms^{-1}). The top panels determined from NCEP-NCAR reanalyses and the middle and bottom panels the NCEP MRF ensemble mean forecasts. Color tables apply to all three panels in the column.

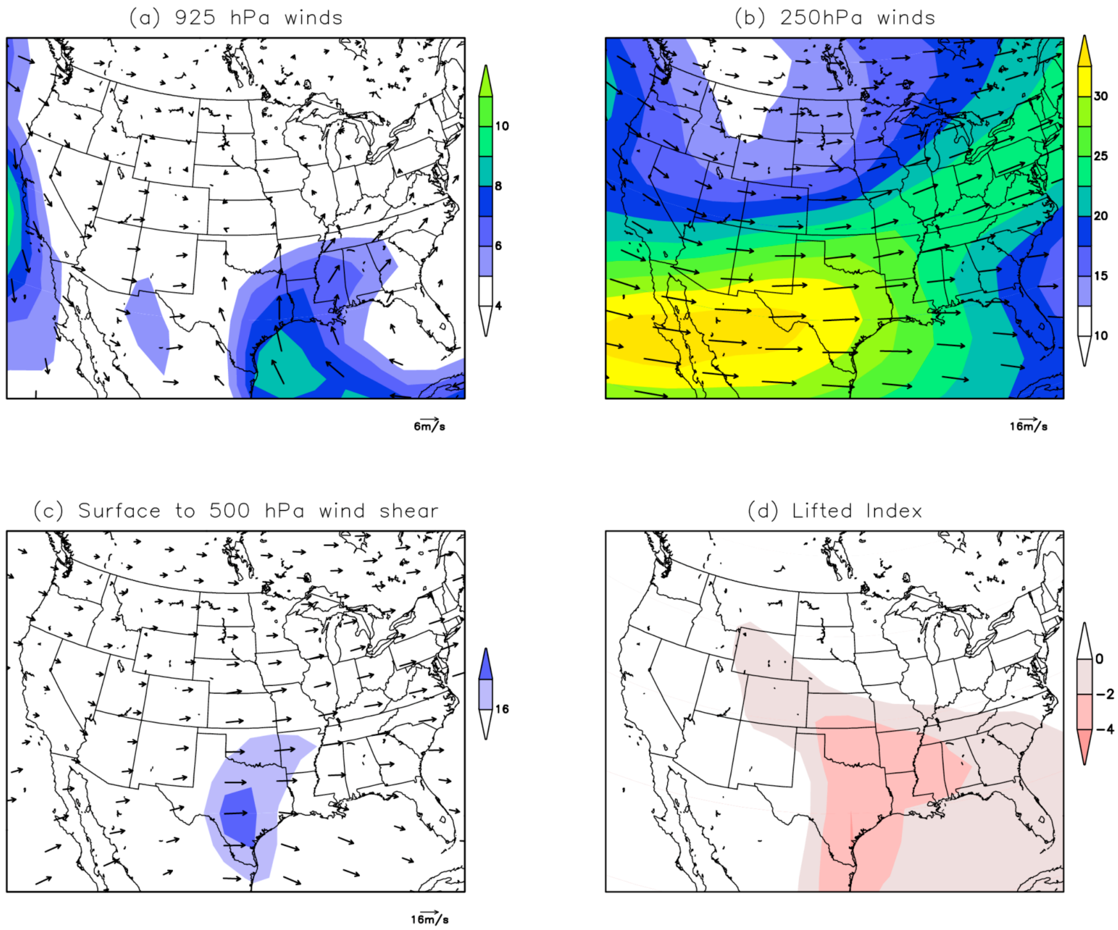

Figure 12. As in Figure 4, but here for a 15-member ensemble-mean forecast started at 0000 UTC 28 April 2003, valid for the period 0000 UTC 4 May 2003 – 0000 UTC 11 May 2003, (a 6- to 13-day forecast). (a) Wind direction and magnitude at 925 hPa, (b) wind direction and magnitude at 250 hPa, (c) wind shear, the vector difference between surface winds and winds at 500 hPa, (d) lifted index (deg C).