The tornadoes of spring 2011 in the USA: an historical perspective

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Introduction

In April 2011, 748 tornadoes were reported in the United States of America (USA), more than in any month in its history. 360 people died as a direct result of the tornadoes, 316 of them during a particularly destructive outbreak over southern parts of the country on 27 April. The first half of May was comparatively quiet, but on 22 May a violent EF5 (EF: the Enhanced Fujita scale – Doswell *et al.,* 2009) tornado, with estimated winds in excess of 200mph, produced close to a mile-wide swath of destruction in Joplin, a city in the extreme southwest of Missouri with a population of about 50 000. 158 people were killed by this tornado, making it the deadliest in the USA in over 60 years. The 550 fatalities due to tornadoes in 2011 puts it in 4th place in the annual death toll rankings, trailing only 1917 (551), 1936 (552), and 1925 (794). 1925 was the year of the infamous Tri-State tornado of 18 March (Grazulis, 1993) in which 695 deaths were recorded in Missouri, Illinois, and Indiana.

When major severe weather events occur, certain questions are inevitably raised. Is this devastating weather the result of global climate change? Can we expect more years like this? Is this as bad as it can get or are even more violent weather events in store for us? Why has the atmosphere seemingly gone mad? What caused this disastrous weather?

We intend to offer answers to these and other questions by drawing upon the historical record of tornadoes in the USA. The past offers considerable insight into the deadly tornado events of this past spring, and may also provide a glimpse into the future.

Tornado outbreak frequency

Although tornadoes happen in the USA every year, they are rare at any particular location. Even in central Oklahoma, the odds that any individual community will be hit in any given year by a violent tornado are small – of the order of a million to one, or less (Doswell, 1998). Most tornadoes are considered 'weak' (EF0-EF1); 'strong' tornadoes (EF2-EF3) are infrequent, and 'violent' tornadoes (EF4-EF5) even less likely. Figure 1 shows those areas at the greatest risk of violent tornadoes in days per century (Brooks *et al.,* 2003). Reports over the last 50 years indicate that the USA experiences an average of 800 weak, 173 strong and 9 violent tornadoes annually (NOAA Storm Prediction Center).

Nevertheless, it is virtually certain that a few violent tornadoes will happen *somewhere* in the USA, typically from late March to mid-June; they most often occur in what are termed tornado outbreaks, a group of tornadoes associated with a single large-scale weather system (Shafer and Doswell, 2010). The significance of any given tornado outbreak depends on many factors, including non-meteorological ones. A tornado that strikes in an area with little or no human population may have minimal societal impact even if it is large and violent; these rural events are likely to be underrated on the EF scale and some may go entirely unreported.

In a major tornado outbreak, violent tornadoes commonly will be quite fast-moving, anomalously long-lived and have relatively wide damage paths (Brooks, 2004), thereby resulting in damage tracks that affect large areas. Therefore, the odds of such a tornado encountering a densely populated area are much greater than with lesser events. Major tornado outbreaks, depending on how the significance of such events is measured and defined, happen a few times each year (Doswell *et al.,* 2006). However, a major tornado outbreak in which tornadoes strike large metropolitan areas occurs only every 20 years or so.

Shafer and Doswell (2010) have developed a method for ranking severe weather outbreaks of all types; their ranking scheme has been designed to account for both the societal and meteorological significance of such outbreaks. The most extreme events on their scale are major *tornado* outbreaks (Figure 2), and these represent only a small percentage of the total number of severe weather outbreaks; only the infamous tornado outbreak of 3 April 1974 is ranked above the 27 April 2011 event on this scale (based on a preliminary analysis of last year's event).

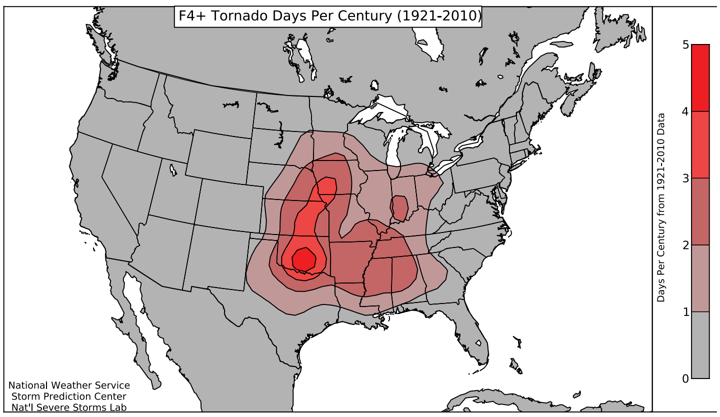

Figure 1. The number of days per century a violent tornado (EF4 to EF5) touched down within 25 miles (40km) of a point during the period 1921–2010 (inclusive).

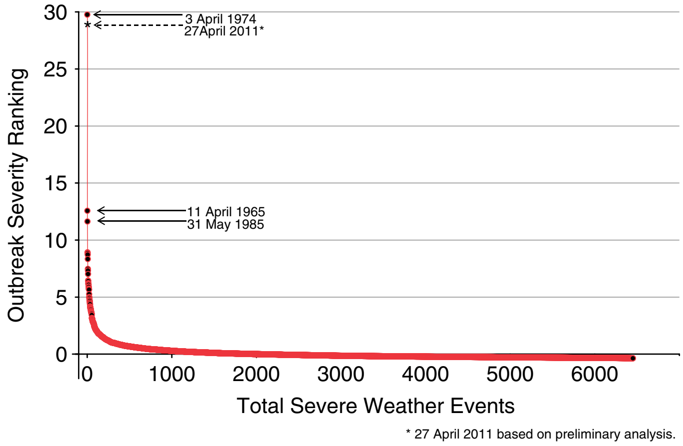

Figure 2. The ordered distribution of severe weather outbreak rankings for the period 1960–2010 (inclusive), from the highest ranked to the lowest, using the N15 outbreak ranking method described in detail in Shafer and Doswell (2010). Note that the ranking index can become negative in severe weather outbreaks that include few or no tornadoes. The 27 April 2011 event is denoted by an asterisk on this curve, based on a preliminary analysis.

In order to estimate how often outbreaks like those of 27 April 2011 or 3 April 1974 occur, we may consider the annual fatality counts over a long period (Figure 3). The data prior to 1960 have a number of problems, as discussed by Doswell and Burgess (1988), Grazulis (1993), Brooks *et al.* (2003) and Verbout *et al.* (2006): for example, it is likely that official fatality counts from older events may be underestimated. If high death tolls from outbreaks of a relatively small number of tornadoes in a year (such as the Tri-State outbreak of 1925) are excluded, it can be seen that significant tornado outbreaks resulting in 200 or more fatalities occur erratically but roughly every 20 years, or about five per century. The apparently extended gap in significant outbreak events from 1974 to 2011 is at least partly attributable to improved tornado forecasts and warnings having reduced the death tolls (Brooks and Doswell, 2002). Unfortunately, 2011 shows that high fatality counts continue to be possible when long-track, violent tornadoes strike populated areas.

The recipe for a tornado

Tornadoes form when the atmosphere is configured so as to bring several relevant ingredients together. Unfortunately,

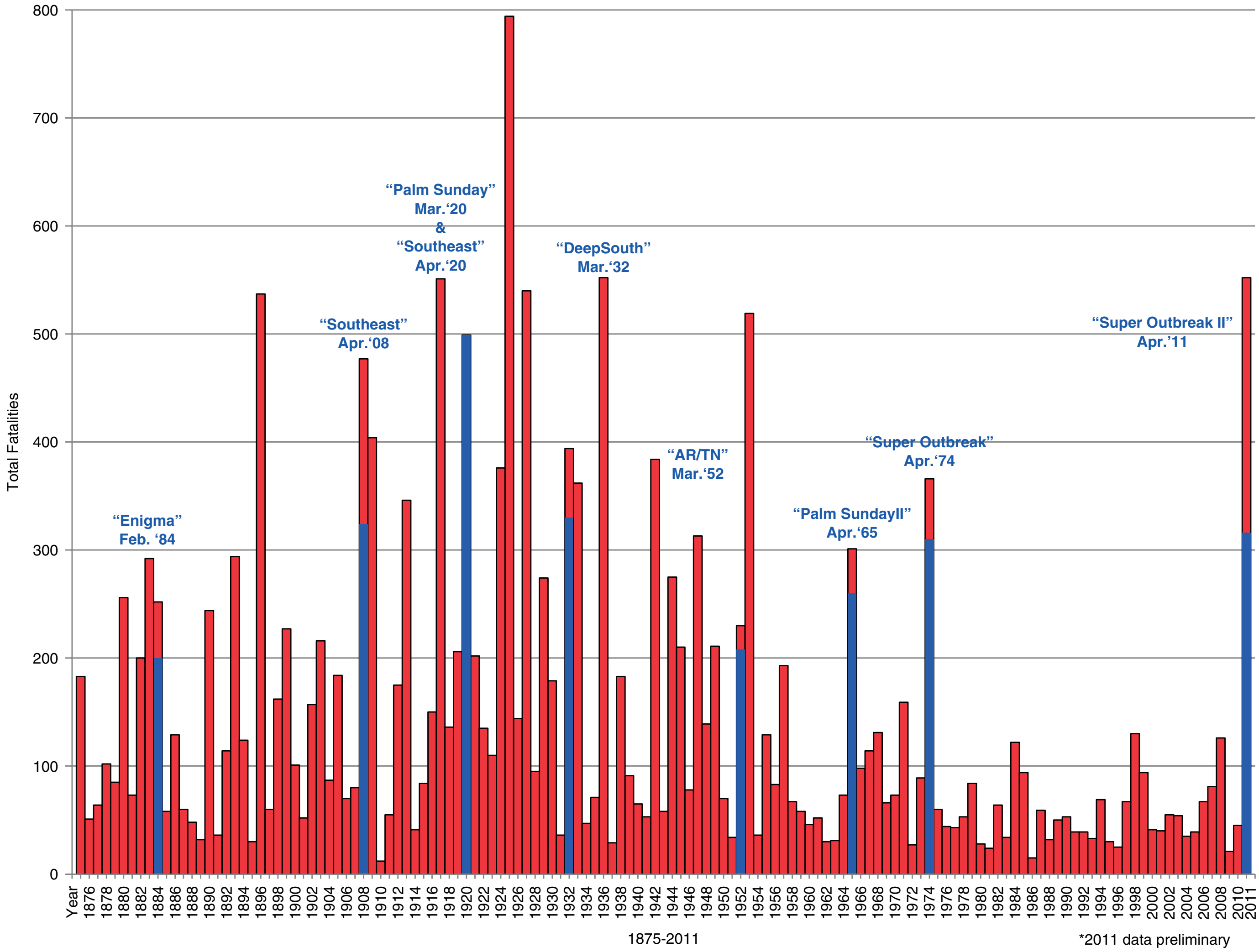

Figure 3. Annual fatality totals (data for 2011 are incomplete as of this writing) for the period 1875–2011 (prior to 1950 from Grazulis (1993); from 1950-present from NOAA/SPC data). Total annual figures are shown in red whereas total fatalities for significant tornado outbreaks (those resulting in at least 200 fatalities and numerous strong-to-violent tornadoes) are shown in blue. Many of the fatality peak years are those (such as 1925) in which a single tornado (or only a small number of tornadoes) dominates the year's fatality count.

Extratropical cyclone brings ingredients together

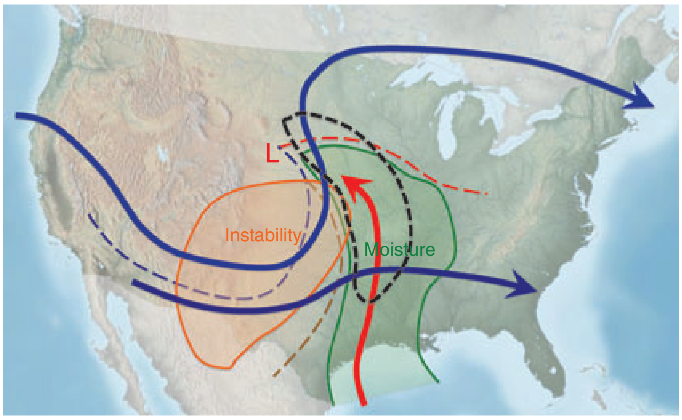

Figure 4. Schematic showing how ingredients come together in an ETC: blue arrows indicate the middle and upper-tropospheric jet stream axes; red arrow indicates the low-level jet stream axis. Green shaded area shows the location of the low-level moisture while the orange shading locates the low-to-mid-tropospheric region of conditionally unstable lapse rates. A cold front is denoted as a blue dashed line, the red dashed line denotes a warm front, and the brown dashed line is the surface location of the dryline. The black dashed region is the location of severe weather outbreak potential.

atmospheric science does not yet provide a complete recipe, but there are several factors of which we are reasonably certain. First, conditions for tornado outbreaks require the development of thunderstorms because it is known that major tornado outbreaks (in the USA) occur in association with widespread and intense thunderstorms. Thus, *moisture* must be present and the temperature should fall relatively rapidly with height (that is, the lapse rate indicates conditional instability) in the presence of a process that enables the air to be lifted sufficiently to initiate thunderstorms. The relative magnitudes of moisture content, instability and lift combine to modulate both the extent and intensity of thunderstorms.

Nevertheless, most thunderstorms do not produce tornadoes: tornado research has shown that most tornadoes in major outbreaks are produced by a special type of thunderstorm known as a *supercell* thunderstorm (Browning, 1962; Lemon and Doswell, 1979). There must be at least one other ingredient, in addition to those already listed, and research reveals that tornadic supercells are favoured when both wind direction and wind speed change with height – a condition referred to as *vertical wind shear*. It is normal for some wind shear to be present owing to surface friction and the so-called jet streams of middle latitudes, but when that wind shear becomes large it enhances the development of large-scale atmospheric disturbances known as *extratropical cyclones* (ETCs); these are the low-pressure systems seen on weather maps. Hence, tornadic supercells in major tornado outbreaks are normally associated with ETCs, and the 2011 tornado outbreaks were no exception. ETCs occurring in the spring usually have considerable vertical wind shear because that ingredient is enhanced when the temperature difference between the poles and the equator is large, as it usually is in the transition

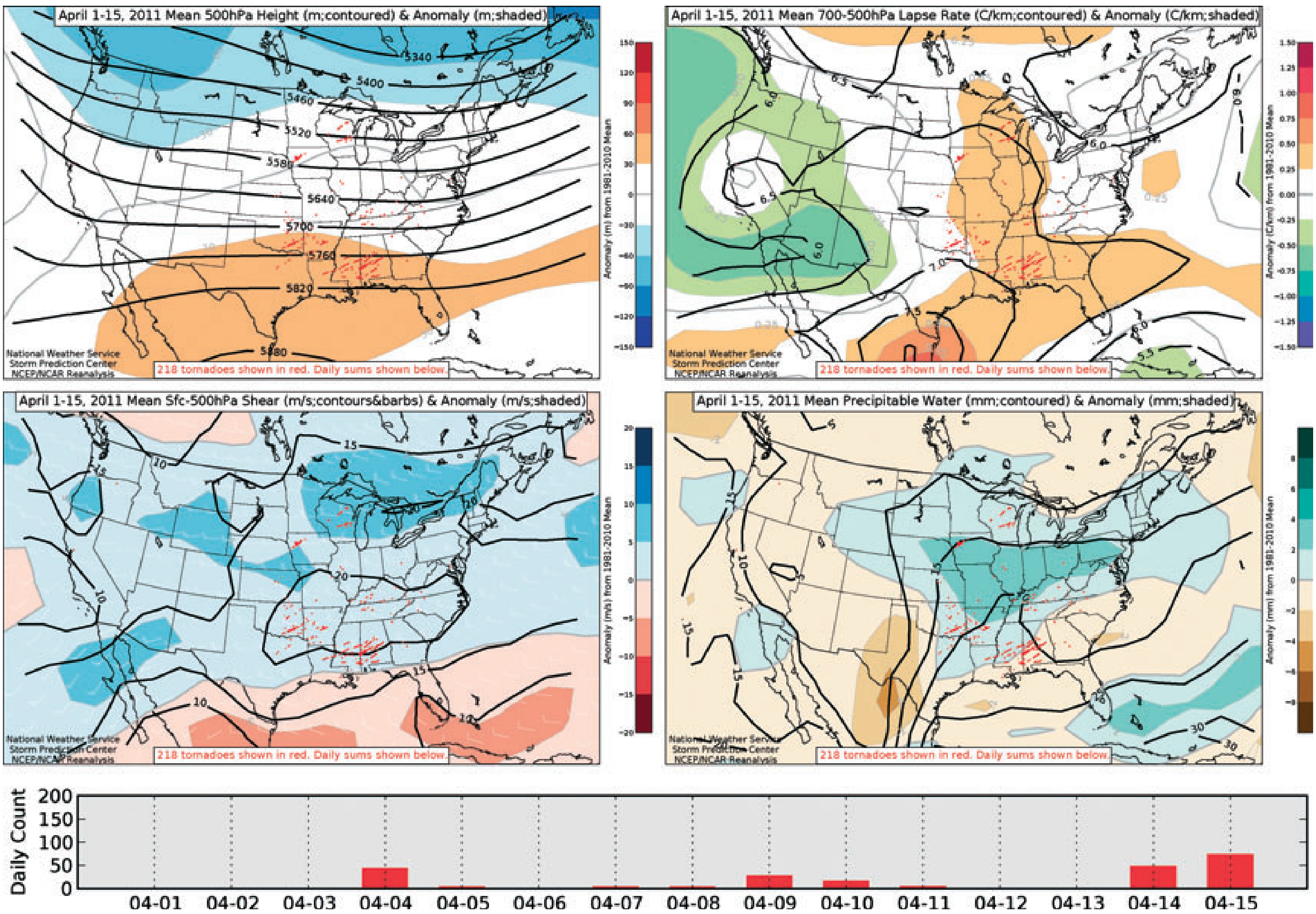

Figure 5. Means and anomalies for the period 1–15 April: 500mbar heights (upper left), 700–500mbar lapse rates (upper right), precipitable water (lower right) and surface to 500mbar wind shear (lower left). At the foot is the daily tornado count during the period.

seasons of spring and autumn. Furthermore, increasing solar heating warms the ground rapidly during the spring, so lapse rates may become large; increasing lapse rates also enhance the intensification of spring ETCs, so the likelihood of bringing together the ingredients for tornado outbreaks is greatest in the spring in the USA.

The winds in an ETC can bring together the ingredients that result in tornado outbreaks (Figure 4). In the USA, the high desert terrain of the Rocky Mountain plateau is ideal for generating high lapse rates, which then are transported by the strong mid-level winds over the regions east of the continental divide. Those same cyclones also bring low-level moisture northward from its source over the warm tropical waters of the Caribbean and the Gulf of Mexico. Finally, there are fronts and other processes connected to ETCs that can provide a source of concentrated upward motion (lift), enabling the initiation of thunderstorms. When thunderstorms develop in a region of strong vertical wind shear, they may become supercell storms capable of producing powerful tornadoes. Not all ETCs produce major tornado outbreaks, of course. The ingredients may not come together for various reasons, and it can be challenging for forecasters to predict that a particular cyclone will produce a tornado outbreak; there is a degree of uncertainty in all forecasts.

Spring 2011 tornado outbreaks

During 2011, the majority of reported tornadoes, and all but a few of the tornado fatalities, occurred during April and May, though even within these two months there were periods of relatively quiet weather. The following sections describe the large-scale atmospheric conditions during these months, with a special focus on the historic tornado outbreak of 27 April and the devastating Joplin (Missouri) tornado of 22 May.

1–15 April

There were fewer than 100 tornadoes and only one reported fatality during the first 13 days of April, giving little indication of what was to come (by the end of the month, over 600 more tornadoes and an additional 359 fatalities). Severe thunderstorms did, however, became much more numerous on the 14th and 15th.

The large-scale pattern during the first half of April was broadly close to the long-term mean across the middle of the USA, with no strong indications supporting ETC development (Figure 5). Lapse rates, moisture and shear all showed weak positive anomalies, and these conditions probably came together on the last two days of this period (14–15 April) to support a serial tornado outbreak from Oklahoma across the Deep South. Of the 218 tornadoes during the first 15 days of the month, over half occurred on the 14th and 15th.

16–30 April

The second half of April was extremely active, with a record number of 530 tornadoes, culminating in the historic outbreak of 27 April. The series of tornado events that began on 14 April continued eastwards to bring an unusual and deadly tornado episode on 16 April when 56 tornadoes and 26 associated deaths were reported, primarily over eastern North Carolina.

In contrast to the beginning of the month, the large-scale pattern during the last two weeks of April was dominated by a broad upper-level trough on the average across the middle of the country (Figure 6). This trough was anomalously deep for this time of year across the north-central USA and much of western Canada; meanwhile, upper-level ridging was anomalously strong along the east coast and over the Atlantic.

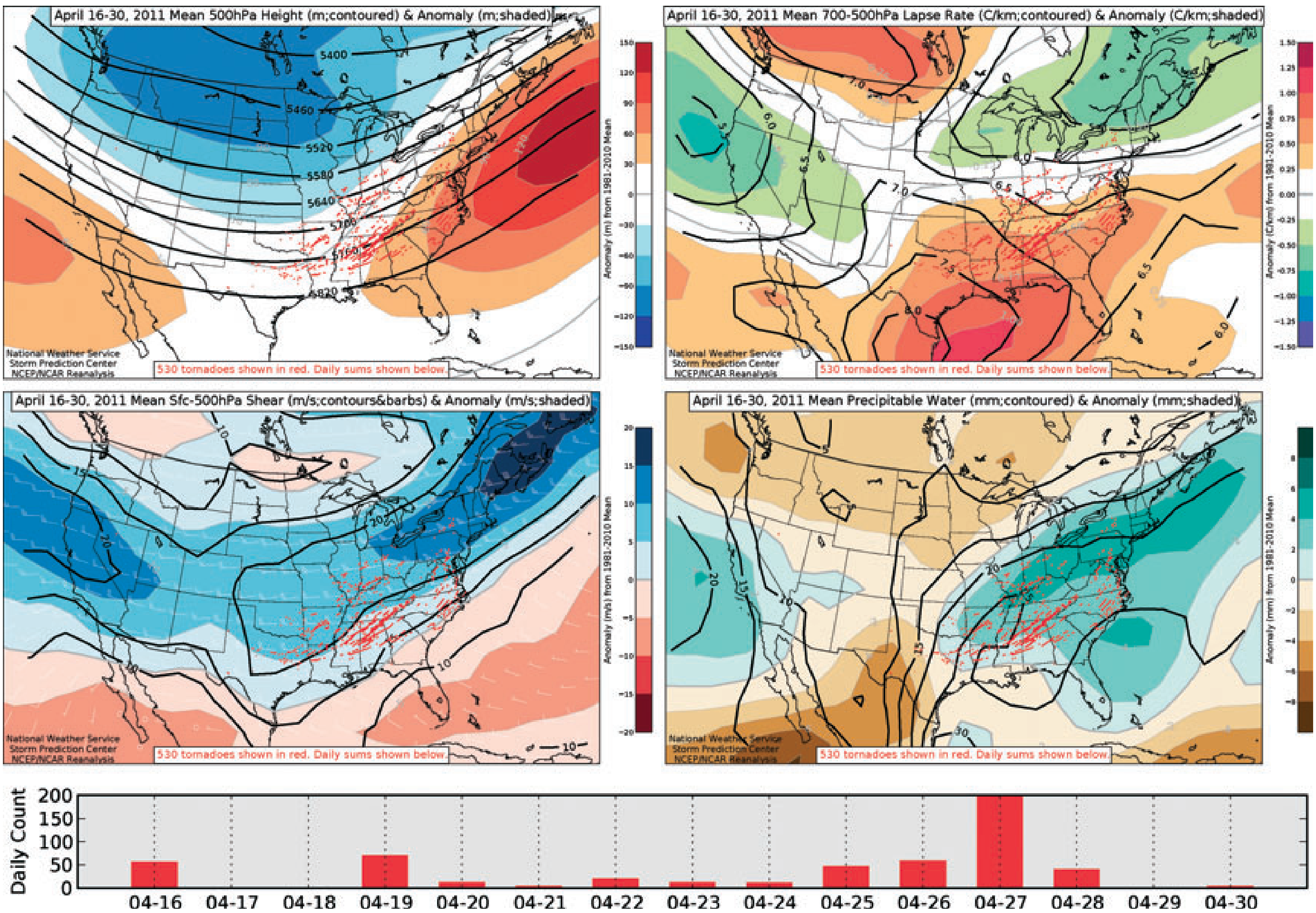

Figure 6. As in Figure 5, but for the period 16–30 April.

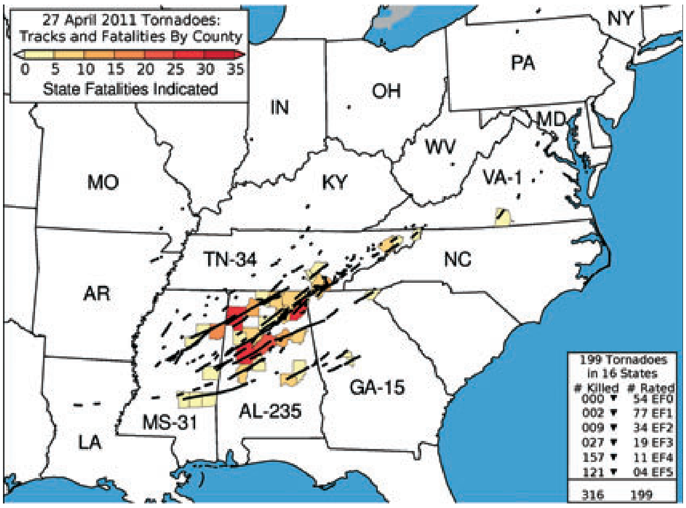

Figure 7. Tornado tracks (black), county fatalities (shaded) and state fatality totals for the 27 April 2011 tornado outbreak.

It should be noted that this average pattern resulted in several travelling ETCs during the period, encouraging their development in the southern plains of the USA and intensification as they moved northeastwards. This pattern favoured the northward transport of moisture at low levels and the eastward transport of high lapse rates above that moisture, so the lapse rates and moisture during this period were also highly anomalous and further supported the potential for widespread severe thunderstorms. The ETCs tied to the large-scale trough had strong fronts and drylines to provide the necessary lift of the moist, unstable air. The gradient between the pronounced upper-level height anomalies provides a particularly strong jet stream and associated vertical wind shear that is the other necessary ingredient for supercells and tornadoes.

By far, the most destructive round of tornadoes was on 27–28 April from the states of Tennessee and Mississippi east across Alabama and Georgia (Figure 7). Early on the 27th, a leading complex of intense thunderstorms produced damaging winds and four killer tornadoes over the South. Of the four early fatalities reported, two were in northern Alabama and one each in Mississippi and Tennessee. As the morning thunderstorms moved east and weakened, clearing skies across Mississippi and Alabama contributed to the development of strongly unstable conditions, given the abundant moisture and very steep lapse rates already present. As a very strong jet stream and intense vertical wind shear spread eastwards through the unstable air during the day, supercell thunderstorms redeveloped.

While the ETC continued to bring together all the ingredients for supercell thunderstorm development, the cyclone itself intensified and tracked northeast from Arkansas across the Ohio River Valley early on 28 April, when nearly 200 tornadoes were reported across 16 states. The deadliest and most destructive of these affected Alabama, Georgia, Mississippi, Tennessee and Virginia where a total of 25 killer tornadoes claimed 316 lives.

1–15 May

Following the historic southern USA tornado outbreak (called the 'Dixie Outbreak'

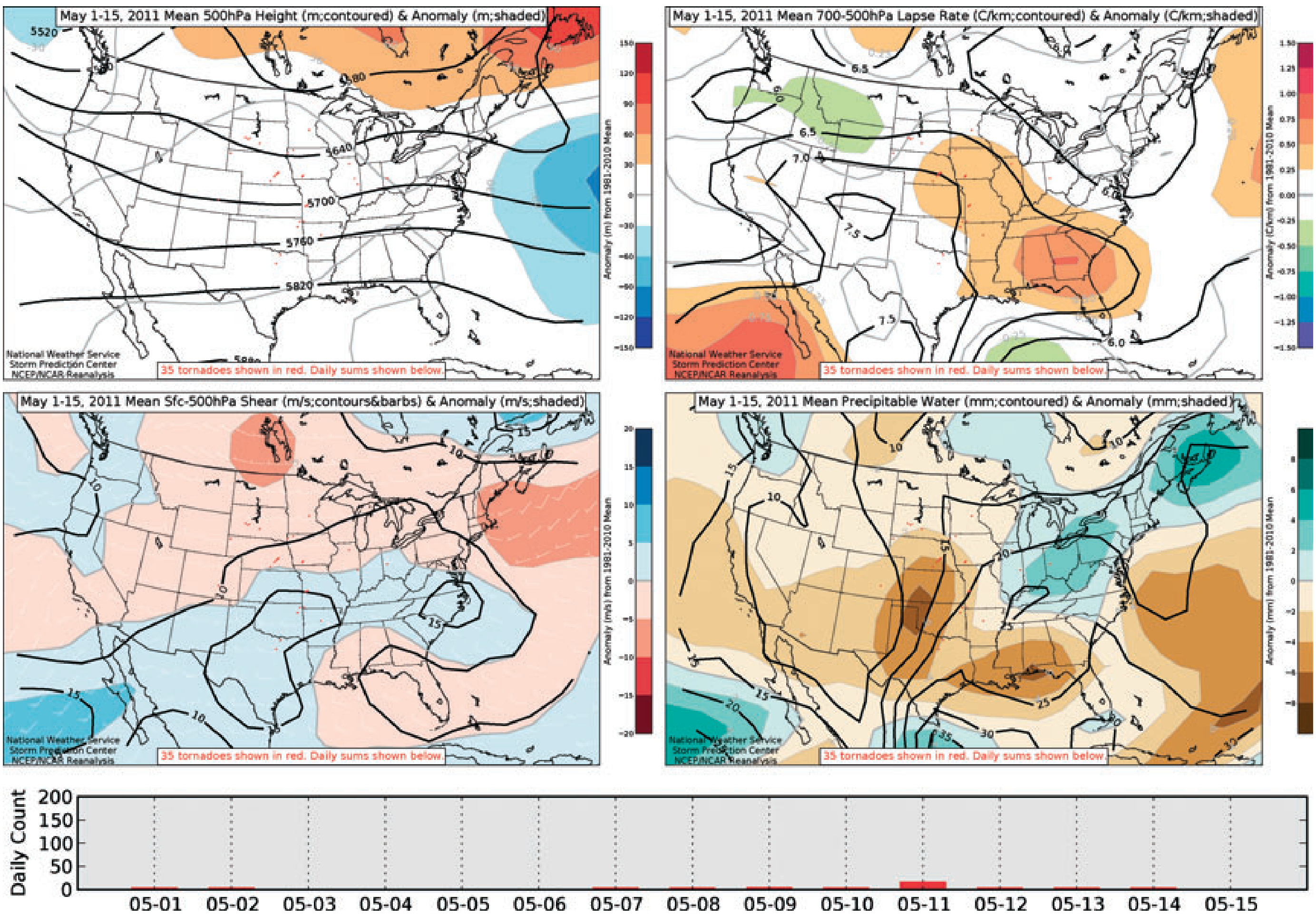

Figure 8. As in Figure 5, but for the period 1–15 May.

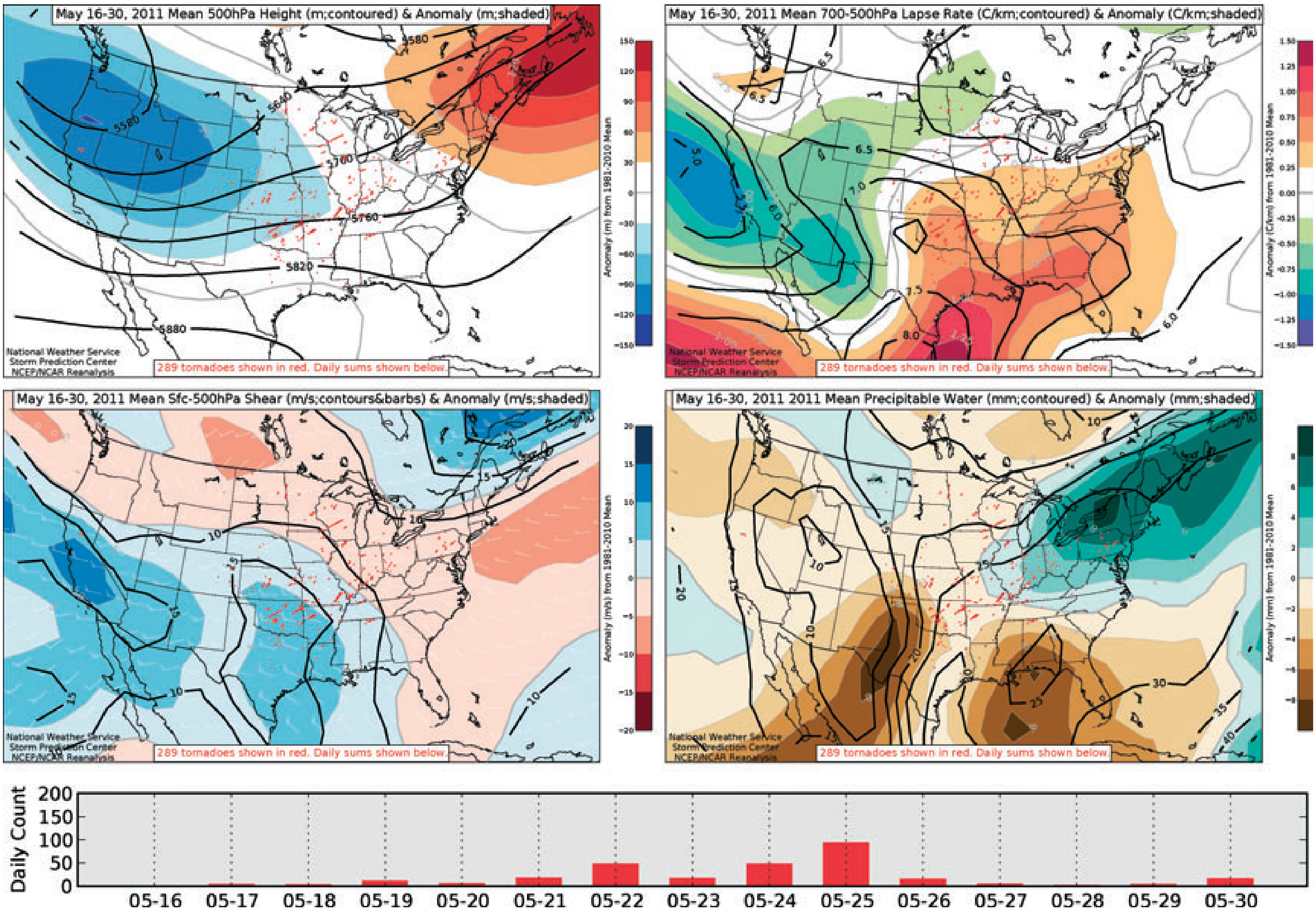

Figure 9. As in Figure 5, but for the period 16–30 May.

in reference to its location in the southeastern USA) of late April, the large-scale weather pattern changed considerably during the first half of May. The processes required for thunderstorms and subsequent tornado potential all but disappeared during this period, and there were only 35 tornadoes with no reported fatalities.

The means and anomalies of the larger-scale pattern during 1–15 May (Figure 8) stand in stark contrast to the same chart for late April (Figure 6). In the mean, the lapse rates, moisture and shear all indicate an environment generally unfavourable to severe thunderstorm development. Indeed, the first 15 days of May 2011 experienced the fewest number of tornadoes for this period of the year in the past 25 years! Maybe the events of late April played some role in keeping the first part of May unusually quiet, but any such suppression of the tornado potential did not last.

16–30 May

The trough position and lapse rates, moisture and shear anomalies (Figure 9) during the second half of May were similar to those observed in the second half of April and in contrast to those of the relatively quieter periods of early April and early May.

Unlike late April, the deadliest tornado event of late May was a single violent tornado (rated EF5) on 22 May in Joplin (Missouri) that killed 158 people, the largest single tornado fatality count since the infamous Woodward (Oklahoma) tornado of 9 April 1947 (Doswell and Burgess, 1988). Another (EF1) tornado on 22 May claimed a life near Minneapolis (Minnesota), a long way from the widespread violence and destruction unleashed in Joplin. On 24 May three violent tornadoes occurred in central Oklahoma; none involved a violent storm in a densely-populated area, although there were some near-misses. The most active tornado day during the second half of the month was 25 May, when 93 tornadoes hit 12 states.

Discussion

Despite the similarities exhibited in the large-scale pattern means and anomalies for the most active periods of spring 2011, differences in the way some of the deadly tornado events manifested themselves during these periods reveal the variable nature of these events, as evidenced by the outbreaks on 27 April and 22 May. The large number of long-track, strong-to-violent tornadoes on 27 April makes this event one of the most notable in the modern era of tornadoes in the USA, whilst before the Joplin tornado on 22 May, the most recent single tornado to produce more than 100 fatalities occurred on 8 June 1953, in the vicinity of Flint (Michigan). From the point of view of the large-scale weather system and the ingredients for tornadoes, the two cases are somewhat similar, but the details differ considerably: every meteorological event is unique in detail, but has similarities with other events. Both the similarities and differences are important, and the clash between them makes forecasting and research into tornado outbreaks challenging.

We are now in a position to try to answer the common questions we posed in the Introduction arising from this tragic tornado year in the USA. Regarding the causes for all the tornadoes of spring 2011, there is no evidence that this spring's events are meteorologically unprecedented when considered against the backdrop of similar outbreaks in the USA's history. The atmosphere fell into large-scale circulation patterns that were particularly favourable for such events during the latter half of both April and May 2011. It has done so in the past, as evidenced by some similarities between 27 April 2011 and the 'Super' outbreak of 3 April 1974 (not shown). There are differences, as well, of course, but there is nothing particularly surprising (to severe weather meteorologists) or exotic about the events of 2011.

The historical similarities also reveal that it is inevitable that more *such outbreaks will occur in the future*. We certainly are in no position to say precisely where and when, but there can be no doubt that large outbreaks of tornadoes will continue to happen and some of those tornadoes will interact with populated areas to produce the potential for large fatality counts. In the period before the mid-1950s, there were no public tornado forecasts and warnings were primitive compared to the present, so large fatality counts were relatively common. When strong-to-violent tornadoes strike without warning, large casualties are possible, but the major tornado outbreaks of 2011 were relatively well-forecast (NOAA, 2012). We now are confronting directly the reasons for fatalities even when forecasts and warnings are provided; new research involving social scientists is underway to investigate why tornado fatalities occur despite proper warning. But there clearly are situations where large death tolls could occur even with adequate weather warnings as, for example, when a violent tornado strikes a packed large-event venue (such as a sports stadium or theme park) with little or no shelter for those present (Edwards and Lemon, 2002). There would be far too little warning lead time to allow evacuation and, with thousands of people unable to find proper shelter, the potential danger is extreme. Although such an event is unlikely, it inevitably will happen at some time in the future. Hence, it seems that modern meteorological science and technology has not eliminated the threat of large casualty counts in tornado outbreaks.

Regarding the topic of climate change, it should be understood that the climate is *always* changing. The current discussions about global warming and its consequences are important to society, but climate change occurs on time scales of many decades and longer. Unfortunately, our knowledge of past events is far from complete and is compromised by many non-meteorological artifacts (Diffenbaugh *et al.*, 2008). The record of severe weather events in the USA is the best in the world, but it is not even remotely adequate enough to enable an answer to the question of how climate change might influence the occurrence of major tornado outbreaks, owing to the numerous non-meteorological effects on the record. The relative rarity of these events means that the modern era of tornado report data is far too short to provide much quantitative information about how climate changes in the past might have affected the frequency and intensity of tornado outbreaks (Doswell, 2007).

What indications we have (e.g., Trapp *et al.*, 2007) are that the existing global warming scenarios suggest that low-level moisture would increase, perhaps making thunderstorms somewhat more likely. However, the forecasts also show that warming would be strongest in the polar regions, thereby reducing the overall temperature contrast between the equator and the poles. This would probably be linked to a decrease in the average vertical wind shear, thereby contributing to a decrease in ETC intensity and making supercell thunderstorms less frequent. But these indications are only preliminary and we do not believe they provide absolutely certain forecasts of the likelihood of major tornado outbreaks in global warming scenarios. In our scientific opinion, then, the future regarding changes in tornado outbreak intensity and frequency remains unknown. The safest prediction is that such outbreaks will continue to occur as they have in the past and it would be prudent to expect little or no immediate change. What the record shows is considerable year-to-year variability, so what happens in one year's tornado season is not a good predictor of the following year's activity.

We believe the disastrous tornado outbreaks of spring 2011 cannot be used to justify any contention that such events are increasing in frequency and/or intensity. These outbreaks are weather events, and climate is most properly considered as the long-term *average* of the weather. It would be logically absurd to point to the high temperature on one extremely hot day in the summer to indicate that average temperatures are rising, and in the same way severe weather events during one year cannot be used to imply anything about how the average over many decades would be likely to change. 2012 might turn out to be a record-breaking *minimum* in major tornado events, just as the record-breaking two-week period including the 27 April 2011 tornado outbreak was followed by a strong decrease in the number of tornadoes in the first two weeks of May.

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