P60 AN EXAMINATION OF TORNADO ENVIRONMENTS, EVENTS, AND IMPACTS FROM 2003-2012

Andrew R. Dean* and Russell S. Schneider
DOC/NOAA/NWS/Storm Prediction Center, Norman, OK

1. INTRODUCTION

This study looks at tornado environments, events, and impacts over the 9.5 year period from January 2003 through June 2012. Environments are assessed in terms of the buoyancy and shear of the convective profile. Events are examined from a broad prospective (in terms of all tornadoes) and also with respect to individual tornado outbreaks. Impacts are analyzed by examining the human toll (in terms of injuries and casualties) of tornadoes in conjunction with population density characteristics of the areas affected. Finally, we explore interrelationships between environments, events, and impacts in order to identify areas where the effort to protect human life from tornadoes can potentially be improved from a forecast perspective.

2. DATA PREPARATION AND METHODOLOGY

2.1 *SPC Environment Database*

The NOAA Storm Prediction Center (SPC) has created a database of environmental parameters associated with observed severe convection (Schneider and Dean 2008), based on archived SPC hourly mesoscale analysis (hereafter SfcOA) grids which have a horizontal resolution of 40 km (Bothwell et al. 2002). The database includes severe weather parameter estimates for over 99% of all tornado reports from January 2003 through June 2012 (14 032 tornado county segments), an archive of all SPC forecast products, and access to gridded US lightning data.

2.2 *Environmental Parameters Associated With Tornadoes*

In this study, we focus on the near-storm environments associated with tornado events. Previous research into tornado forecasting (e.g., Johns and Doswell 1992; Thompson et al. 2003; 2007) has identified several important environmental parameters, which include:

- Convective available potential energy (CAPE) in a column that includes the boundary layer
- Limited or absent convective inhibition (CIN)
- Deep-layer (e.g., from 0-6 km AGL) wind shear
- Low-level (e.g., from 0-1 km AGL) wind shear and/or storm-relative helicity (SRH)
- Favorably low lifted condensation level (LCL) heights

***** *Corresponding author address*: Andrew R. Dean, NOAA/NWS/Storm Prediction Center, 120 David L. Boren Blvd., Norman, OK 73072. E-mail: Andy.Dean@noaa.gov

For simplicity, the environmental analysis presented here focuses on just two parameters: CAPE calculated using a mean mixed-layer parcel from the lowest 100 hPa AGL (hereafter MLCAPE) and deep-layer shear defined as the bulk wind difference between 0-6 km AGL (hereafter SHR6).

2.3 *SPC Tornado Watches*

In addition to looking at the environments of tornado events, we also examine the forecast performance of SPC tornado watches as a function of environment. A tornado watch is issued by the SPC when there is an enhanced and imminent risk of multiple tornadoes (or at least one EF2 or greater tornado) over an area of at least 8 000 mi^2 (~ 20 700 km^2) and a duration of at least 2 hours (National Weather Service 2010). In practice, the average size of a tornado watch is around 25 000 mi^2 (~ 65 000 km^2) and the average duration is around 6 hours.

SPC verifies tornado watches using severe storm reports which are collected by National Weather Service (NWS) field offices and published in *Storm Data* (NCDC 2003-2012). In this study, we examine tornado watch probability of detection (POD), which is defined as the fraction of tornado reports that occur in a watch, and a measure of areal false alarm (FAR) defined as the fraction of 40km grid boxes in a watch where a verifying report did not occur (Weiss et al. 1980). A measure known as good area percentage (GAP) can be calculated as GAP = 1 – FAR. This provides a positively oriented (i.e., higher values are better) metric for areal false alarm.

2.4 *Terminology and Plotting Conventions*

In many of the figures presented below, results are accumulated in discrete bins in a 2-dimensional "CAPE-Shear" space, with MLCAPE on the x-axis and SHR6 on the y-axis. The bin sizes were arbitrarily defined as 250 J kg^{-1} for MLCAPE and 5 kts (2.5 m s^{-1}) for SHR6. SfcOA grid points where MLCAPE = 0 are not considered in this study, since these would otherwise dominate some of the distributions.

Some commonly used terms in the analysis below are defined as follows:

- *Environment hour* – An hourly grid point from SfcOA that is mapped into CAPE-Shear space. Only grid points located over the continental U.S. are considered.

- *Lightning hour* – An environment hour that contained at least one cloud-to-ground lightning flash, as detected by the National Lightning Detection Network (Orville 2008).

- *Report hour* – An environment hour that contained at least one tornado report. Reports are mapped back to the most recent analysis prior to their occurrence (i.e. a report that occurred at 2245 UTC is mapped back to the 22 UTC SfcOA analysis).

- *Conditional probability of a tornado* – The probability of a tornado report occurring in a SfcOA grid box, based upon the presence of at least one lightning flash in the grid box. In CAPE-Shear space, this is defined as the number of report hours divided by the number of lightning hours in a given bin.

- *Watch hour* – An environment hour that was within a valid SPC convective watch. Since watches cover an area of multiple grid points and hours, there is no single environment that can be assigned to a given watch; rather, the hourly grid points contained in a watch are distributed across the environment space as determined by the SfcOA.

- *False alarm hour* – A watch hour that was not a report hour.

3. TORNADO ENVIRONMENTS

An examination of the environment, lightning, and severe report distributions in CAPE-Shear space for the period JAN 2003-JUN 2012 confirms the following intuitive results:

- Thunderstorms are far more common in environments characterized by relatively low values of MLCAPE and SHR6 than in environments characterized by high values of one or both of these parameters (Fig. 1).
- The conditional probability of tornadoes generally increases with increasing MLCAPE and SHR6 values (Fig. 2).
- Most tornado reports occur in environments falling somewhere in between the two conditional extremes described above, with tornadoes generally associated with higher values of SHR6 (Fig. 3).
- EF2 or greater tornadoes occur almost exclusively in moderate-to-strong deep layer shear environments, with 98% of EF2+ tornadoes associated with deep layer shear $\geq$ 15 m s^{-1} (Fig. 4).

These results are generally very similar to earlier results presented for the 2003-2007 period in Schneider and Dean (2008).

Tornado watch POD and FAR can also be computed in MLCAPE/SHR6 parameter space, as shown in Figs. 5-8. The results presented here build upon earlier work presented in Dean and Schneider (2008).

POD increases dramatically as MLCAPE and SHR6 increase (Fig. 5), as might be expected, with GAP (Fig. 6) showing a similar but weaker signal. In terms of actual numbers of false alarm area (Fig. 7) and missed (i.e., not in a watch) events (Fig. 8), the greatest numbers of both tend to occur at lower MLCAPE values, with quite a bit of overlap in the low MLCAPE (< 1000 J kg^{-1}) and moderate-to-high SHR6 (15-25 m s^{-1}) part of the parameter space. This is a part of the parameter space where conditional tornado probability is relatively low (Fig. 3) because thunderstorms are relatively common (Fig. 1), suggesting that the greatest forecast challenge lies in the part of the parameter space where the conditional probability is relatively low but nonzero.

4. TORNADO IMPACTS

Fig. 9 shows a map of all tornado county-segment tracks from 2003-2012 overlaid on a grey scale depiction of population density. The population data were derived from the 2010 U.S. Census block-level data (U. S. Census Bureau 2011) interpolated onto a 5 km grid. While a number of tornadoes are noted over the traditional “Tornado Alley” area of the Plains, numerous strong (EF2+) tornado paths are also noted over parts of the Southeast and Ohio Valley, where population density is much greater than in the Plains. A total of 1085 tornado fatalities were reported during the JAN 2003 – JUN 2012 period, with many of these reported across the Southeast and Ohio Valley where major tornado events intersected with denser population (Fig. 10). Other studies have noted the vulnerability of areas in the Southeast (e.g. Ashley 2007, Ashley et al. 2008) to tornado fatalities as a result of population density, prevalence of mobile homes, and the risk of nocturnal tornado events.

Tornado environments in the Southeast tend to be somewhat different than in the Plains. While events in the Plains are characterized by relatively high CAPE (MLCAPE $\geq$ 2000 J kg^{-1}) and moderate-to-high deep-layer shear as shown in Fig. 11 (SHR6 $\geq$ 20 m s^{-1}), more events east of the Plains are associated with lower CAPE (MLCAPE < 1000 J kg^{-1}), as shown in Fig 12. Since forecast difficulty tends to be greater in lower MLCAPE environments (as shown above), this implies that Southeast tornado events, which have potentially higher impact due to higher population density and other factors, are potentially more difficult to forecast.

The danger posed by low CAPE tornadoes is illustrated in Fig. 13, which shows the binned number of tornado fatalities in MLCAPE/SHR6 space. While numerous fatalities are noted in the more extreme parts of the parameter space where stronger tornadoes are more likely, many fatalities are also associated with low MLCAPE (< 1000 J kg^{-1}) events.

5. MAJOR TORNADO OUTBREAKS FROM 2003-2012

There are many possible definitions of a tornado “outbreak.” Since this study is concerned with the impacts of tornadoes, we chose to focus on F3/EF3 and greater tornado events (hereafter F3+), since these events have accounted for over 85% of tornado fatalities since 2003 despite representing only 3% of all tornado events during that span. The total path length of F3+ tornadoes was computed for each convective day (defined as starting at 1200 UTC of the day in question and ending at 1159 UTC the next day). The resulting outbreak rankings are shown in Table 1. The top 10 outbreaks accounted for around half (543 out of 1085) of all tornado fatalities during this period. Not surprisingly, the F3+ tornadoes associated with these top 10 outbreaks occurred in very favorable environments, characterized either by very strong SHR6 for the lower MLCAPE events, or a combination of strong SHR6 and large MLCAPE (Fig. 14).

Meanwhile, in order to calculate population statistics associated with each outbreak, a kernel density estimate (Brooks et al. 2003) was applied to the tornado data for each convective day. The contour defining 10% coverage of F2+ tornadoes was then used to define the areal extent of the outbreak. F2+ events (rather than F3+) were used since they generated a more continuous kernel density estimate, with the 10% threshold corresponding to the probability used in SPC probabilistic forecasts of F2+ tornadoes. Examples of the outbreak contours for some individual events are shown in Fig. 15 and Fig. 16.

The historic nature of the 27 April 2011 event is quite evident from Table 1, with the total F3+ path length over three times greater than the second ranked outbreak on the list. 27 April 2011 (visualized in the red-shaded area of Fig. 15) also had the third highest percentage of area covered by population density of 10 km^{-2} and 100 km^{-2}. A catastrophic loss of life resulted from this intense outbreak occurring over a relatively dense populated area. The fatalities in MLCAPE/SHR6 parameter space from 27 April 2011 are highlighted in Fig. 13, which shows that, unlike many other Southeast events, this outbreak was associated with a higher CAPE (MLCAPE $\geq$ 2000 J kg^{-1}) environment.

One example of the influence of population density on tornado impact is shown in Fig. 16. The outbreaks of 16 April 2011 and 14 April 2012 were very similar in terms of total F3+ path length. However, the 16 April 2011 event occurred over a very highly populated area in the Carolinas and Virginia and of all the outbreaks had the largest percentage (9.6%) of population density over 100 km^{-2} within the outbreak area. Meanwhile, the 14 April 2012 event occurred over a rather sparsely populated area of the Plains, with the lowest percentage of population density over 10 km^{-2} and 100 km^{-2} of any of the outbreaks. The Carolinas outbreak resulted in a much greater human toll, with 26 fatalities and 480 injuries reported, compared to 6 fatalities and 73 injuries in the Plains outbreak. While one example is hardly definitive, this comparison illustrates the effect of population density on the human impact of tornado outbreaks, as shown in Schneider et al. (2009).

Outbreak size and population density are not the only determinants of tornado-related impact, however. Fig. 15 contrasts the tornado event of 22 May 2011 (in blue) with 27 April 2011 (in red). While 27 April 2011 was a large outbreak, 22 May 2011 was not ranked among the top outbreaks, with a few events noted over the upper Midwest and a small cluster of events centered over far southwestern Missouri. Unfortunately, one of those events was a catastrophic EF5 tornado that moved through Joplin, MO, resulting in 158 fatalities.

6. DISCUSSION

In terms of tornado events and environments as a whole, two important findings were presented above:

- Tornado forecast difficulty (in the context of tornado watches in this case) is greatest in the part of the parameter space where the overall frequency of occurrence is high but the conditional event probability is relatively low . Notably, this includes events were deep-layer wind shear is favorable (i.e., strong) but CAPE is low.
- Low CAPE/favorable shear events are most common in the Southeast, where risk to human life is greater due to population density and other factors.

These two findings raise the following question: How can performance of tornado forecasts be improved in these low CAPE, relatively low conditional probability environments? While accurate forecasts are important in any case, these types of events pose a particular risk given the vulnerability of the area where they tend to occur.

If the relationship between high conditional probability and better forecast performance can be generalized beyond what was shown here, then the answer to the question above will likely require a refinement of the conditional probability estimate of tornadoes in low CAPE environments. Additional research into discriminating events from non-events in these environments is required, both from the traditional approach of identifying useful environmental predictors, and potentially also by incorporating storm characteristics from high-resolution model guidance.

The second part of this study focused on tornado outbreak environments and impacts, with the following important results:

- Tornado outbreaks account for a large number of fatalities; around 50% of tornado fatalities over the 9.5 year span of this study occurred on 10 outbreak days.
- Tornado outbreaks tend to occur in rarely sampled areas of the MLCAPE/SHR6 parameter space where conditional probability and predictability (in terms of tornado watch performance) is high.

While it is discouraging that events that are predictable on the large scale still produce many fatalities, the question, “How many lives have been saved by successful prediction?”, remains unanswered here, as does the question, “What can be done to improve outcomes in the future?”. These two questions are obviously related and must involve both the field of meteorology and various aspects of the social sciences to be properly addressed.

7. REFERENCES

Ashley, W. S., 2007: Spatial and Temporal Analysis of Tornado Fatalities in the United States: 1880–2005. *Wea. Forecasting*, **22**, 1214–1228.

Ashley, W. S., A. J. Krmenec, R. Schwantes, 2008: Vulnerability due to Nocturnal Tornadoes. *Wea. Forecasting*, **23**, 795–807.

Bothwell, P. D., J. A. Hart, and R. L. Thompson, 2002: An integrated three dimensional objective analysis scheme in use at the Storm Prediction Center. *Preprints, 21st Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., J117–J120.

Brooks, H. E., C. A. Doswell, M. P. Kay, 2003: Climatological estimates of local daily tornado probability for the United States. *Wea. Forecasting*, **18**, 626–640.

Dean, A. R., and R. S. Schneider, 2008: Forecast challenges at the NWS Storm Prediction Center relating to the frequency of favorable severe storm environments. *Preprints, 24th Conf. Severe Local Storms*, Savannah GA.

Johns, R. H., and C. A. Doswell III, 1992: Severe local storms forecasting. *Wea. Forecasting*, **7**, 588-612.

National Weather Service, 2010: National Weather Service Instruction 10512. [Available online at http://weather.gov/directives/sym/pd01005012curr.pdf.]

NCDC, 2003-2012: *Storm Data*. Vols 45-54.

Orville, R. E., 2008: Development of the National Lightning Detection Network. *Bull. Amer. Meteor. Soc.*, **89,** 180–190.

Schneider, R. S. and A. R. Dean, 2008: A comprehensive 5-year severe storm environment climatology for the continental United States. *Preprints, 24th Conf. on Severe Local Storms*, Savannah, GA.

Schneider, R. S., A. R. Dean, and H. E. Brooks, 2009: Estimating potential severe weather societal impacts using probabilistic forecasts issued by the NWS Storm Prediction Center. *Preprints*, 23rd Conf. Weather Analysis and Forecasting, Omaha NE.

Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore and P. M. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Wea. Forecasting,* **18**, 1243-1261.

Thompson, R. L., C. M. Mead, and R. Edwards, 2007: Effective storm relative helicity and bulk shear in supercell thunderstorm environments. Wea. Forecasting, **22,** 102-115.

U. S. Census Bureau, 2011: 2010 Census Summary File 1 United States.

Weiss, S. J., D. L. Kelly, and J. T. Schaefer, 1980: New objective verification techniques at the National Severe Storms Forecast Center. *Preprints, 8th Conf. on Weather Analysis and Forecasting*, Denver, CO, Amer. Meteor. Soc., 412-419.

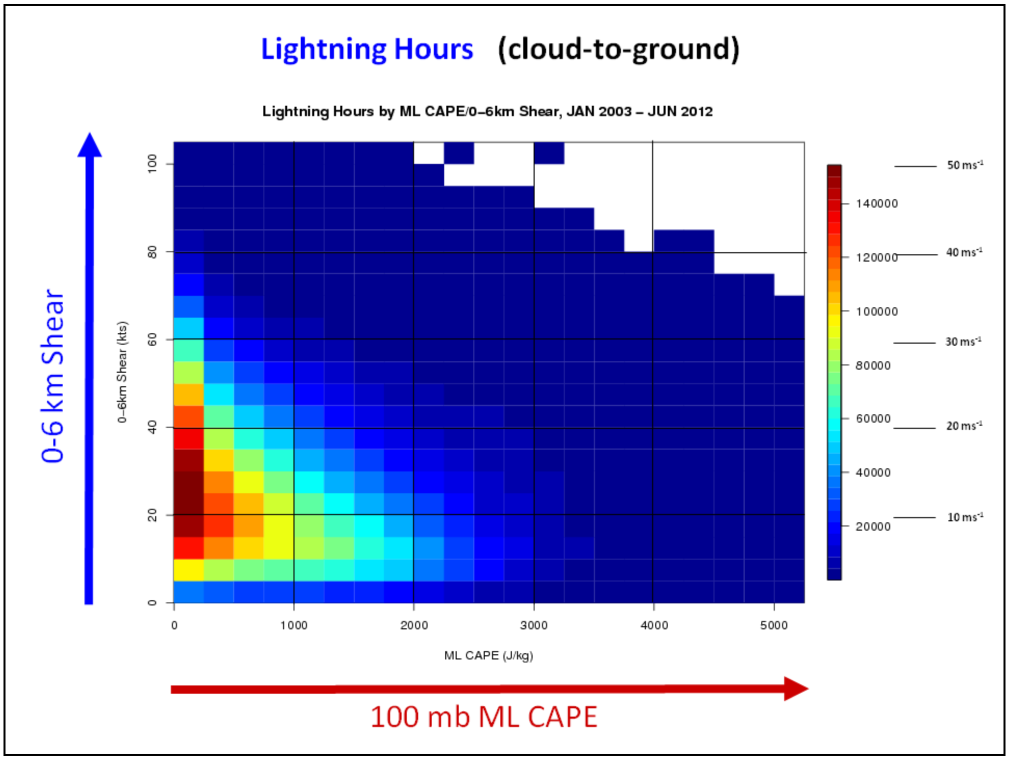

Fig. 1. Lightning hours binned by MLCAPE/SHR6, valid from JAN 2003-JUN 2012.

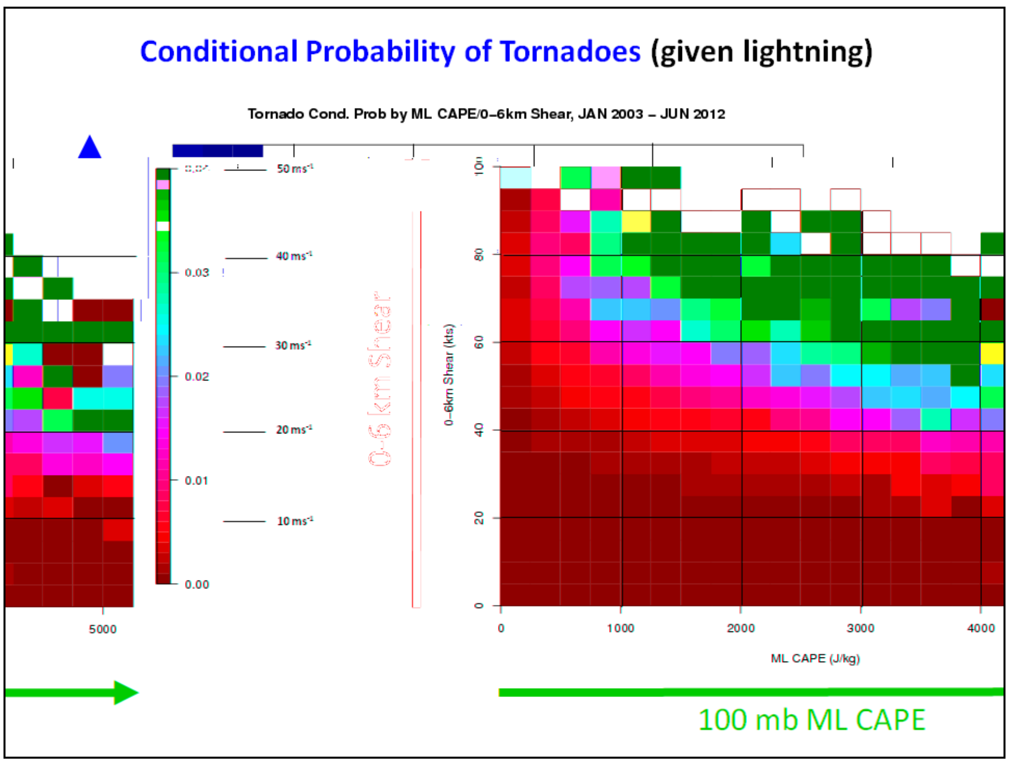

Fig. 2. Conditional probability of tornadoes, given lightning, binned by MLCAPE/SHR6 space, valid from JAN 2003-JUN 2012.

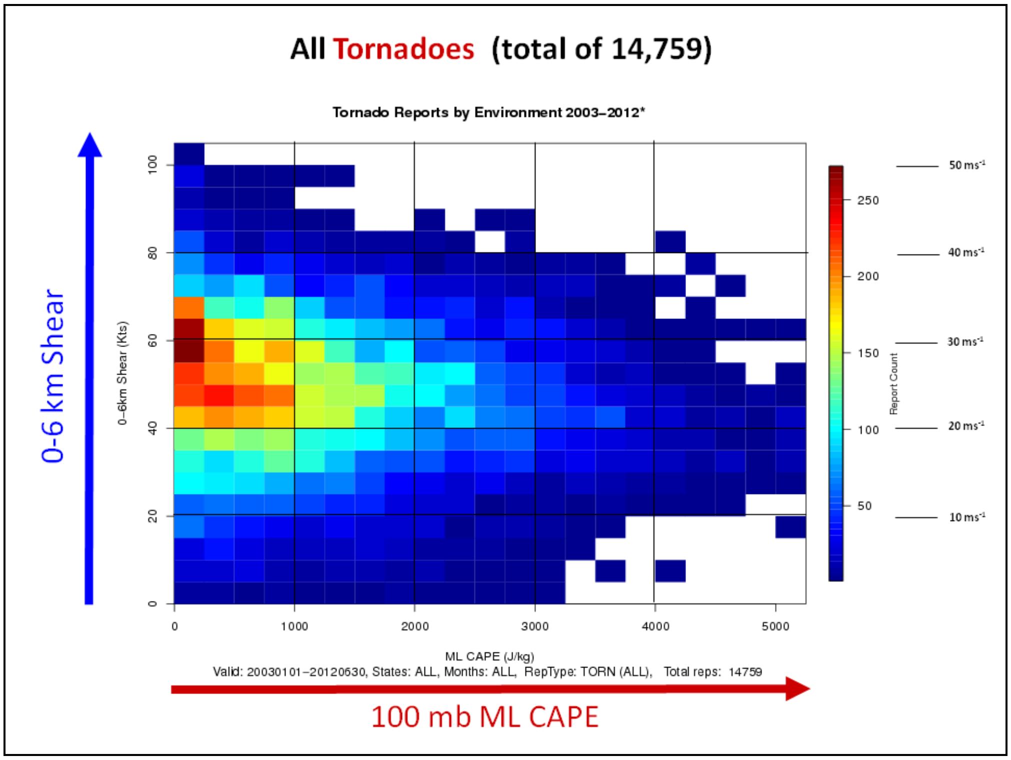

Fig. 3. Tornado counts binned by MLCAPE/SHR6, valid from JAN 2003-JUN 2012.

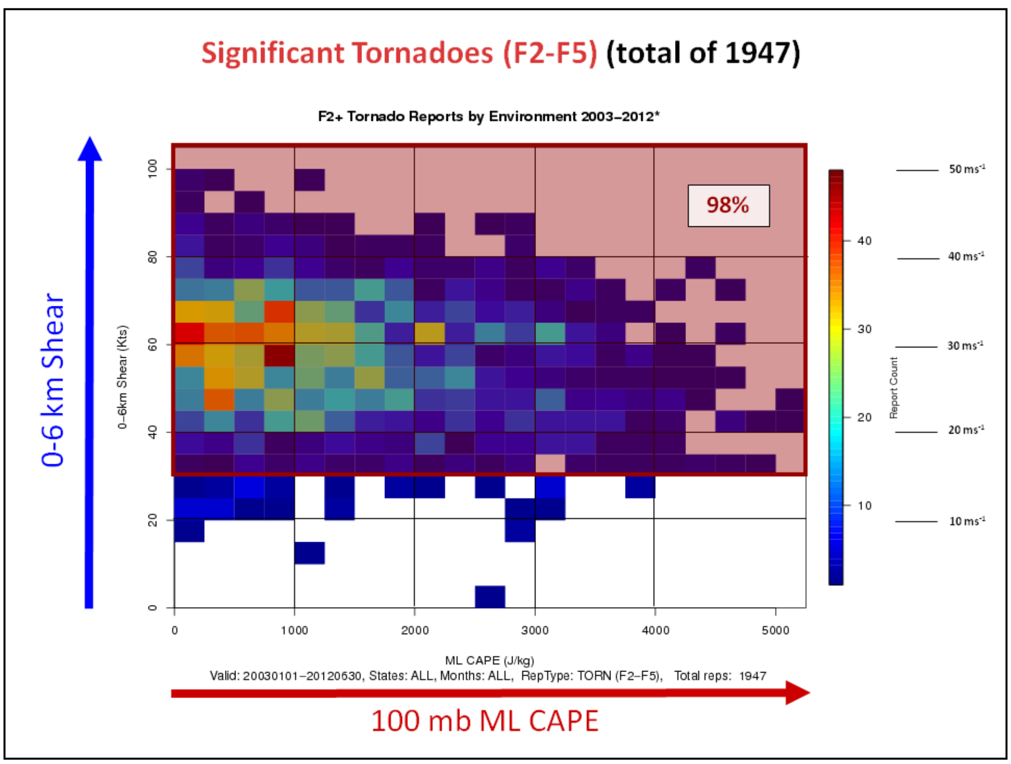

Fig. 4. F2+/EF2+ tornadoes binned by MLCAPE/SHR6, valid from JAN 2003 – JUN 2012. 98% of these events occurred with 0-6km shear ≥ 15 m s^{-1}, as indicated by shaded area.

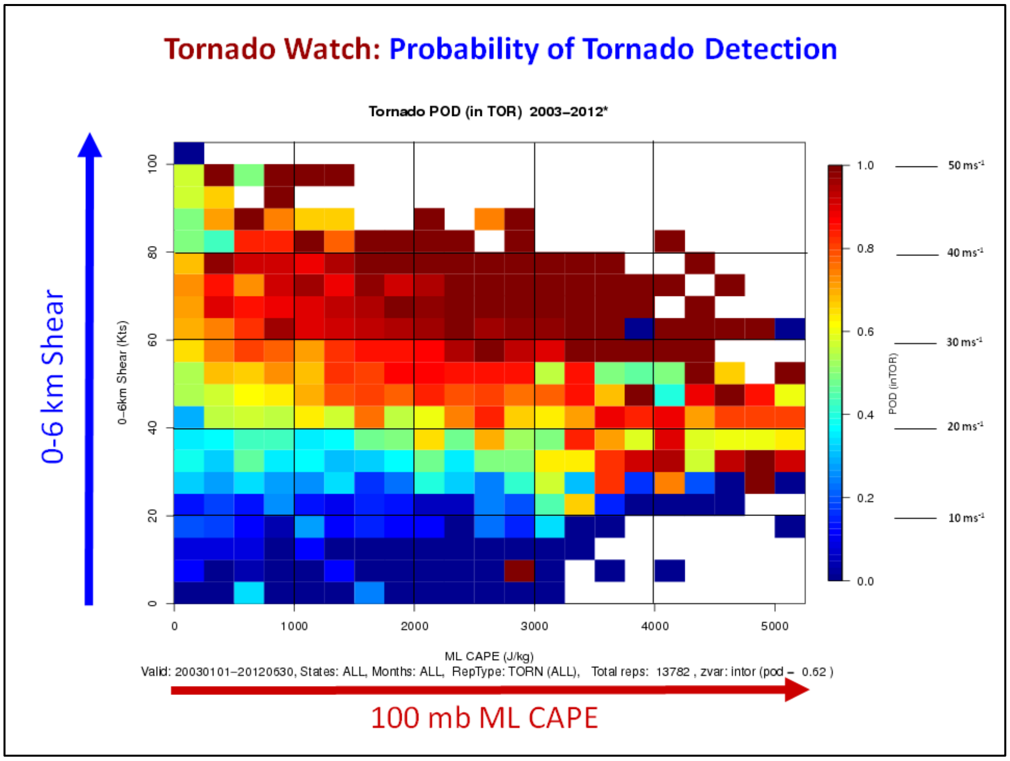

Fig. 5. Tornado watch POD binned by MLCAPE/SHR6, valid from JAN 2003-JUN 2012.

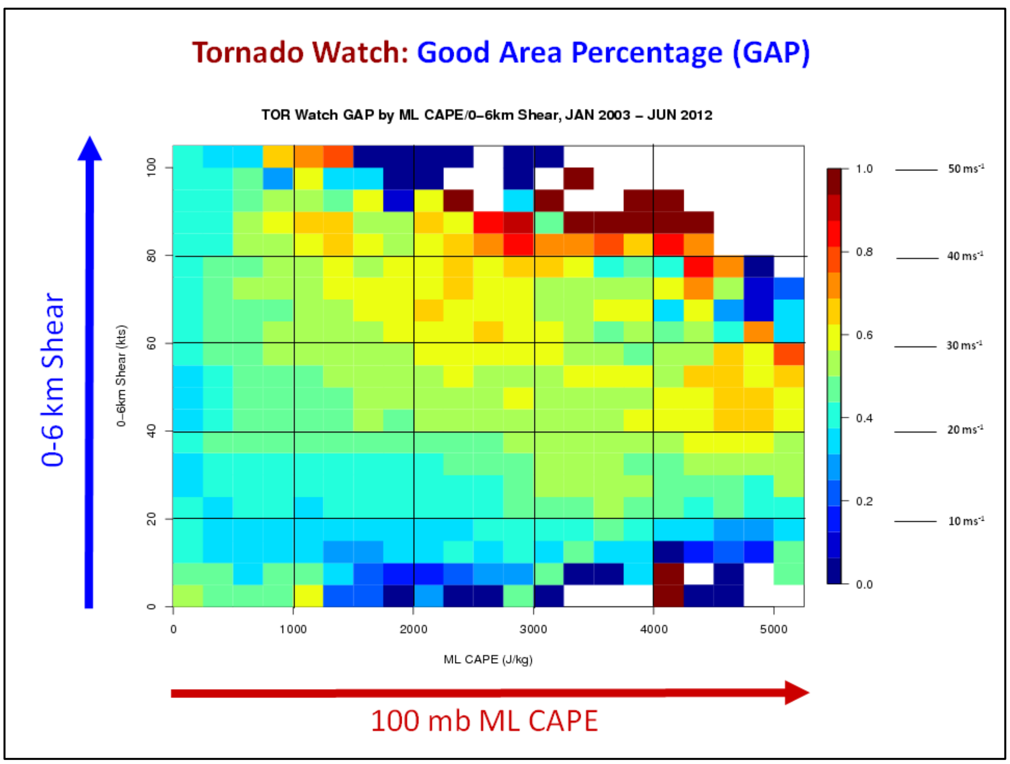

Fig. 6. Tornado watch GAP (GAP = 1 – FAR) binned by MLCAPE/SHR6, valid from JAN 2003 – JUN 2012.

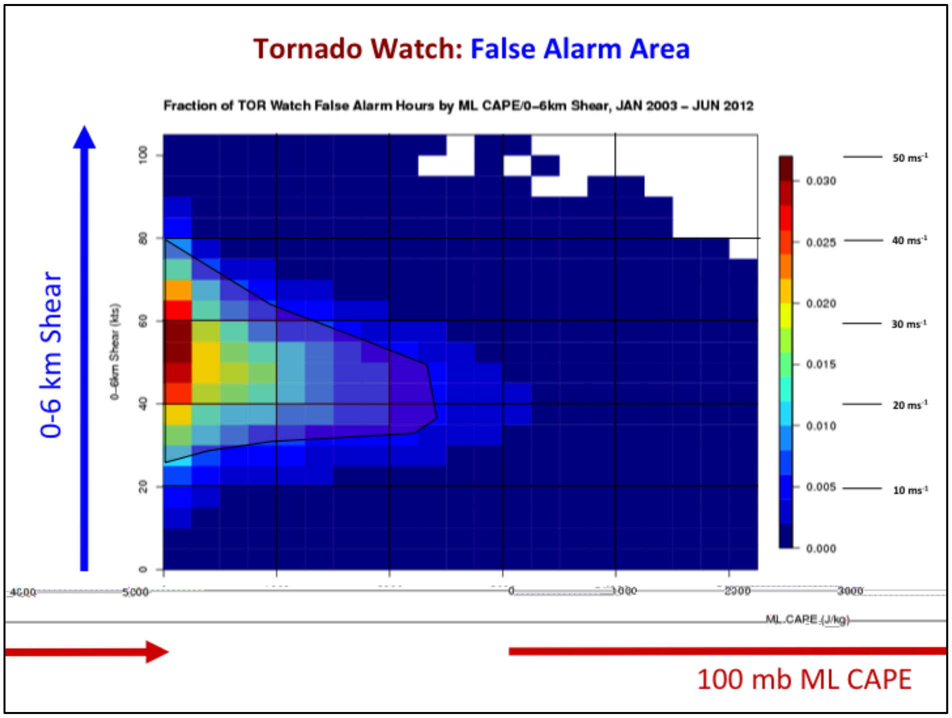

Fig. 7. Fraction of total false alarm (FAR) area in tornado watches binned by MLCAPE/SHR6. Transparent shading highlights the area where false alarms are most common.

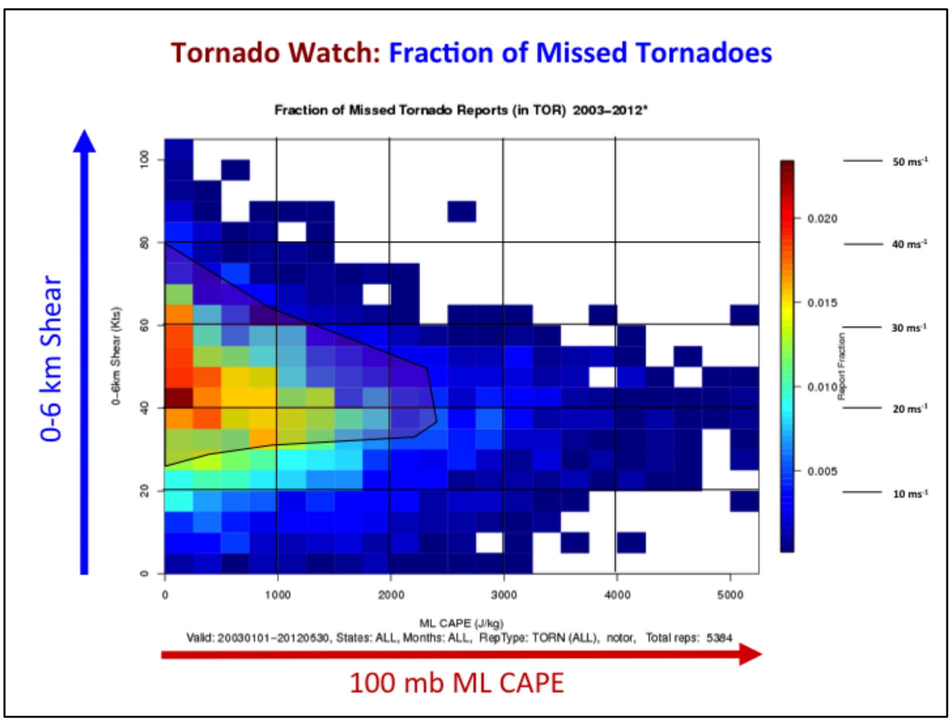

Fig. 8. Fraction of missed tornado events (not in a Tornado Watch) binned by MLCAPE/SHR6. Transparent shading shows where most false alarms tend to occur (from Fig. 7), which has significant overlap with where missed events tend to occur.

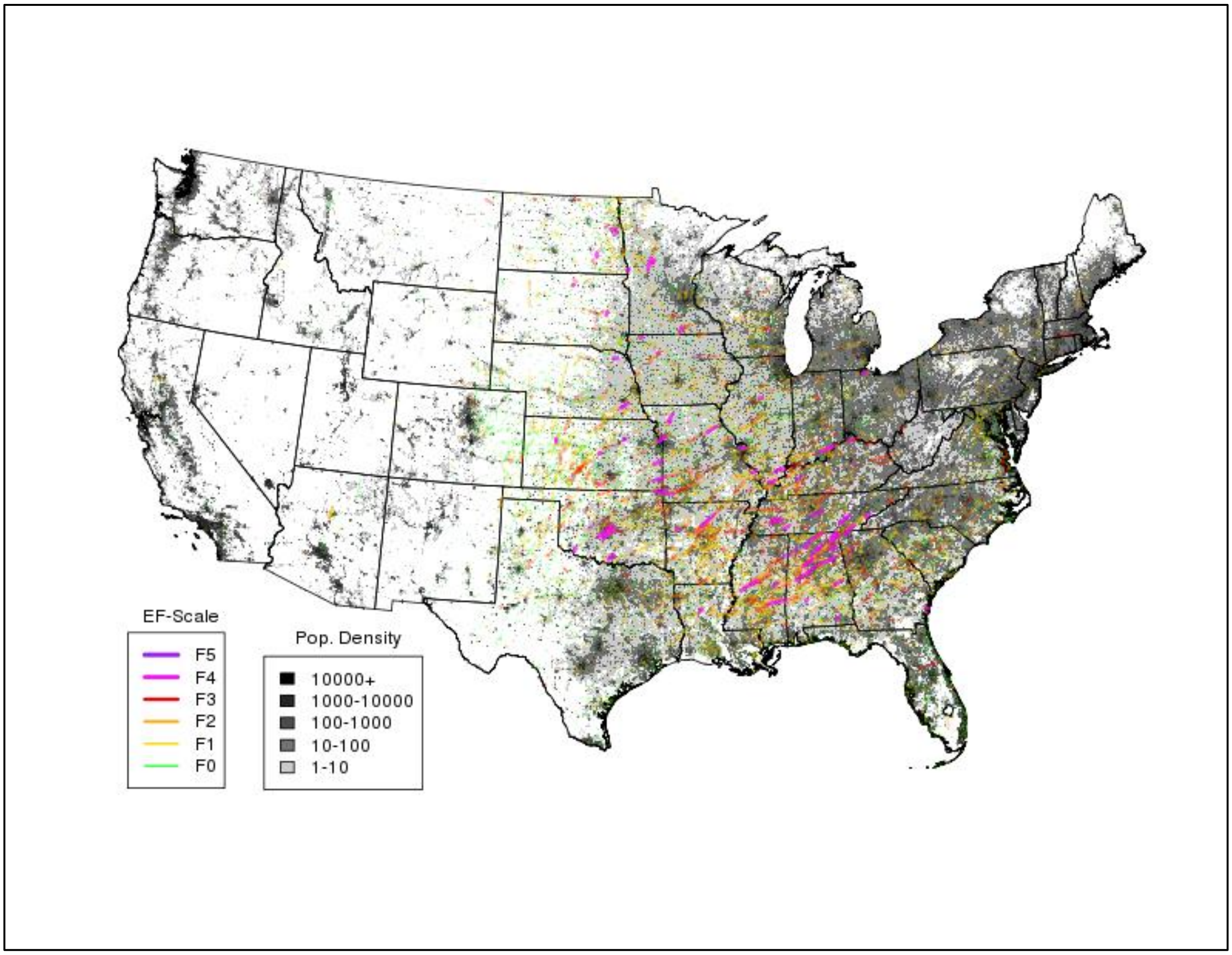

Fig. 9. Tornado tracks and population density, valid JAN 2003 – JUN 2012. Tornado county segments are plotted on this map and color-coded by F-/EF-Scale rating. Population density is on a ~5 km grid.

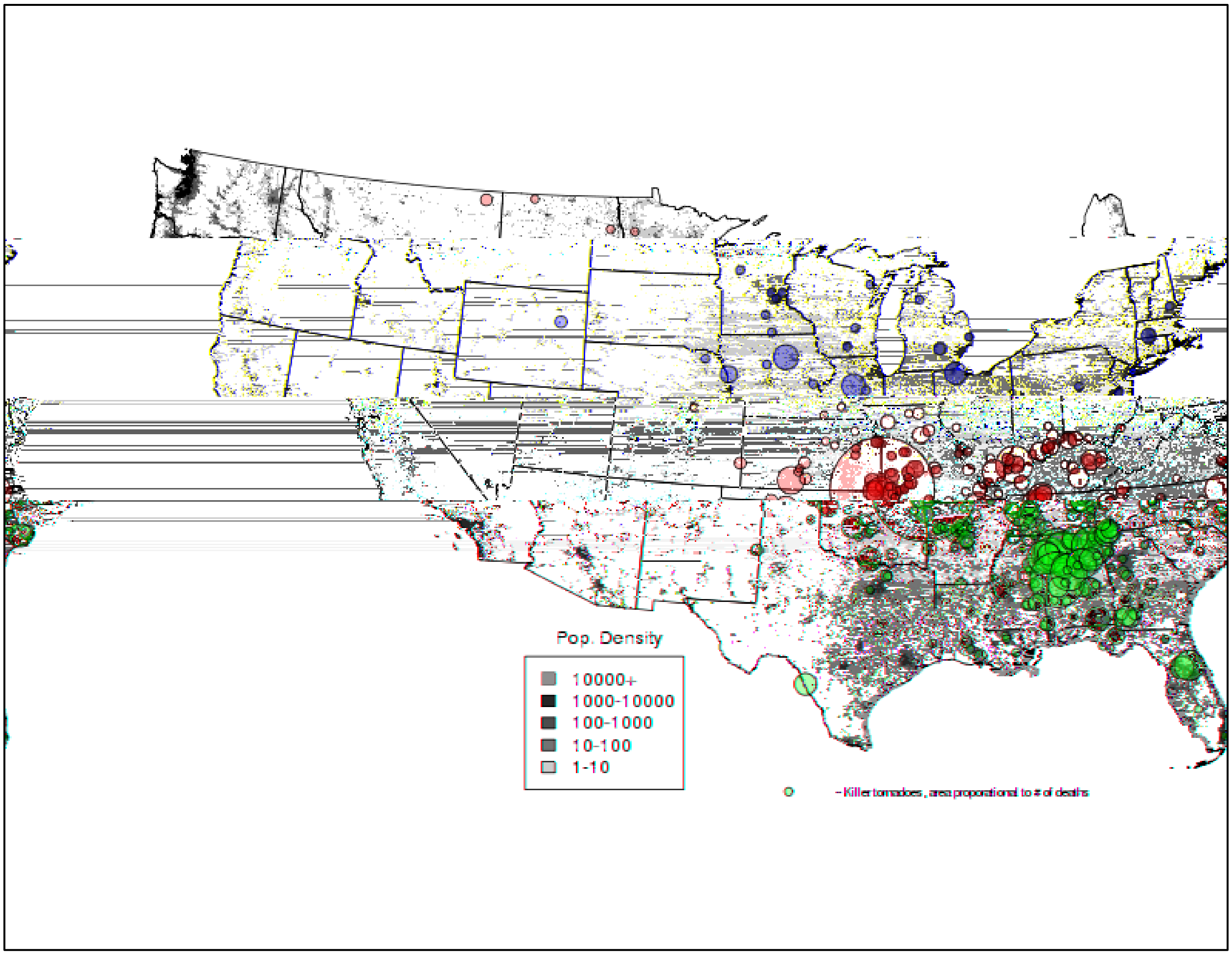

Fig. 10. Location of killer tornadoes from JAN 2003 – JUN 2012, overlain on population density map. Area of circles is proportional to the number of fatalities associated with a particular event.

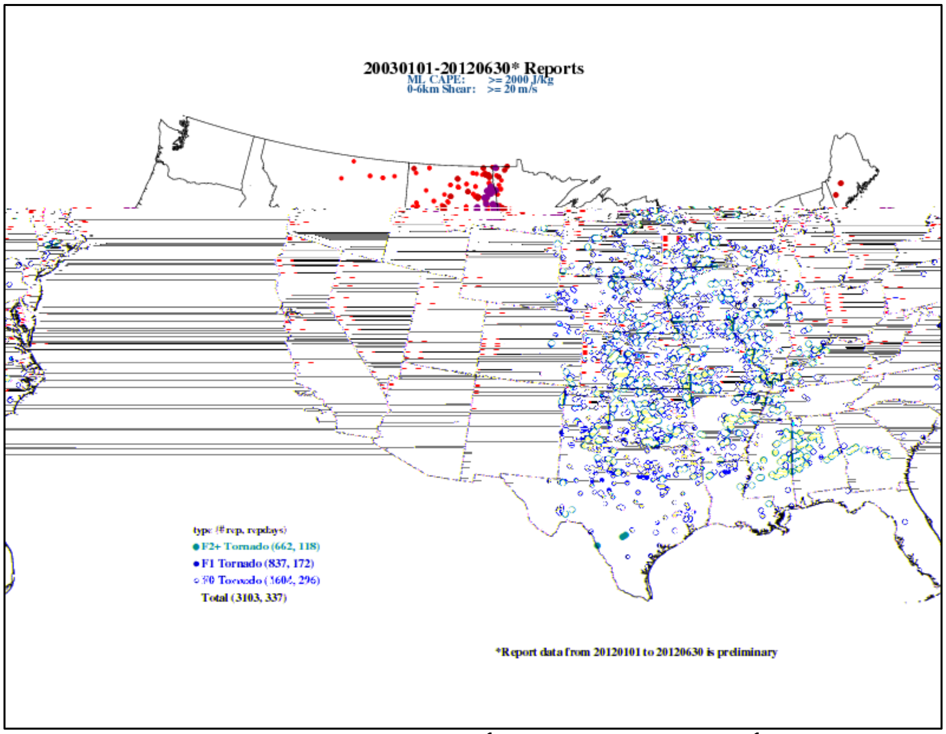

Fig. 11. Plot of high MLCAPE ($\geq$ 2000 J kg^{-1}), high SHR6 ($\geq$ 20 m s^{-1}) tornadoes, from JAN 2003 – JUN 2012. Purple dots indicate F2/EF2 or greater events.

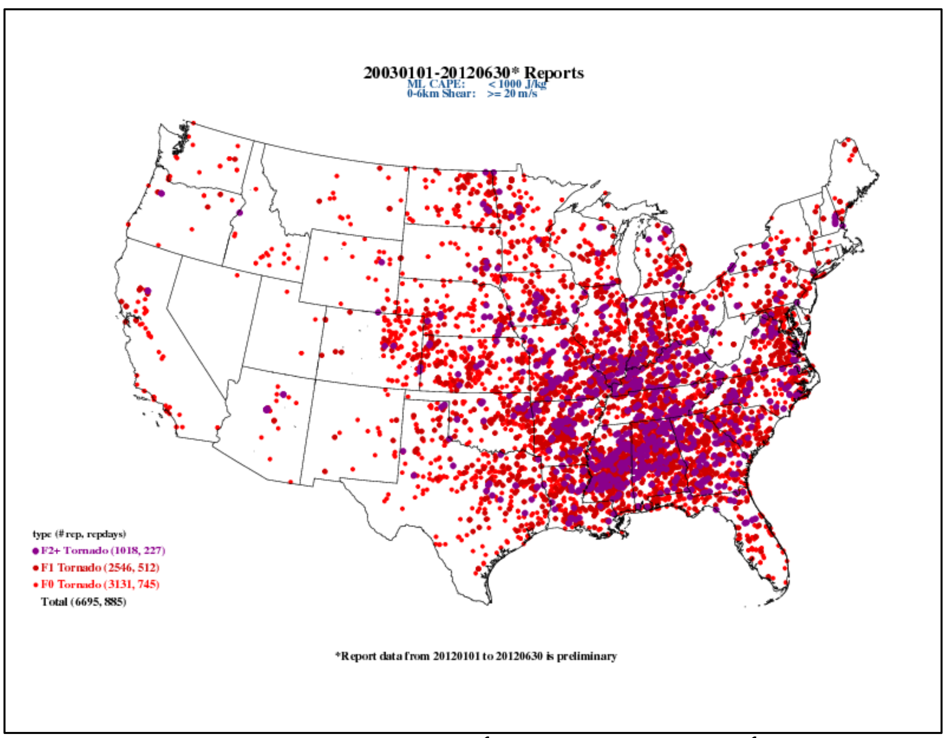

Fig. 12. Plot of low MLCAPE (< 1000 J kg^{-1}), high SHR6 ($\geq$ 20 m s^{-1}) tornadoes, from JAN 2003 – JUN 2012. Purple dots indicate F2/EF2 or greater events.

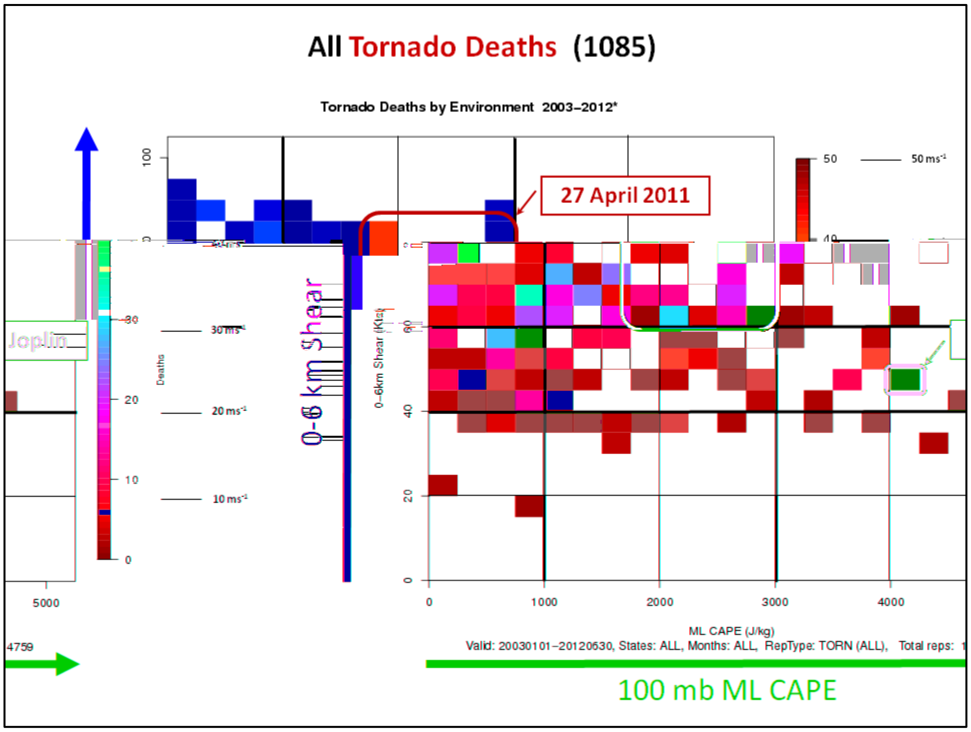

Fig. 13. Tornado deaths binned by MLCAPE/SHR6, valid from JAN 2003 – JUN 2012. The single bin indicating the Joplin event (22 May 2011) is outlined, as are the representative bins from 27 April 2011. Many fatalities have occurred in the low CAPE (< 1000 J kg^{-1}) part of the parameter space.

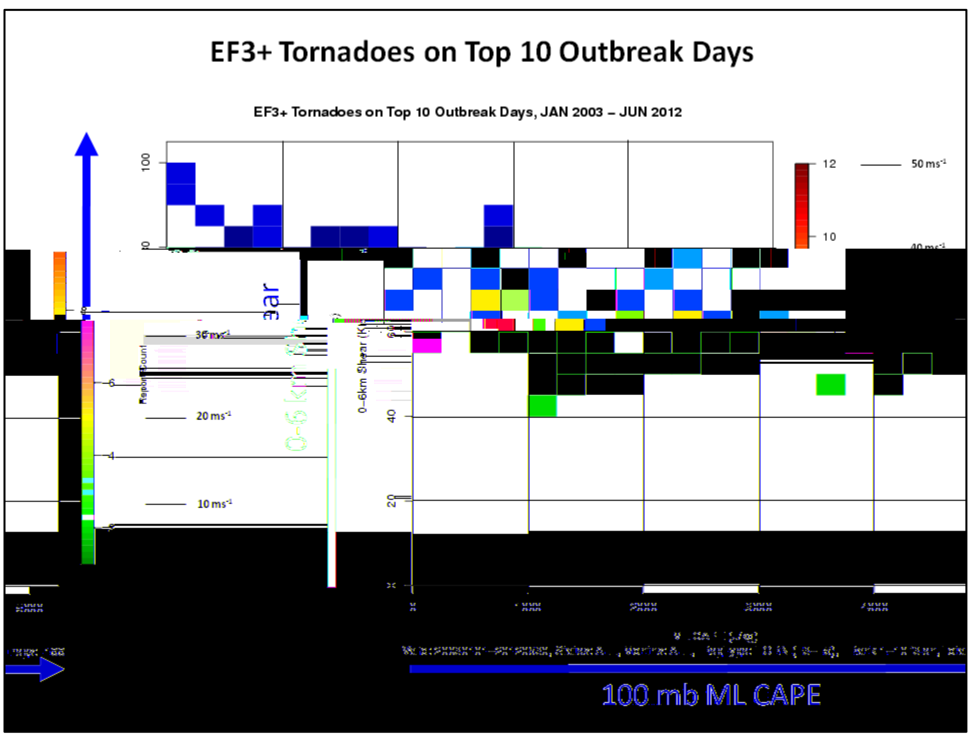

Fig. 14. Plot of F3+/EF3+ tornadoes from the top 10 outbreak days, binned by MLCAPE and SHR6.

Outbreaks: 22 May 2011 vs. 27 Apr. 2011

Date	F3+ PL	∑ Pop.	> 10 km^{-2}	> 100 km^{-2}	Deaths	Injuries
22 May 2011	43 km	10,883,176	26.3%	4.3%	159	1218
27 Apr 2011	1694 km	49,680,374	44.7%	8.0%	313	2753

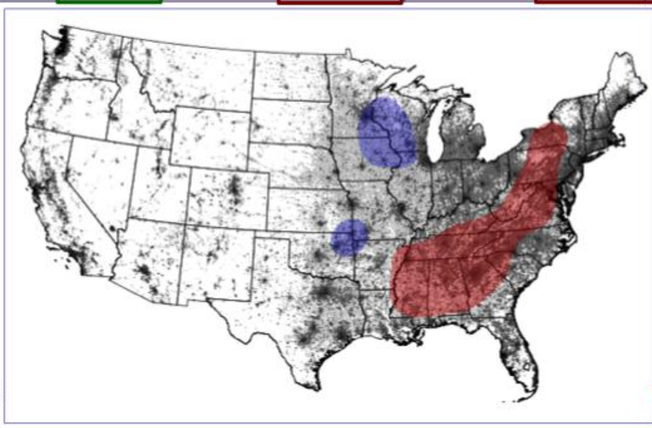

Fig. 15. Comparsion of 22 May 2011 (blue, including EF5 in Joplin, Mo) and 27 April 2011 (red) outbreaks. Grey shading indicates population density using the same scale as Fig. 8. The table shows the same information as seen in Fig. 9.

Outbreaks: 14 Apr. 2012 vs. 16 Apr. 2011

Date	F3+ PL	∑ Pop.	> 10 km^{-2}	> 100 km^{-2}	Deaths	Injuries
14 Apr 2012	223 km	5,288,056	6.0%	1.4%	6	73
16 Apr 2011	230 km	17,686,983	48.3%	9.6%	26	480

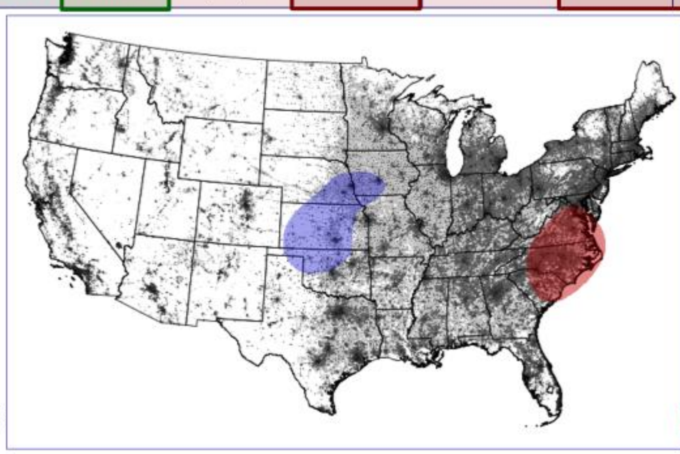

Fig. 16. Same as Fig. 14, only comparing 14 April 2012 (blue) to 16 April 2011 (red).

Tornado Outbreaks (2003-2012)

Date	F3+ PL	∑ Pop.	$> 10\ km^{-2}$	$> 100\ km^{-2}$	Deaths	Injuries
27 Apr 2011	1694 km	49,680,374	44.7%	8.0%	313	2753
4 May 2003	563 km	14,589,932	28.4%	3.8%	38	346
5 Feb 2008	411 km	19,204,988	36.7%	4.9%	57	425
2 Mar 2012	378 km	28,102,835	49.4%	8.2%	40	309
12 Mar 2006	309 km	10,013,368	22.5%	3.7%	8	163
2 Apr 2006	307 km	14,687,696	26.9%	4.1%	27	348
24 May 2011	287 km	7,212,195	18.4%	2.9%	18	375
24 Apr 2010	267 km	7,954,992	35.3%	4.8%	10	199
16 Apr 2011	230 km	17,686,983	48.3%	9.6%	26	480
14 Apr 2012	223 km	5,288,056	6.0%	1.4%	6	73

Top 10 Outbreaks Ranked by summed F3+ Path Length

Table 1. Table showing top 10 tornado outbreaks from 2003-2012 ranked by path length (PL) of F3+/EF3+ tornadoes. Population numbers are calculated inside of the 10% "practically perfect" contour for F2+/EF2+ events on the given day. Percent values indicate the percent area affected by the outbreak with population density of 10 km^{-2} and 100 km^{-2}.