6A.5 THE CONDITIONAL RISK OF SEVERE CONVECTION ESTIMATED FROM ARCHIVED NWS/STORM PREDICTION CENTER MESOSCALE OBJECTIVE ANALYSES: POTENTIAL USES IN SUPPORT OF FORECAST OPERATIONS AND VERIFICATION

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1. INTRODUCTION

The NOAA/NWS Storm Prediction Center (SPC) maintains a database of environmental parameters associated with severe convection (Dean and Schneider, 2006). These parameters are archived from hourly SPC mesoscale analysis (SfcOA) grids (Bothwell et al. 2002) available on a 40 km grid that are available from 2003-present. The database also includes severe weather reports, gridded CG lightning data, and archived SPC forecast products.

Using the environmental analyses in conjunction with lightning and report data, we can calculate the conditional probability of severe convective elements (tornado, wind, hail) given the presence of deep convection (using lightning as a proxy). In particular, we have used a 5-year sample (2003-2007) from the environment database to estimate the conditional risk of severe convection (defined by the presence of large hail $\geq$ 0.75 in. [~ 19 mm] in diameter, wind gusts $\geq$ 50 kts [~ 25.7 m s^{-1}] or damage consistent with such wind speeds, or tornadoes) as a function of convective available potential energy (CAPE) and deep-layer (0-6 km) bulk shear. We have also populated a 5-dimensional parameter space that includes CAPE, convective inhibition (CIN), deep-layer shear, 0-1 km storm-relative helicity (SRH1) and lifting condensation level (LCL) height in order to develop a multi-parameter estimate of the conditional tornado risk.

The utility of this work to the SPC is two-fold. First, an objective multi-parameter estimate of the conditional tornado (or wind/hail) risk would be a valuable real-time tool in assisting forecast operations. Second, this conditional risk can be used as a proxy for the difficulty of the forecast, which would provide a valuable context for SPC's forecast verification, particularly in terms of SPC convective watches.

1.1 SPC Convective Watches

A convective watch is issued by the SPC when it is determined that there is an enhanced, imminent risk of severe convection 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 2005). In practice, the average size of a watch is around 25,000 mi^2 (~65,000 km^2) and the average duration is around 6 hours. Tornado Watches are issued when multiple tornadoes, or at least one EF2 or greater (on the Enhanced Fujita Scale) tornado is expected. Severe Thunderstorm Watches are issued when the main risk is determined to be severe wind and/or hail.

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2. THE CONDITIONAL RISK OF SEVERE CONVECTION IN CAPE-SHEAR SPACE

In the figures presented below, results are accumulated in discrete bins in a 2-dimensional "CAPE-Shear" space, with most-unstable parcel (MU) CAPE on the x-axis and 0-6 km bulk shear (SHR6) on the y-axis. The bin sizes were arbitrarily defined as 250 J kg^{-1} for MU CAPE and 5 kts (2.5 m s^{-1}) for SHR6. SfcOA grid points where MU CAPE = 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 (NLDN).
- *Report (tornado) hour* – An environment hour that contained at least one severe weather (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 severe (tornado)* – The probability of a severe weather (tornado) report occurring in an hourly 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

An examination of the environment, lightning, and severe report distributions in CAPE-Shear space for the period 2003-2007 confirms the following intuitive results:

- Convective environments characterized by relatively low values of MU CAPE and SHR6 are far more common than environments characterized by high values of one or both of these parameters (Fig. 1).
- Most severe reports occur in environments with higher MU CAPE and SHR6 compared to the general distribution of convection (see Fig. 2).
- The conditional probability of severe thunderstorms and tornadoes increases with increasing MU CAPE and SHR6 values (Fig. 3).

For a more detailed environmental analysis of severe convection for the 2003-2007 period, refer to Schneider and Dean (2008).

2.1. Smoothed Severe Conditional Probability Estimates

The raw conditional probability values shown in Figure 3 become noisy as MU CAPE and SHR6 become very large, where the sample size is small. In order to create a smoothed field of conditional probability, a 2D Gaussian kernel density estimator (Wilks, 2006) was applied to the binned MU CAPE and SHR6 values. A smoothing parameter of 500 J/kg was arbitrarily chosen for MU CAPE and 10 kts (~ 5 m s^{-1}) was used for SHR6 in the calculation. The smoothing was applied to the report hours and lightning hours individually and then the smoothed conditional probability was computed (Fig. 4).

2.2 Smoothed 5D Tornado Conditional Probability Estimates

Previous analyses of tornado environments (such as Thompson et al. 2003) have identified additional parameters (beyond just CAPE and deep-layer shear) that are associated with tornado occurrence. The five parameters used in this study are the lowest 100 hPa mean mixed parcel (ML) CAPE, SHR6, SRH1, ML LCL and ML CIN. These parameters are already in use at SPC in diagnostic metrics such as the significant tornado parameter (Thompson et al. 2003, Thompson et al. 2007). The focus here is to attempt to generate actual probabilities from the parameter space, rather than combining the parameters into a numeric value.

In order to compute a smoothed conditional tornado probability estimate, a Gaussian kernel density estimator was applied to binned values in the 5-dimensional parameter space consisting of ML CAPE, SHR6, SRH1, ML LCL, and ML CIN. This approach is similar to what was suggested in Doswell and Schultz, 2006. In order to fill the 5D parameter space, coarser bin sizes and smoothing parameters were used compared to the 2D smoothing described above. As before, the smoothed value of report hours in each bin was divided by the smoothed value of lightning hours to compute the conditional probability.

2.3 Discussion

A couple of caveats relating to the work done so far should be mentioned before further analysis is presented. First, this work is very preliminary and no effort has been made (yet) to optimize the smoothing parameters used in the kernel density estimator, which were arbitrarily chosen for this study. Future work will involve trying many different combinations of smoothing parameters in order to optimize the construction of the parameter spaces.

Second, the conditional probability estimates for severe convection and especially tornadoes resulting from the process described above can be quite small; values above 0.15 were rarely observed for severe convection and values above 0.02 were rarely observed for tornadoes. This is not unexpected however, given that severe convection and tornadoes are rare events and that the probability value in question is for an event occurring in a single 40 km grid box over 1 hour.

For the six-year period 2003-2008, the mean value of severe conditional probability in a single hourly grid box (given lightning) was 0.02 and the mean value of tornado conditional probability was 0.001. It is also useful to consider the magnitude of the probability values in the context of convective watch verification (see section 4). In Severe Thunderstorm Watches that exactly meet the minimum watch criteria (6 severe reports in the watch), the median severe conditional probability from 2003-2008 was 0.04. In Tornado Watches that exactly meet the minimum watch criteria (2 tornado reports or 1 EF2+ tornado report), the median tornado conditional probability from 2003-2008 was 0.01. These values should be kept in mind when examining the range of probabilities produced from the parameter space. Possible future work will involve mapping the raw hourly probabilities to probability values more relevant to the SPC forecast process, such as the probability of 2 or more tornadoes occurring over the typical time and space scale of a watch.

3. RELIABILITY OF CONDITIONAL PROBABILITY ESTIMATES

Reliability diagrams (Wilks, 2006) for the smoothed severe and tornado conditional probabilities are shown in Figs 5 and 6. In order to create the reliability curves for the conditional probabilities, the smoothed probability estimates were binned and then the observed conditional probability was calculated for each probability bin.

We generated reliability curves for both the 2003-2007 data and the 2003-2007 conditional probability estimates applied to 2008 data. The 2003-2007 reliability curves were assessed in order to evaluate the effects of the smoothing process on the conditional probabilities. The 2008 reliability curves were examined to evaluate the possible real-time diagnostic value of the smoothed conditional probability estimates, treating the 2003-2007 data as a “training set” as the 2008 data as an independent verification dataset.

Fig. 5 indicates that, as would be expected, the estimated severe conditional probability estimate for 2003-2007 is very reliable for probabilities where the sample size is not negligible (up to around p = 0.15), with the reliability curve very close to the perfect reliability line. The conditional probability estimate applied to the 2008 data shows a slight underestimation bias compared to the 2003-2007 training set, but also shows an encouraging correspondence between higher estimated and observed probabilities. Given that 2008 had the most severe reports observed in a single year, the underestimation bias is not surprising.

For the tornado conditional probability estimates, Fig. 6 indicates encouraging reliability for both the 2003-2007 data and the 2008 data. For 2003-2007, a slight overestimation bias is noted at lower probabilities and a slight underestimation is noted a higher probabilities, which is likely a result of the smoothing process. Observed conditional probability for the 2008 data is generally higher at each probability bin compared to the 2003-2007 data, similar to what was observed with the severe conditional probabilities.

4. SPC WATCH VERIFICATION AS A FUNCTION OF SEVERE CONDITIONAL PROBABILITY

4.1 Watch Verification Methodology

SPC verifies watches using severe storm reports which are collected by National Weather Service (NWS) field offices and published in *Storm Data*. Important watch verification measures include probability of detection (POD) of severe reports in watches, average lead time between watch and severe event, and false-alarm ratio (FAR). While report-based measures like POD are straightforward to calculate (simply the fraction of severe reports that occur in watches), there are many ways that the false-alarm aspect of watch verification can be computed. Historically, watches and reports have been placed onto a 40 km grid, with each report in a watch activating a 5x5 grid box area (Weiss et al. 1980). Any unactivated grid boxes in the watch are considered to be false alarm area and it is then possible to define FAR as the percentage of false alarm grid boxes in the watch.

Watch verification as a function of severe conditional probability will be discussed mainly in terms of POD and FAR, as described above. We define a quantity "good area percentage" (GAP) to use in the FAR analysis, defined as GAP = 1 – FAR, so that both aspects of verification can be described in terms of positively oriented (higher is better) variables.

4.2 Verification Results

SPC watch performance for the period 2003-2008 improved as the conditional severe probability of the environment increased, as shown in Fig. 7. Both POD and GAP increase as the environment becomes more favorable for severe convection. However, most lightning (gold line) and reports (green line) tend to occur where the conditional probability is relatively low, which exemplifies one of the difficulties facing SPC forecasters; the greatest forecast challenge lies in the most common convective environments where the severe conditional probability is low but not zero, while the forecast is less difficult in the relatively rare environments where the risk is very high.

The forecast dilemma is further illustrated in Fig. 8, which shows (in addition to the fraction of lightning and severe reports as before) the fraction of total missed severe reports (in blue) and the fraction of total false alarm area (in red) as a function of severe conditional probability. The shaded area between p=0.015 and p=0.035 represents a range in conditional probability where the forecast appears particularly difficult; 40% of all convection (using lightning as a proxy) and 36% of all severe reports occur in this range, along with 48% of all missed reports and 42% of watch false alarm area. The range also falls slightly below the median conditional probability of 0.04 in watches that just meet the minimum report criteria, as described in section 2.3 above.

This analysis was taken a step further by analyzing the spatial patterns of convection that occur in the difficult range of conditional probability described above, as a way of quantifying the predictability (or lack thereof) of severe convection in different parts of the country.

Fig. 9 shows the fraction of all lightning hours that occur with the marginal severe conditional probability between 0.015 and 0.035. The highest values are noted in the eastern half of the country and particularly in the Southeast U.S., where warm-season severe convection is a notorious challenge for SPC forecasters. Meanwhile, the western U.S. has the highest fraction of convection in low conditional probability below the 0.015 threshold (Fig. 10) and the central U.S. has the highest fraction of convection in higher conditional probability above 0.035 (Fig. 11). These results are not surprising, but this type of analysis is a useful way of quantifying and confirming what is already believed to be known about the challenges of severe convective forecasting in different regions of the country.

5. POTENTIAL OPERATIONAL USES OF THE SEVERE CONDITIONAL PROBABILITIES

The hourly mesoscale analysis is produced in real time; thus, in addition to providing context to forecast verification, the conditional probability estimates computed in environment parameter space also have potential use in real time forecast operations. The encouraging reliability of the 2003-2007 conditional probabilities applied to 2008 data (described in section 3 above) suggests that these values could be used as a real-time diagnostic tool. While work is very preliminary in this area, two cases are briefly described below to show the type of data that could be made available to forecasters.

Fig. 12 shows all severe reports between 23 UTC, 11 July 2003, and 02 UTC, 12 July 2003. Of particular note is the cluster of wind reports over the Carolinas. Though no watch was issued in this area, the number of reports clustered in this area over a 3 hour time span would have verified a watch if one had been issued. The observed sounding from Greensboro, NC at 00 UTC, 12 July 2003 (Fig. 13) shows a commonly observed warm-season convective environment, with moderate CAPE (MU CAPE = 1660 J kg^{-1}) and marginal deep layer shear (~ 30 kts). The estimated conditional probability from 00 UTC, 12 July 2003 is shown in Fig. 14. A slightly elevated risk of severe (above background values) is indicated over the Carolinas, but with values in the marginal range where both missed events and false alarms are common (as described above).

Fig. 15 shows all tornado reports between 21 UTC, 8 May 2003 and 00 UTC, 9 May 2003, including an F4 tornado that struck the Moore/Oklahoma City area around 2230 UTC. The Norman, OK sounding taken around 90 minutes after the event shows an extremely favorable environment for tornadoes, with very large CAPE (ML CAPE ~ 4000 J kg^{-1}), strong shear (SHR6 ~ 70 kts [~36 m s^{-1}]) and storm-relative helicity (SRH1 > 300 m^2 s^{-2}), and relatively low LCL height (ML LCL ~ 1 km). The corresponding tornado conditional probability estimate valid at 22 UTC, 8 May 2003 shows a highly elevated conditional risk of tornadoes east of the dryline (not shown) over the eastern half of Kansas and Oklahoma.

6. SUMMARY AND FUTURE WORK

Conditional probabilities of severe convection and tornadoes generated from a multi-dimensional parameter space show promise in providing context to SPC forecast verification and also show potential in providing useful diagnostic guidance to operational forecasters. A great deal of work remains to be done in optimizing the smoothing process used to create the conditional probabilities in the parameter space.

Further analysis along the lines of what was presented in section 4.2 should provide further insight into the types of environments that provide a particular challenge for SPC forecasters. Once such environments are identified, further research can focused on forecast improvements in these areas.

While current work has focused on the conditional probability of all severe types, as well as just on tornadoes, future research will focus on the possibility of developing probabilities for severe wind and hail individually. Conditional probabilities for strong (EF2+) tornadoes will also be explored, though the small sample size of these events will provide a challenge in terms of developing a well populated multi-dimensional parameter space.

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8. FIGURES (see below)

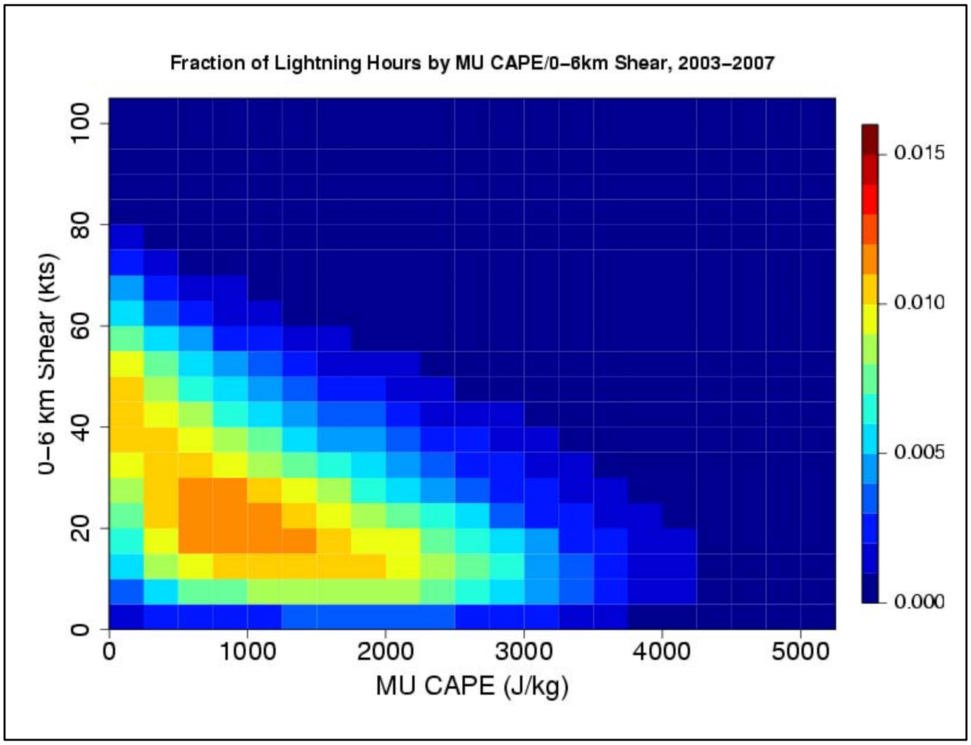

Fig. 1. Distribution of lightning hours for 2003-2007 that occurred in each MU CAPE/0-6km Shear bin, normalized by the total number of lightning hours in the sample.

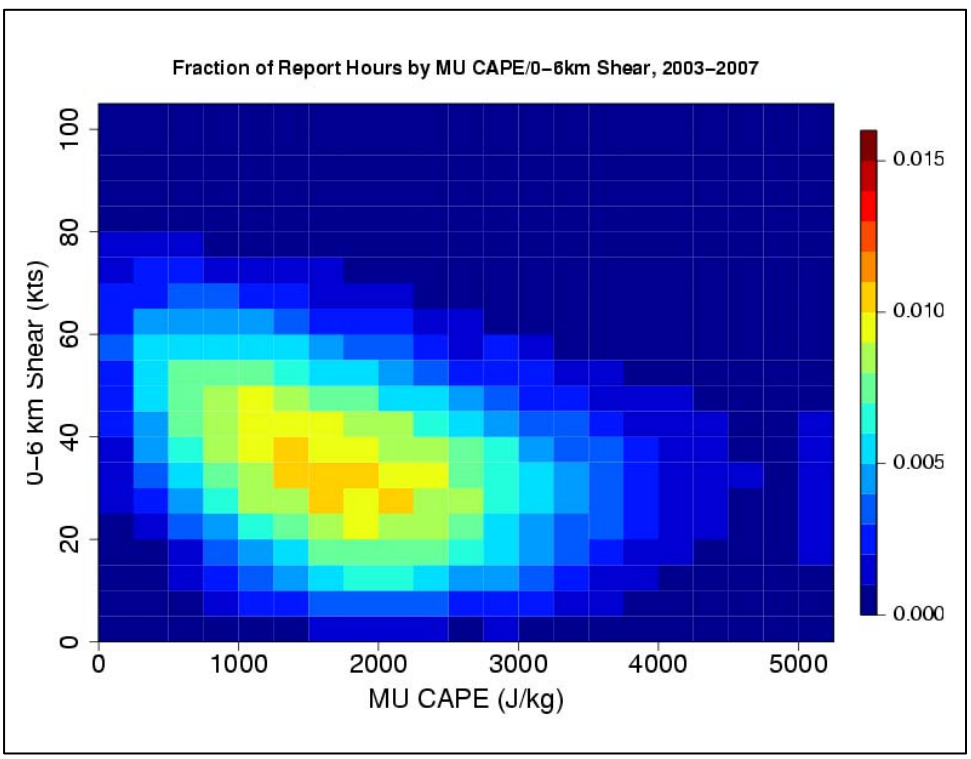

Fig. 2. Distribution of severe report hours for 2003-2007 by MU CAPE/0-6km Shear bin, normalized by the total number of severe report hours in the sample.

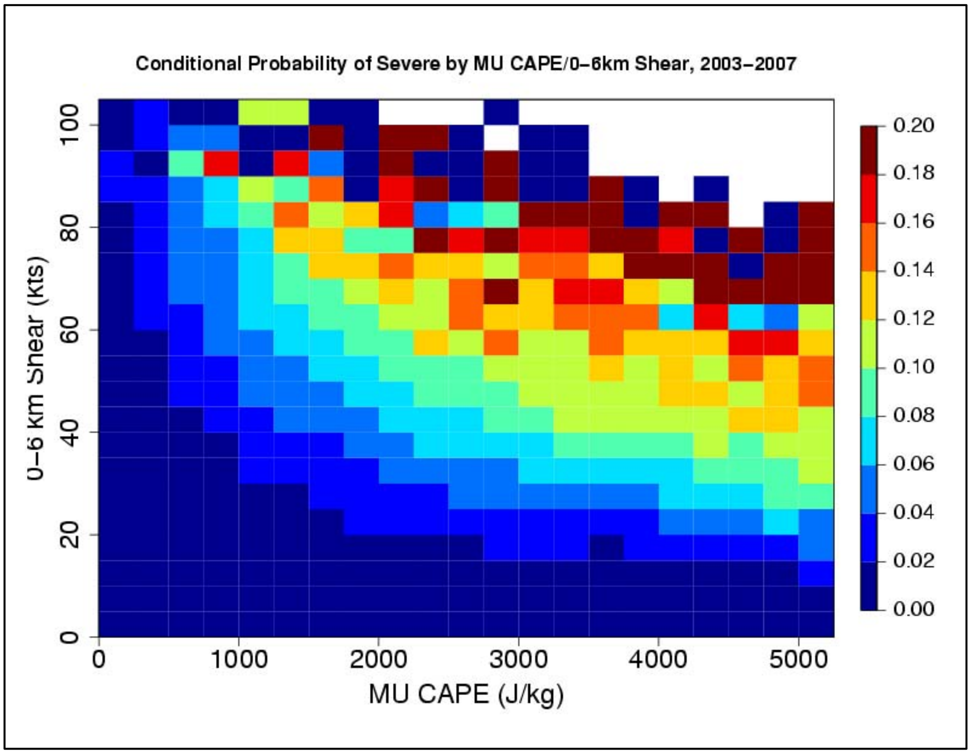

Fig. 3. Conditional probability of severe thunderstorms (including tornadoes) for 2003-2007 by MU CAPE/0-6km Shear bin, conditional on the presence of lightning.

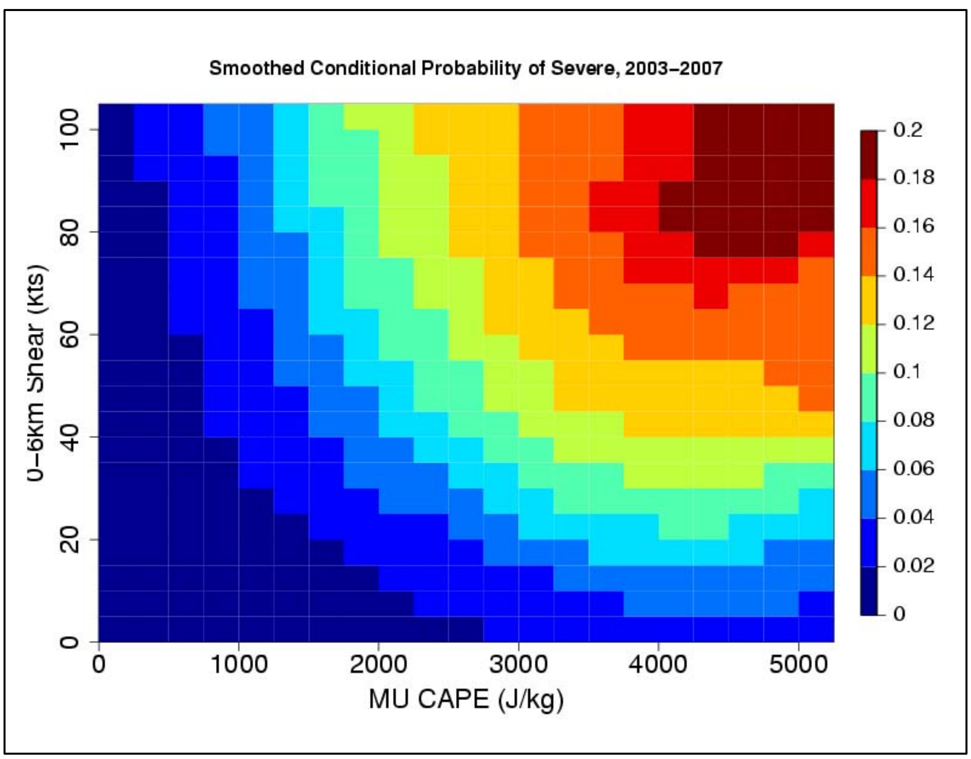

Fig. 4. Smoothed conditional probability of severe thunderstorms (including tornadoes) for 2003-2007 by MU CAPE/0-6km Shear bin, conditional on the presence of lightning.

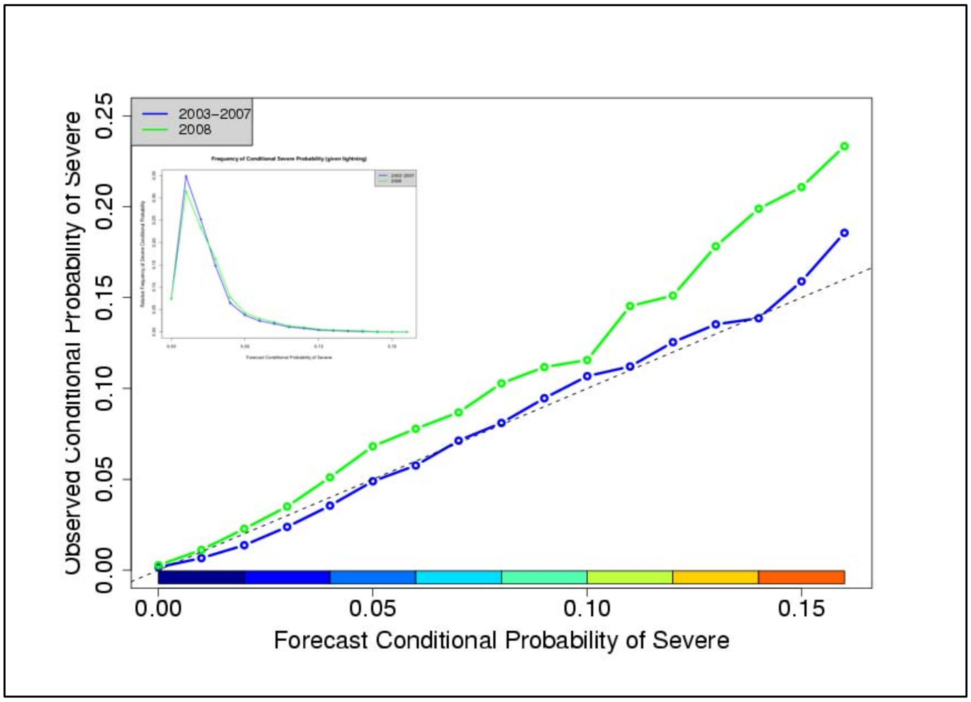

Fig. 5. Reliability diagram for smoothed conditional probability estimates of severe thunderstorms for 2003-2007 (training set, in green) and 2008 (verification set, in blue). Relative frequency of the conditional probability estimates is shown in the upper left.

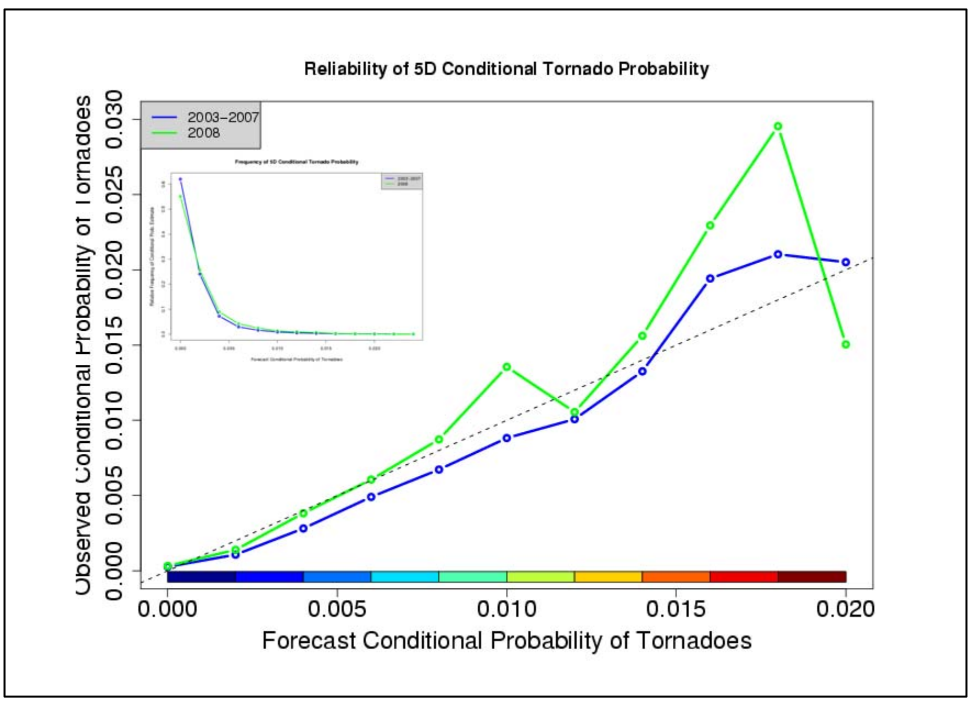

Fig. 6. Reliability diagram for smoothed conditional probability estimates of tornadoes for 2003-2007 (training set, in green) and 2008 (verification set, in blue). Relative frequency of the conditional probability estimates is shown in the upper left.

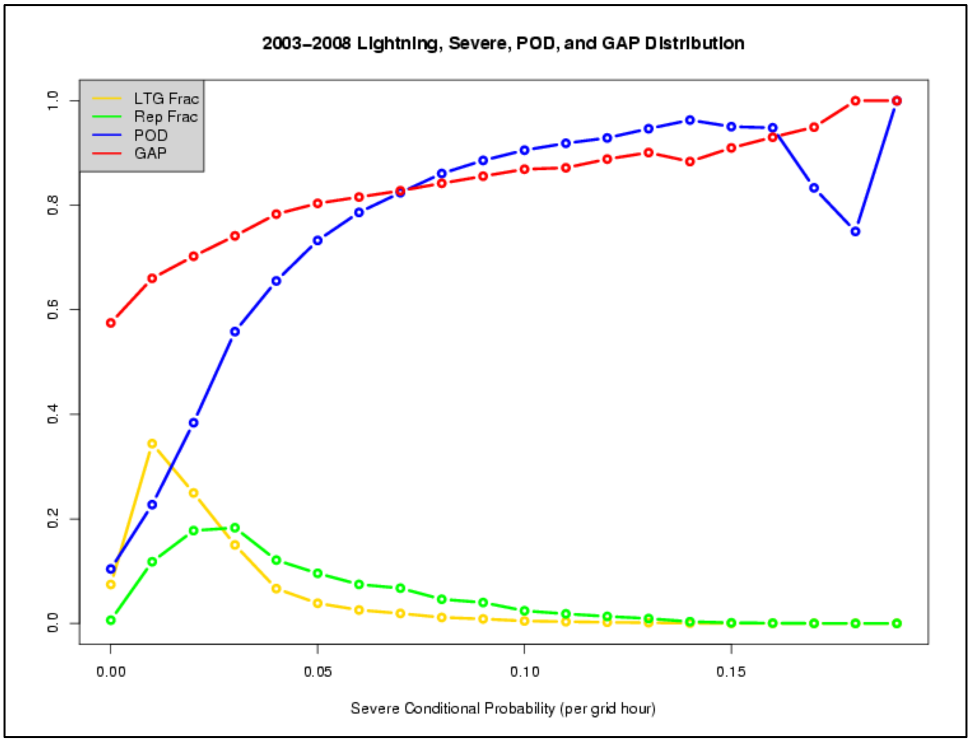

Fig. 7. The fraction of lightning hours (gold), the fraction of report hours (green), watch POD, and watch GAP as a function of the hourly severe conditional probability, for the period 2003-2008.

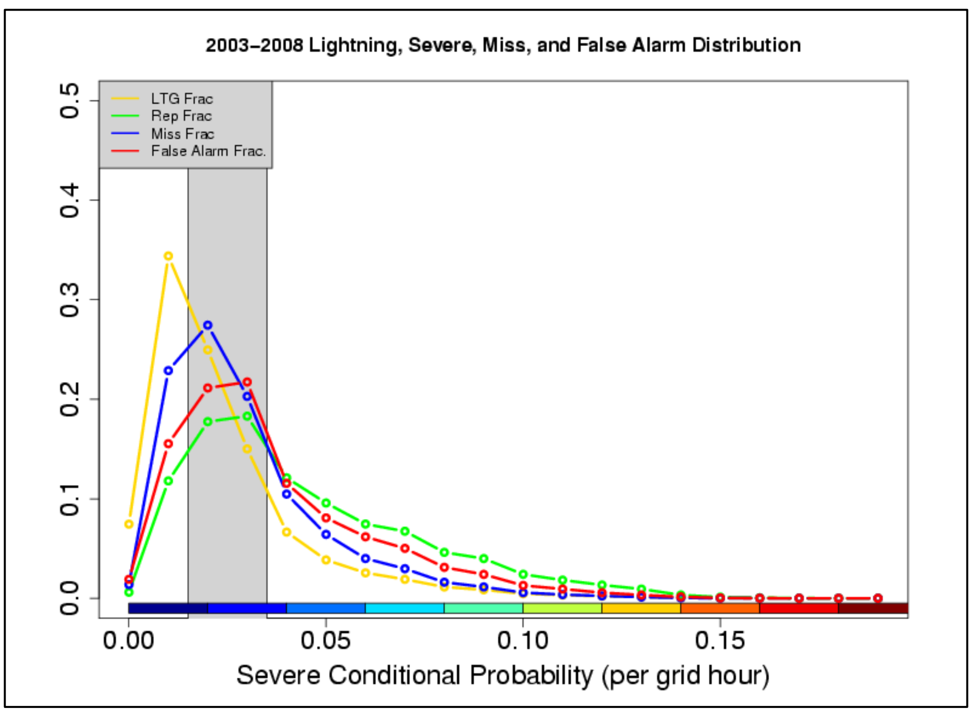

Fig. 8. The fraction of total lightning hours (gold), total report hours (green), missed reports (blue), and watch false alarm area (red) as a function of the hourly severe conditional probability, for the period 2003-2008. The shaded area indicates conditional probability values between 0.015 and 0.035, where both missed events and false alarms are commonly observed.

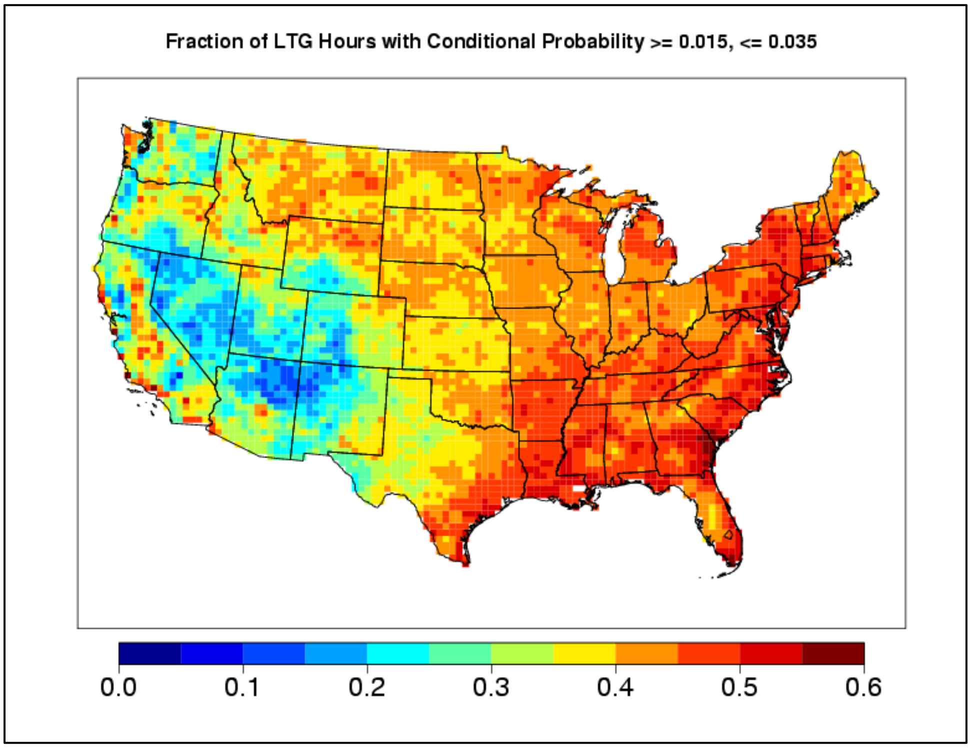

Fig. 9. The fraction of lightning hours at each grid point with marginal severe conditional probability (between 0.015 and 0.035, see Fig. 8), for the period 2003-2008.

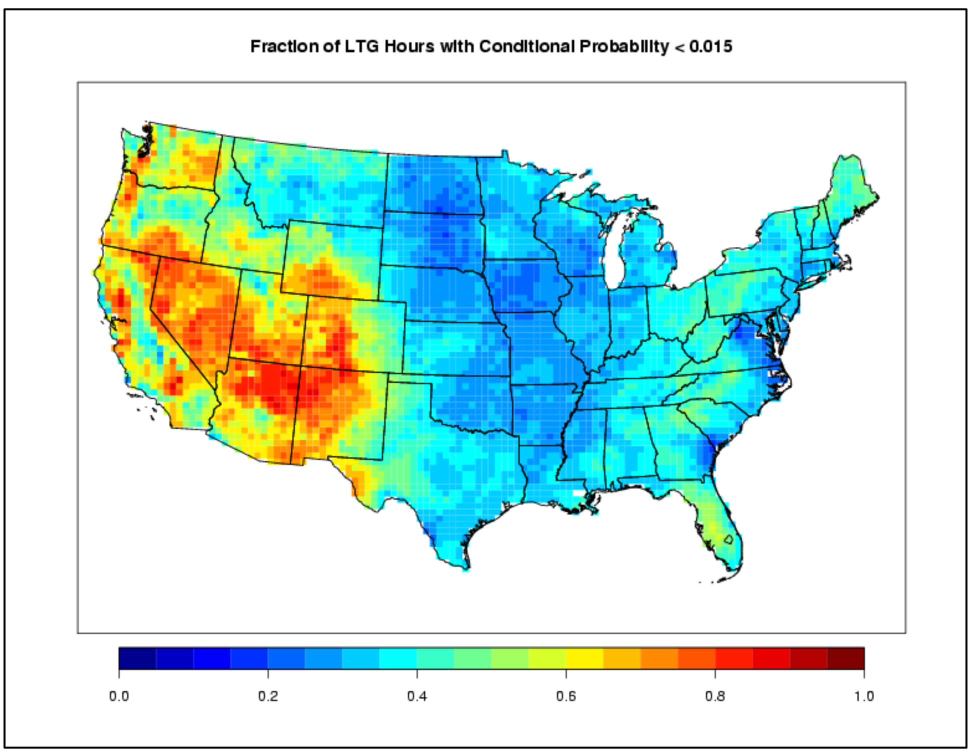

Fig. 10. The fraction of lightning hours at each grid point with low severe conditional probability (less than 0.015), for the period 2003-2008.

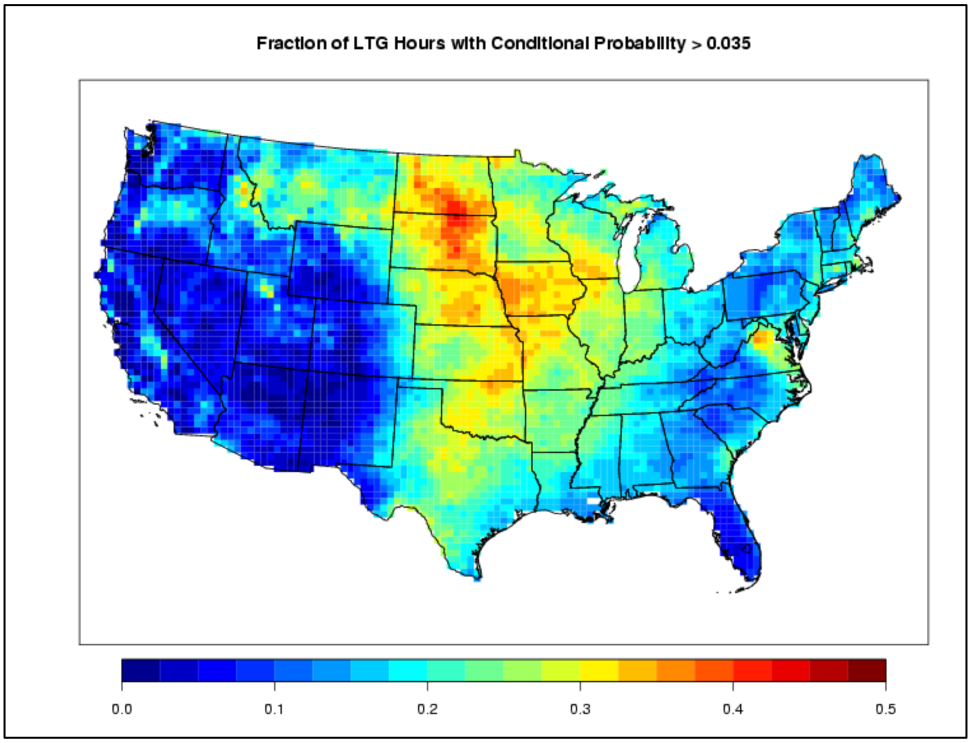

Fig. 11. The fraction of lightning hours at each grid point with high severe conditional probability (greater than 0.035), for the period 2003-2008.

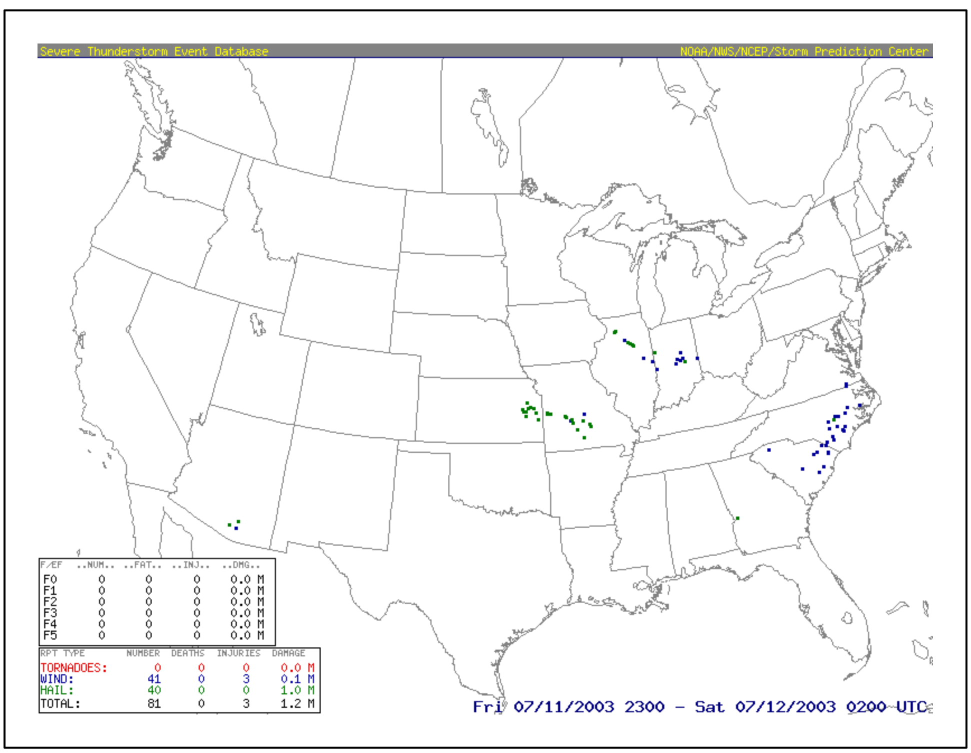

Fig. 12. Severe storm reports from *Storm Data* between 23 UTC 11 July 2003 and 02 UTC 12 July 2003.

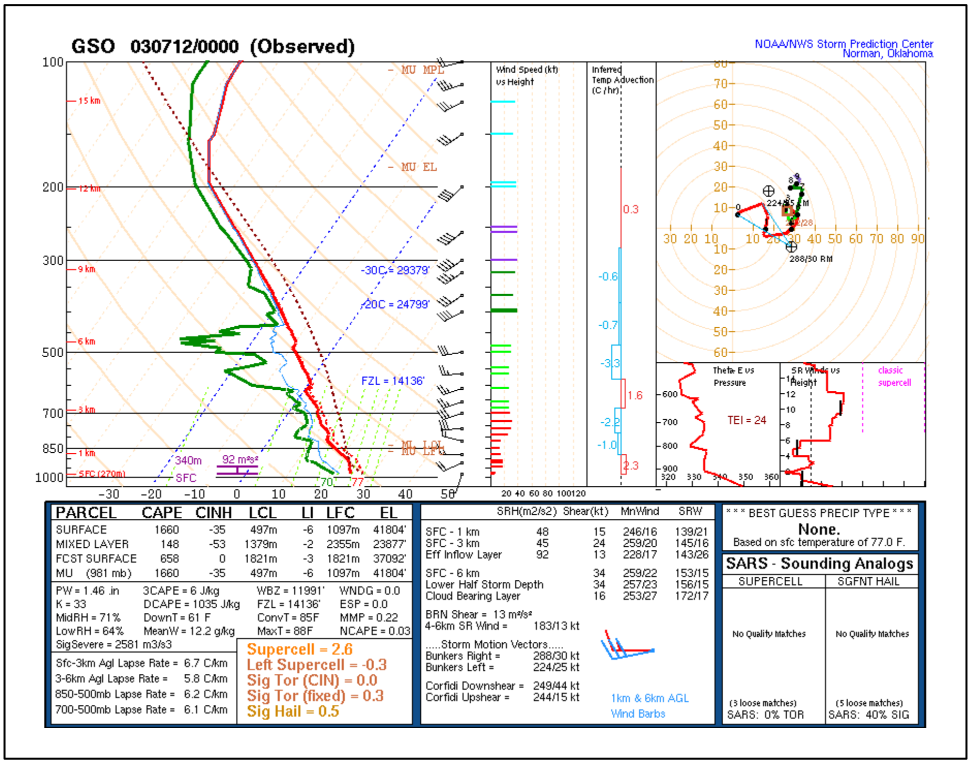

Fig. 13. Greensboro, NC sounding from 00 UTC, 12 July 2003.

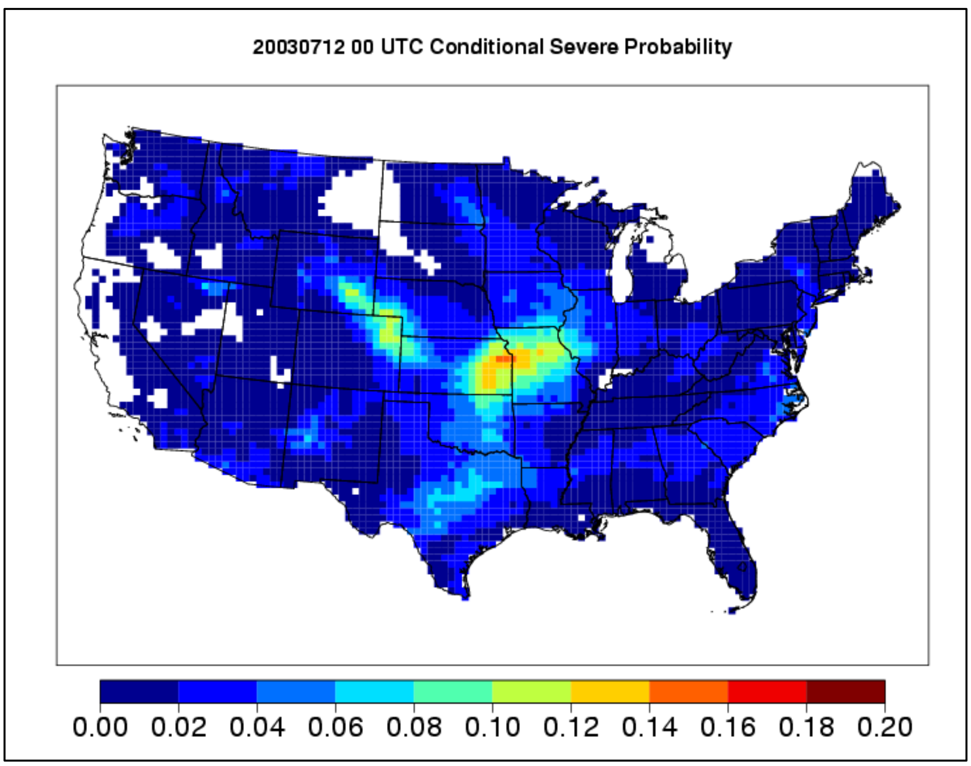

Fig. 14. Conditional severe probability estimate from 00 UTC, 12 July 2003.

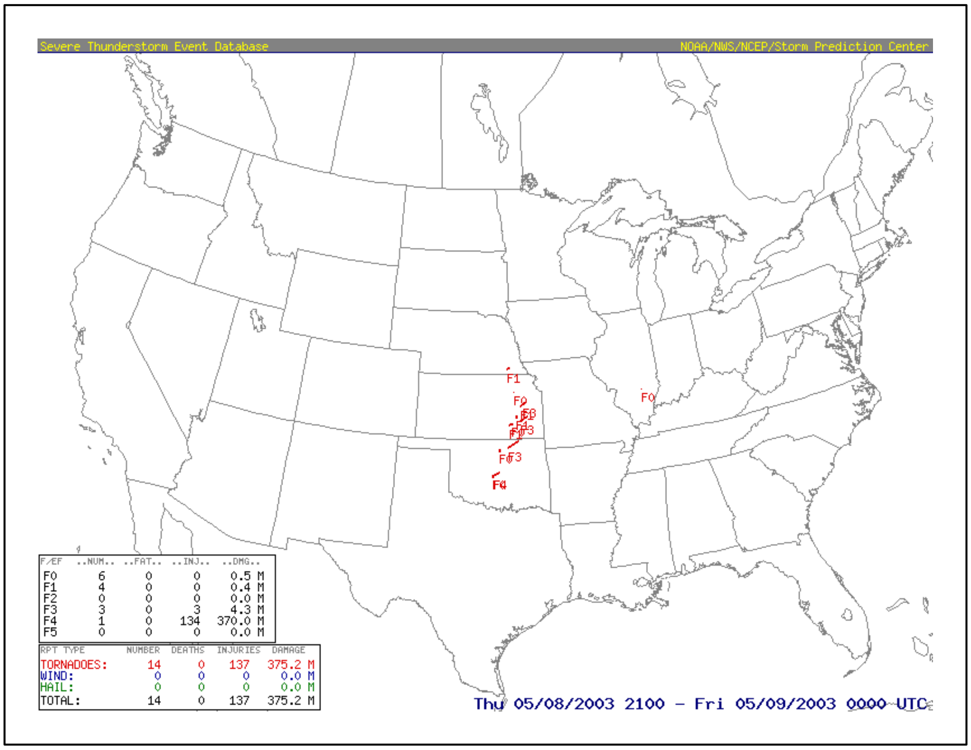

Fig. 15. Observed tornadoes between 21 UTC, 8 May 2003 and 00 UTC, 9 May 2003 from *Storm Data*. Of particular note is the F4 tornado reported in the Oklahoma City area.

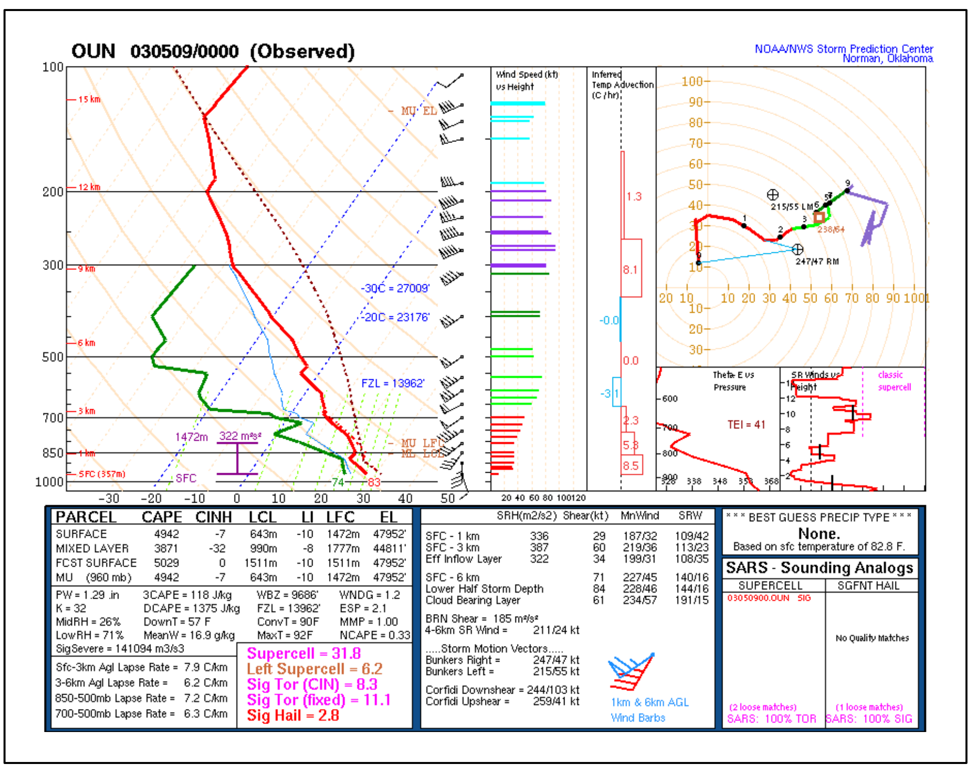

Fig. 16. Observed sounding from Norman, OK at 00 UTC, 9 May 2003, around 90 minutes after a F4 tornado struck the Moore/Oklahoma City area.

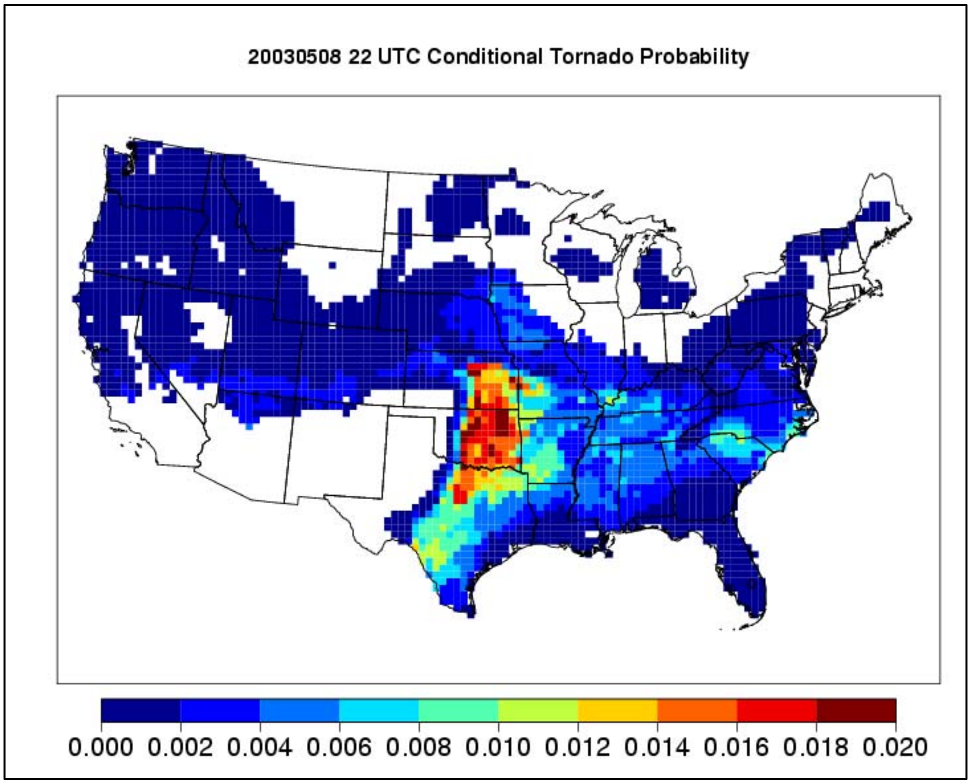

Fig. 17. Conditional tornado probability estimate from 22 UTC, 8 May 2003, around 30 minutes before an F4 tornado struck the Moore/Oklahoma City area.