17.1 The Storm Prediction Center Tornadic Storm and Environment Database: Development and Application

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1. Introduction

A limited number of studies have examined convective mode and severe weather occurrence (e.g., Trapp et al. 2005, Gallus et al. 2008), but a comprehensive examination of the relationship between convective mode and the near-storm environment was lacking in formal literature. Therefore, an ambitious effort to develop a multi-faceted severe storms database began at the Storm Prediction Center (SPC) in 2009 and continues to the present. The primary motivation was to develop a tornadic storm and environment database to document convective mode for tornadoes, significant hail (i.e., 2 inches in diameter or larger), and significant measured or estimated wind gusts (i.e., 65 kt or greater), and associate near-storm environment data to each report (Smith et al. 2012a; Thompson et al. 2012).

Building upon early promising relational database work by Dean et al. (2006) focusing on severe reports and their incipient environments, we added radar attributes to a subset of the Dean et al. (2006) database in order to include information routinely considered by operational forecasters in a severe storms forecast setting. As a result, a manual analysis of radar-identified convective modes was undertaken for an 11-year sample of tornadoes (>12,000), and 10-year samples of hail ≥ 2 inches in diameter (sighail; >5100 events) and thunderstorm wind gusts ≥ 65 kt (sigwind; >8200 events), reported in the contiguous United States (CONUS) during 2003-2013. Near-storm environment data, used for estimating the convective environment for a severe report, were assigned to each event and originated from the SPC hourly mesoscale objective analyses (Bothwell et al. 2002) archive (Dean et al. 2006). Similar to other large-sample environment databases [e.g., 100s or more events, (Thompson et al. 2003, Davies 2004)], this study sought to develop a dataset for tornadoes, sighail, and sigwind by investigating a wide range of environments across the CONUS over a multiple-year period. The goal of developing a large dataset is to apply the results for multiple regions and environments rather than have the results limited to, or overly influenced by, a specific region or environment.

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2. Data and Methodology

a. Data and event filtering

All tornado (2003-2013), sighail, and sigwind (2003-2012) reports were filtered for the largest magnitude report per hour (based on the initial time of the report) on a 40-km horizontal grid. Tornado segment data (i.e., tornado damage paths broken down by individual tornadoes and counties) were used in order to provide higher tornado damage intensity resolution for long track tornadoes. This filtering procedure produced a sample of 25824 severe thunderstorm grid-hour events, including 12387 tornadoes (76.8% of all county tornado segments), 5189 sighail (78.1% of all sighail), and 8248 sigwind (80.3% of all sigwind) during the respective 11-year and 10-year periods. For a thorough discussion pertaining to the caveats of the severe report database, see section 2a in Smith et al. (2012a).

Within the framework described above, the authors made careful manual adjustments to a small portion (7.9%) of the database. Many of the suspected report errors involved incorrectly listed report times, as determined by time-matching the reports to radar data. Examples of this suspected error type included reports well-removed from existing radar echoes and time displaced on the order of tens of minutes to an hour or more. In situations where a suspected error could not be easily corrected, *Storm Data* was used to examine the description of the questionable reports in an effort to identify the storm responsible for the event.

b. Radar-based convective mode classification

The Gibson Ridge radar-viewing software (http://www.grlevelx.com/) was used to analyze archived WSR-88D level-II single site radar data (Crum et al. 1993) from the National Climatic Data Center (http://www.ncdc.noaa.gov/nexradinv/) using the closest radar to classify convective mode based on Smith et al. (2012a). Convective mode was determined using full volumetric radar data, especially when data through a deep layer were needed to perform a more thorough assessment of storm structure and based on the volume scan immediately prior to the time of the severe event.

Discrete or embedded cells with focused areas of cyclonic (or anticyclonic) azimuthal shear were further scrutinized as potential supercells, following the mesocyclone nomograms developed by the Warning Decision Training Branch of the NWS (after Andra 1997 and Stumpf et al. 1998). Supercells required a peak rotational velocity ≥ 10 m s-1 (i.e., a peak-to-peak azimuthal velocity difference of roughly 20 m s^{-1} over a distance of less than 10 km). Range dependence was included in the mesocyclone designation, per the 1, 2, and 3.5 nm mesocyclone nomograms.

A QLCS is defined as consisting of contiguous reflectivity at or above the threshold of 35 dBZ for a horizontal distance of at least 100 km and a length-to-width aspect ratio of at least 3 to 1 at the time of the event, similar to Trapp et al. (2005). Other modes included disorganized cellular modes that did not include supercell structures (e.g., single cell, multicell), and consisted mainly of conglomerates meeting the reflectivity threshold but not satisfying either supercell or QLCS criteria (e.g., short line segment). Additionally, storms exhibiting transient (i.e., 1-2 volume scans) rotation below supercell rotation criteria were assigned to the other modes category. For a more thorough discussion pertaining to the complexity and challenges of categorizing convective mode, please refer to Smith et al. (2012a).

c. Near-storm environment

Rapid Update Cycle (RUC; Benjamin et al. 2004) model 0- and 1-h forecasts provided the basis for the SPC hourly mesoscale analyses from 2003 through April 2012 (Bothwell et al. 2002), but the RUC was replaced by the Rapid Refresh (RAP) model in May of 2012. The RUC (and later the RAP) analyses at the lowest model level are used as a first-guess field in an objective analysis of the hourly surface observations, but no further modification of the model profiles is attempted. Hundreds of sounding-derived parameters are calculated at each analysis grid point by the SPC mesoanalysis system. A subset of these convective parameters is archived[1] at the SPC (Dean et al. 2006), and these data provide the basis for the analyses herein. Environmental information, consisting primarily of supercell-related convective parameters from the hourly SPC objective analyses, accompanied each grid-hour event. For an in-depth discussion the quality of the SPC mesoanalysis data, see section 2a in Smith et al. (2014a).

d. 0.5° circulation intensity identification

0.5° peak rotational velocity (V_{rot}) was manually analyzed using super-resolution radar data (Torres and Curtis 2007) during the life span of each tornado event for a subset of tornado data [(2009-2013), Fig. 1]. Peak inbound and outbound velocities were examined for each volume scan from immediately prior to tornado formation through tornado dissipation. Only combinations of velocity maxima exhibiting cyclonic (anticyclonic) azimuthal shear within 5 n mi and < 45° angle from one another were considered, to avoid primarily convergent or divergent signatures (Fig. 2). The maximum 0.5° peak rotational velocity [$V_{rot} = (|V_{in}| + |V_{out}|)/2$], from all volume scans was assigned to each tornadic event. Brief, short-track tornadoes were assigned 0.5° peak V_{rot} immediately prior to the start time for cases not persisting longer than 1 volume scan, whereas longer-lived tornadoes were assigned 0.5° peak V_{rot} from one of the sampling volume scans during the tornado event. Other rotational velocity information immediately prior to the tornado start time was assigned from any elevation tilt ≤10000 ft above radar level (ARL) or from the 0.5° tilt when sampling velocity data ≥10000 ft ARL.

3. Prior Work

a. Convective mode frequency

Part I of the initial formal work on this database (Smith et al. 2012a) introduced the methodology

[1] The date a parameter was first calculated as part of the SPC mesoanalysis system and occasional daily disruptions both affected the length of the archive for each parameter, such that a particular parameter may not have been available for the entire 2003-2013 period of study.

for classifying convective mode. Spatial occurrence of various modes by tornado, sighail, and sigwind were presented. Right-moving supercells were the most common tornadic mode for the plains states and parts of the Carolinas (Fig. 3). A relative minimum in tornadic supercell frequency was noted over the Ohio Valley and southern Great Lakes and was explained by a higher frequency of QLCS tornado occurrence from there southward into northern Alabama and the lower Mississippi River Valley (Fig. 3). This study also confirmed the relationship between supercell mesocyclone strength and tornado intensity using mesocyclone intensity nomograms (i.e., weak, moderate, strong; Andra 1997). Violent (EF4-5) tornadoes almost exclusively (98%) originated from a strong mesocyclone prior to tornado segment start time, while weak mesocyclones contributed to the largest percentage of EF0 tornado events (44%) among the 3-tiered categories for mesocyclone strength.

b. Convective mode environment

Part II of the initial formal work (i.e., Thompson et al. 2012) examined ingredients-based parameters from the estimated near-storm environments of different convective modes. Supercell mesocyclone strength tended to increase with increasing SCP for supercells, and STP tended to increase as tornado damage class ratings increased (Fig. 4). Supercell mode (discrete cell or cell in cluster), strong mesocyclone strength, and a volatile near-storm environment (as represented by large values of STP) accounted for an overwhelming majority of intense tornadoes. These findings prompted additional investigation focusing on finer-resolution storm-scale rotation strength in later studies. Convective mode for tropical cyclone tornadoes was also investigated by Edwards et al. (2012). The environmental and convective mode analyses found tropical cyclone right-moving supercell tornado environments to exhibit lower values of STP —owing primarily to weaker instability— compared to their non-tropical cyclone counterparts (see their Fig. 8).

c. Spatial analysis of ingredient-based parameters by convective mode

The spatial distribution of ingredient-based parameters —specifically, the significant tornado parameter (STP; Thompson et al. 2003) and its four constituent ingredients: 1) lowest 100-mb mean-layer (ML) CAPE; 2) ML lifted condensation level height; 3) 0–6-km bulk wind difference; 4) 0–1-km storm-relative helicity (SRH)— was examined for tornadic convective modes (Thompson et al. 2013). Right-moving supercell EF2+ events displayed considerably higher median values of MLCAPE in a large portion of KS and OK compared to northern AL [2000-2500 Jkg^{-1} versus 1000-1500 Jkg^{-1}, respectively (Fig. 5)]. Conversely, a higher median value of 0–1-km SRH is evident in northern AL (450-500 m^2s^{-2}) compared to most of KS and OK (200-300 m^2s^{-2}).

d. Tornado warning performance metrics related to convective mode and environment

Recent work by Brotzge et al. (2013) revealed National Weather Service (NWS) tornado warning performance, as measured by the probability of detection, was maximized for the more intense tornado events (i.e., higher F-scale damage ratings) when the tornadoes were produced by discrete supercells with strong mesocyclones, close to the radar site, in environments strongly supportive of tornadic supercells. For example, longer median lead time was found for tornado events with higher STP (e.g., $\geq$8, 16 min; vs 0-0.5, 10 min).

e. 0.5° peak rotational velocity

Initial work by Smith et al. (2012b), and updated by Smith et al. (2014b), developed and provided additional details on the rotational strength of low-level circulations compared to the less precise characterizations of mesocyclone strength (i.e., weak, moderate, strong) investigated in prior studies (e.g., Smith et al. 2012a, Thompson et al. 2012, Brotzge et al. 2013). Results from examining environmental and radar attributes, featuring STP and 0.5° peak V_{rot} data, suggest an increasing conditional probability for greater EF-scale damage as both STP and 0.5° peak V_{rot} increase, especially with supercells.

e. Conditional tornado probabilities in the Impact-Based Warning (IBW) era

Smith et al. (2014a) demonstrated a potential role for conditional tornado probabilities in diagnosing tornado intensity, especially within an IBW context. This study sought to highlight the utility of multiple sources of environmental information and radar attributes (Fig. 6) within a conditional probability framework to assign a *best-guess* tornado intensity given a tornado. This type of information may be useful in the context of IBW tornado warning tier damage threat tags (Table 1).

3. Final Thoughts

Results from early work showing relationships among tornadoes, the environment, and radar attributes in this multi-component dataset provide a basis for future research. The SPC tornadic storm database is available for collaborative research, serving to enhance the interaction and communication between the research and operational communities in applied severe storms studies. Similar information is also available as a point-and-click feature within the SPC mesoanalysis graphics on the SPC web page (http://www.spc.noaa.gov/exper/mesoanalysis) and within the U.S. Tornado Environment Browser (http://www.spc.noaa.gov/exper/envbrowser/).

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Table 1. Impact-based warning tiers for tornado warnings.

Tornado Warning Damage Threat Tags	
No Tag	Possible damage and generally a short-lived tornado
TORNADO DAMAGE THREAT… CONSIDERABLE	Credible observational evidence that a stronger variety tornado (EF2+) is imminent or ongoing. Tornado duration generally longer-lived.
TORNADO DAMAGE THREAT… CATASTROPHIC	DIRECT observational evidence that a stronger variety tornado (EF4-EF5) is striking or about to strike a population footprint with 100% certainty. Tornado duration generally long-lived. ***FAR will be zero.

Figures

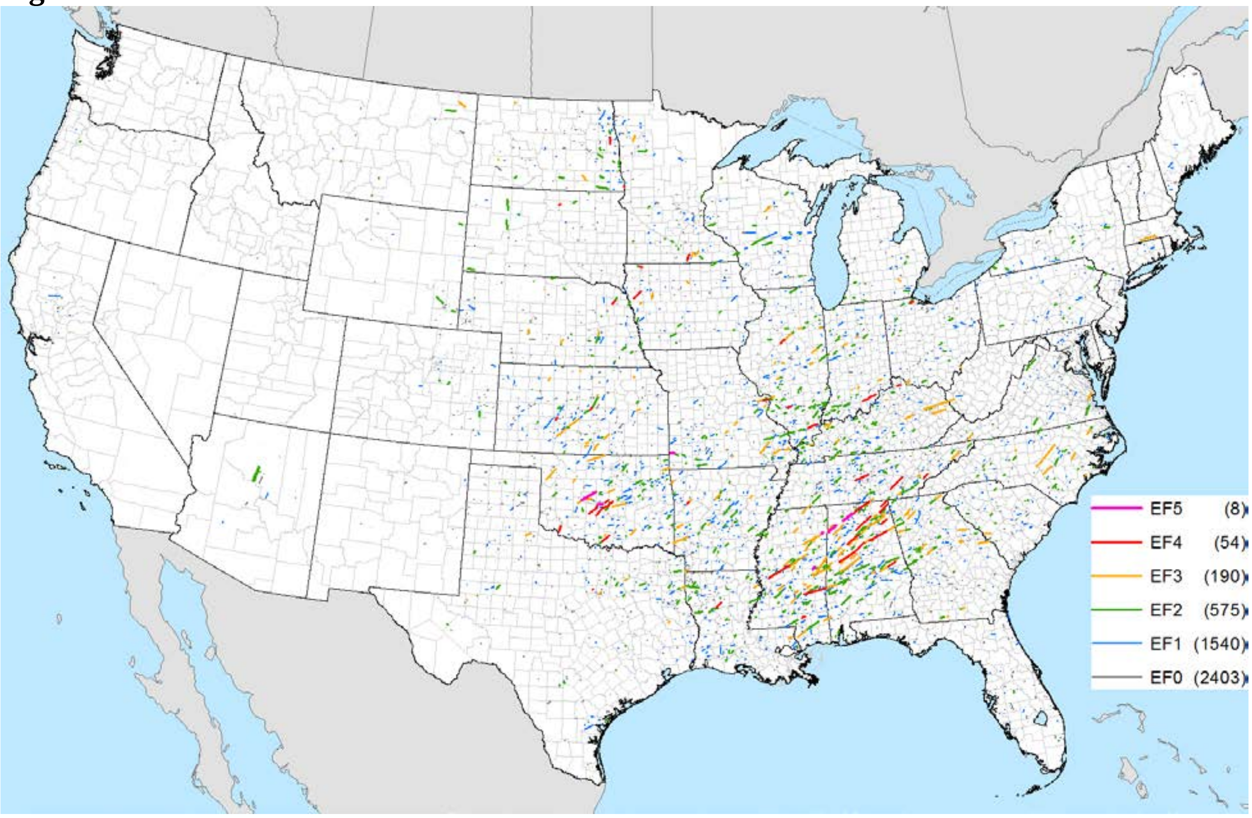

Figure 1. Spatial plot of tornado events by EF-scale (2009-2013) within 101 mi of a WSR-88D and assigned 0.5° peak rotational velocity.

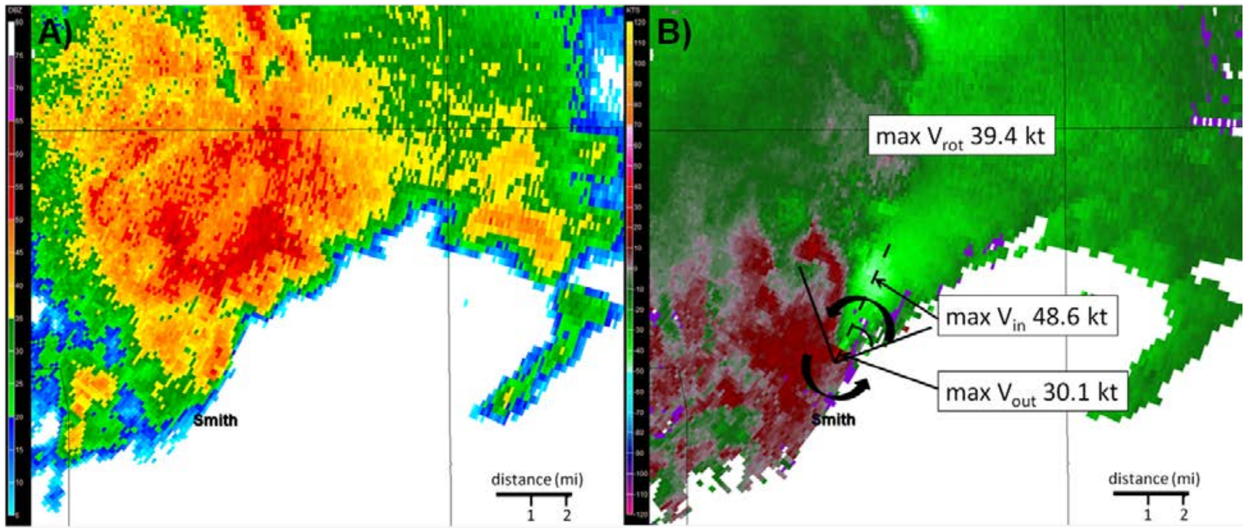

Figure 2. A) WSR-88D base reflectivity (dBZ, color scale on left) at 0.5º beam tilt from Jackson, MS (KDGX) at 0852 UTC on 30 November 2010. A cluster RM produced an EF2 tornado in Smith County MS (start time 0844 UTC). North is up; county borders are black; distance scale (lower right). **B)** Same as Fig. 1A, except for storm relative velocity (kt, scale on left), 45 degree angle insert, and curved arrows signifying rotation. Denoted inserts display maximum inbound storm relative velocity (max V_{in}, 48.6 kt), maximum outbound storm relative velocity (max V_{out}, 30.1 kt), maximum rotational velocity (max V_{rot}, 39.4 kt).

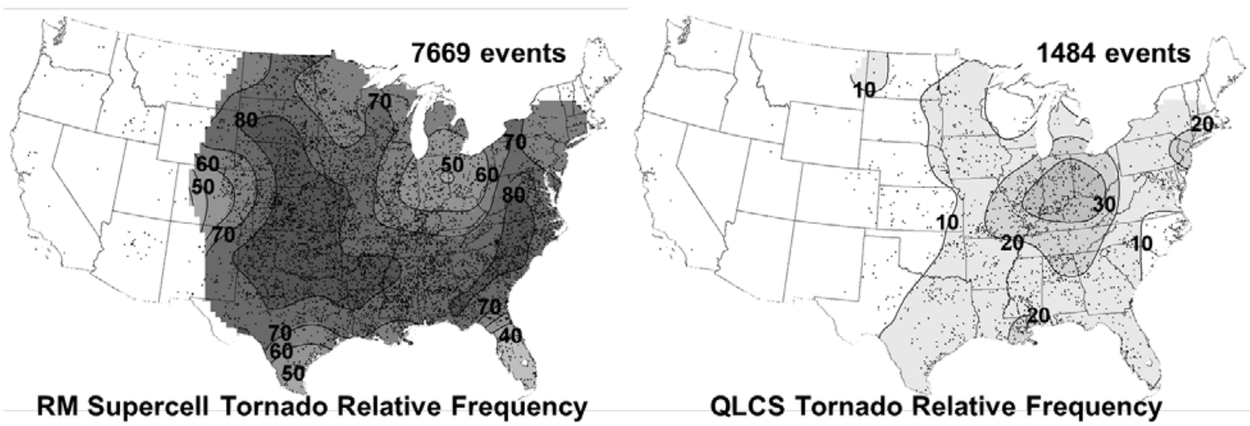

Figure 3. Adapted from Smith et al. (2012a) showing right-moving supercell (left panel) and QLCS (right panel) tornado relative frequency from 2003-2011. Individual tornado events are displayed (small black lines). Darker shading denotes high probability (black labels) and event count located in upper right.

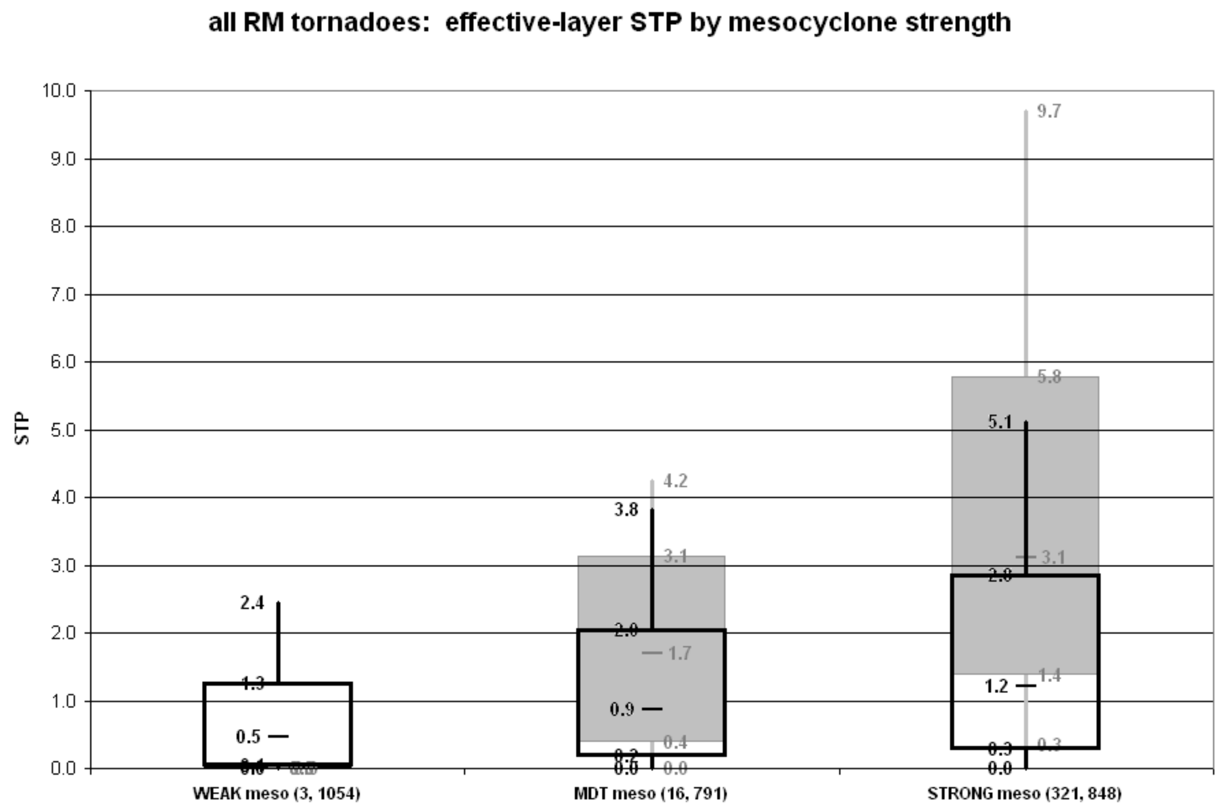

Figure 4. Effective-layer STP (dimensionless; sample period March 2005-December 2011) with all tornadic discrete right-moving supercells (RM) for weak, moderate (MDT), and strong mesocyclones. The shaded boxes (gray labels on the right) denote RM with EF3+ tornado damage, and the black overlays (with labels on the left) represent the RM that produced EF0 tornado damage. Sample sizes are denoted in parentheses (RM EF3+ tornadoes, RM EF0 tornadoes). The sample size for EF3+ tornadoes with weak mesocyclones was too small (3 cases) to justify a box and whisker plot. The shaded boxes span the 25th to the 75th percentiles with the median values marked within the box, and the whiskers extend upward to the 90th and downward to the 10th percentiles.

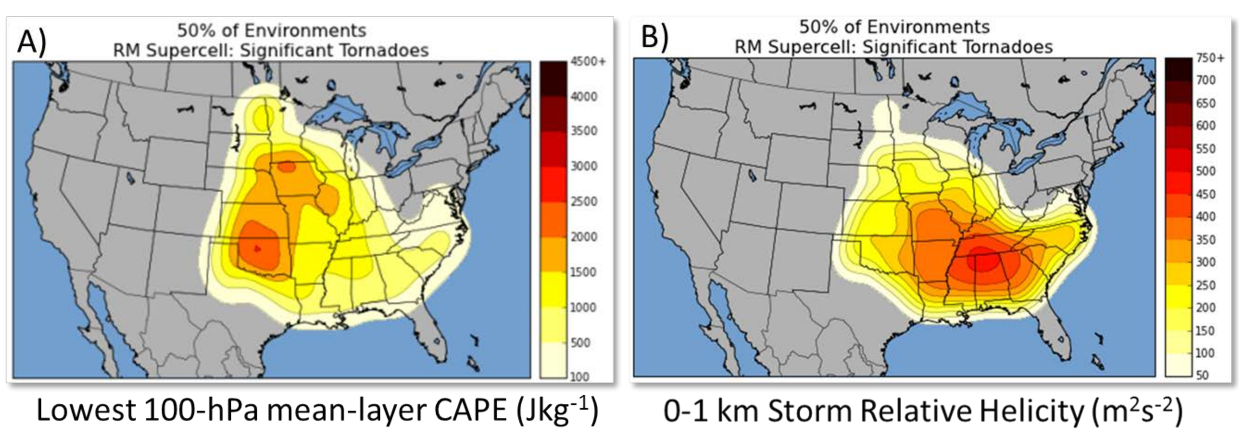

Figure 5. Kernel density estimation of 50th percentile values of a) lowest 100-hPa mean-layer CAPE (Jkg^{-1}) b) 0-1 km storm relative helicity (m^2s^{-2}) for right-moving supercell F2+ tornado events

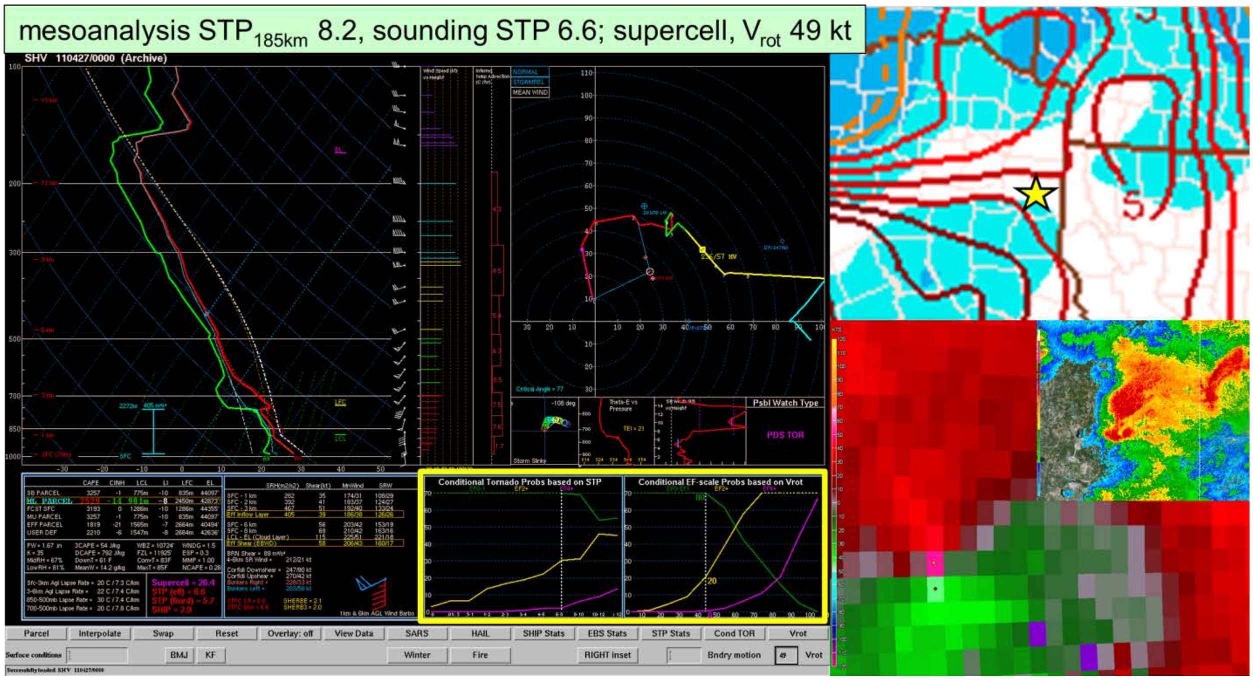

Figure 6. An EF2 tornado occurred in Harrison Co., TX on 26 April 2011 (5.1 mi path, 400 yd wide). Data associated with the tornado event include mesoanalysis STP_{185km} (8.2), sounding STP (6.6), supercell convective mode, and 0.5° peak rotational velocity [(V_{rot}) 49 kt]. Lower left, an observed proximity sounding display with annotated yellow rectangle highlighting conditional tornado probabilities for STP and 0.5° peak rotational velocity. Lower right . 0.5° storm rotational velocity and middle right (0.5° base reflectivity). Top right mesoanalysis STP with annotated yellow star depicting event location.