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Spatial Distributions of Tornadic Near-Storm Environments by Convective Mode

RICHARD L. THOMPSON, BRYAN T. SMITH, AND ANDREW R. DEAN
NOAA/NWS/NCEP Storm Prediction Center, Norman, Oklahoma

PATRICK T. MARSH*
University of Oklahoma, Norman, Oklahoma

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ABSTRACT

All tornado reports across the contiguous United States from 2003–2011 were filtered for the maximum damage rating on an hourly grid with 40-km horizontal spacing. Convective mode was assigned to each grid-hour tornado event via manual examination of full volumetric WSR-88D data, and supercell-related environmental parameters accompanied each grid-hour tornado event from the hourly objective analyses calculated and archived at the Storm Prediction Center. Only tornado events associated with right-moving supercells (RM) or quasi-linear convective systems (QLCS) were considered in this work, which resulted in a sample of 8837 tornado grid-hour events.

Spatial distributions of supercell-related parameters were constructed for the RM and QLCS tornado events. Sample sizes were increased by accumulating tornado events within a 120-km neighborhood to each 40-km grid box. All neighborhoods with ≥10 events were retained for percentile rank distributions of the supercell-related parameters, and then smoothed using a Gaussian kernel with a 120-km influence radius. Regional variations in buoyancy and lifting condensation level (LCL) are apparent—RM tornadoes are more common with greater buoyancy and higher LCL heights across the Great Plains compared to the Mississippi Valley region. QLCS tornadoes tend to be focused across the Ohio and Mississippi Valleys, in environments with weaker buoyancy and lower LCL heights. Vertical wind shear parameters are typically well within the parameter space associated with tornadic RM for both the RM and QLCS tornado events. The significant tornado parameter shows improved discrimination between weak and significant RM tornadoes, compared to individual kinematic or thermodynamic parameters.

1. Introduction

The characteristics of near-storm environments have been elucidated by several studies of observed soundings near reported tornadoes (Maddox 1976; Kerr and Darkow 1996), all soundings for multiple severe weather hazards during a complete year (Rasmussen and Blanchard 1998), or long-period samples of soundings associated with severe thunderstorms (Craven and Brooks 2004). The degree to which a particular sounding represents the environment of a thunderstorm is one concern (Brooks et al. 1994), while Potvin et al. (2010) found that proximity soundings within 40–80 km and 1–2 hours of a storm were most representative of the near-storm environment.

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*Current Affiliation: *NOAA/NWS/NCEP Storm Prediction Center, Norman, Oklahoma*.

Corresponding author address: Richard L. Thompson, Storm Prediction Center, 120 David Boren Blvd. #2300, Norman OK 73072, E-mail: richard.thompson@noaa.gov

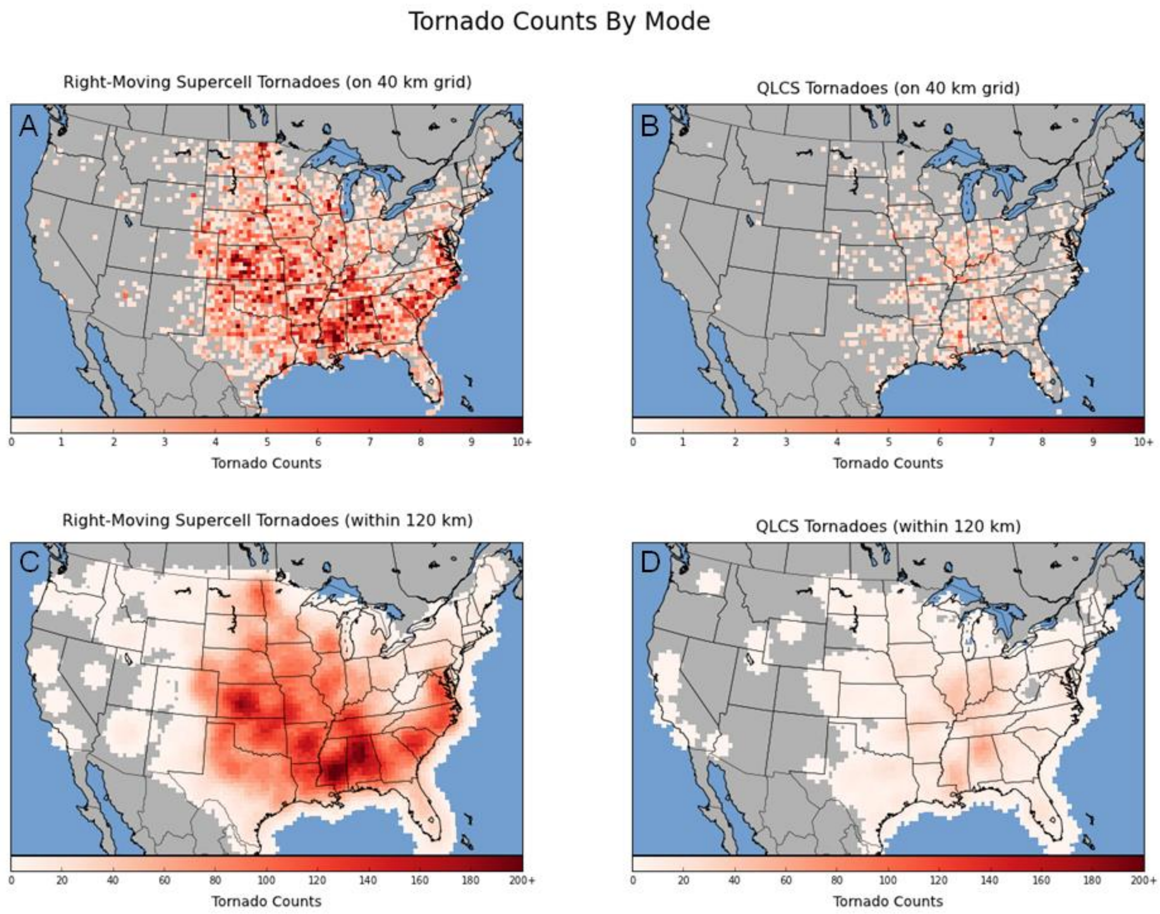


Figure 1: Raw 40 km horizontal grid-hour events for a) 7669 RM tornadoes and b) 1168 QLCS tornadoes from the T12 sample spanning 2003–2011. Peak grid-hour counts are 8 and 17 for QLCS and RM, respectively. Grid-hour event counts for a 120-km neighborhood (centered on each 40-km grid box) are shown for c) RM tornadoes and d) QLCS tornadoes, which form the basis for the kernel density estimates.

Meanwhile, much attention in recent years has focused on convective mode and its influences on severe thunderstorm and tornado events. For example, Trapp et al. (2005) examined tornado events attributed to quasi-linear convective systems (QLCS) across the contiguous U.S. Gallus et al. (2008) looked at a range of convective mode categories associated with severe thunderstorms across the Midwestern U.S. Later work by Duda and Gallus (2010) examined severe weather events with radar-observed supercells in the Midwestern U.S. Grams et al. (2012) combined environmental data with simple convective mode categories to compare tornado and significant severe thunderstorm events across the contiguous U.S. (CONUS).

Specific storm modes, including tornadic and nontornadic supercells, were part of the Thompson et al. (2003; hereafter T03) and Thompson et al. (2007) proximity sounding studies, which also relied on short-term forecast model soundings in close proximity to radar-observed supercells. However, these studies focused on discrete storms only and were somewhat limited by sample size. Building on this previous work, Smith et al. (2012) created a convective mode database for a very large sample of severe thunderstorm and tornado events (22 901 total) over a 9-y period across the CONUS. Thompson et al. (2012; hereafter T12) combined the Smith et al. (2012) convective mode sample with RUC model analysis data archived at the Storm Prediction Center (SPC) (Schneider and Dean 2008) to compare QLCS and right-moving supercell (RM) tornado environments. The large sample of near-storm environmental data allowed for seasonal comparisons of tornado environments by convective mode. Still, the explicit regional variations in near-storm environments were only addressed indirectly. The goal of this work is to use the T12 convective mode and environmental sample to develop CONUS-wide spatial distributions of near-storm environmental ingredients by convective mode for tornadoes. Such distributions will allow the development of explicit regional climatology of near-storm environmental ingredients for two specific convective modes and associated tornadoes.

2. Data and methods

The convective mode database described in Smith et al. (2012) served as the basis for this analysis. Tornado reports from 2003–2011 across the CONUS were filtered for the maximum damage rating per hour, on a grid with 40-km horizontal spacing, which resulted in 8837 tornado events. A radar-derived convective mode was assigned to each event based on level-II data from the closest WSR-88D site. Additionally, each grid-hour event was accompanied by sounding-derived parameters from the SPC hourly mesoanalyses (Bothwell et al. 2002; Schneider and Dean 2008). Like T12, this work considers environmental data associated with all (discrete, cluster, and line) tornadic RM and tornadic QLCSs, including tropical cyclone events. The environmental data used in this study were subject to RUC model errors, though T03 provided empirical evidence that the model pseudo-soundings were reasonably close approximations to the observed storm environments.

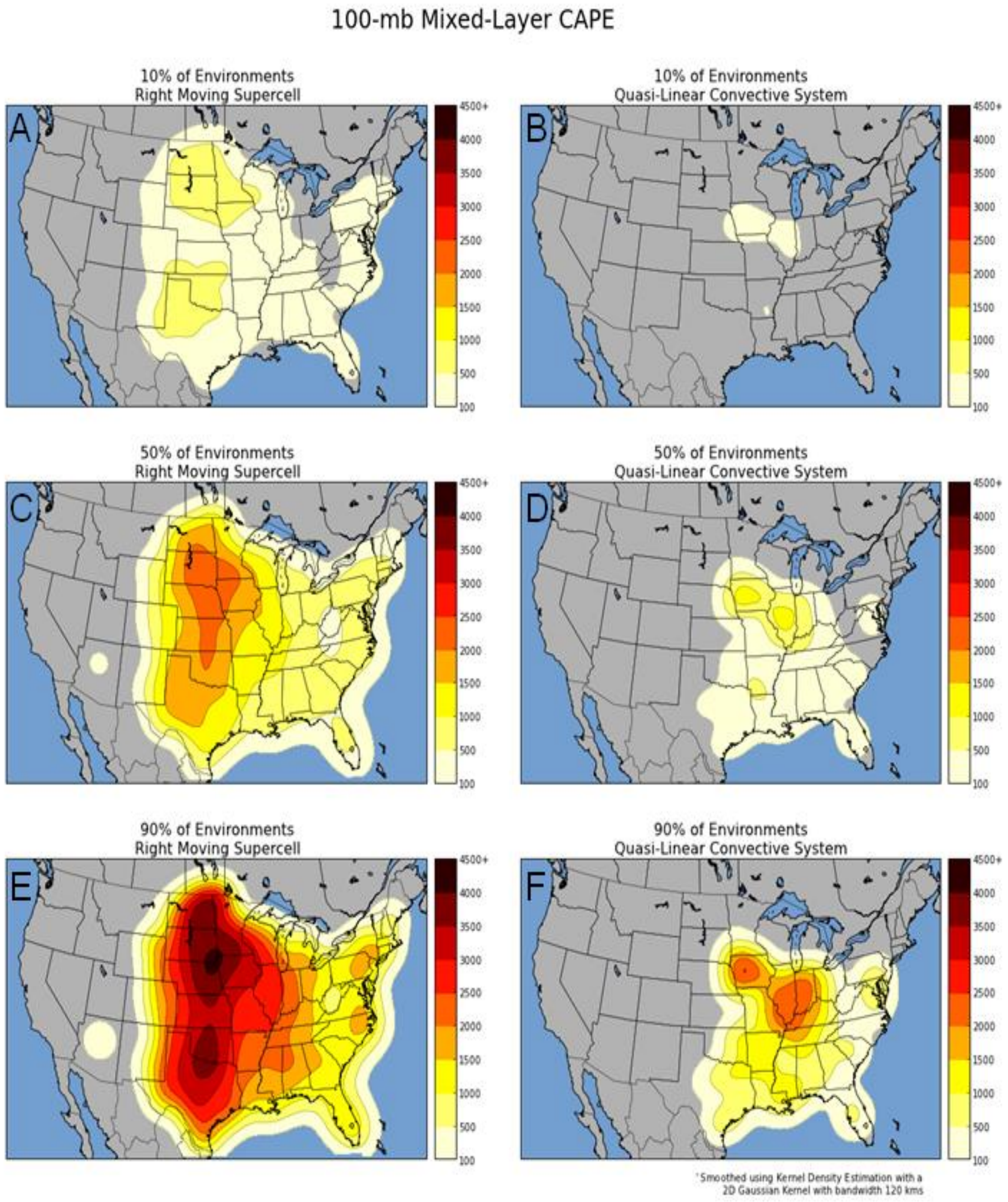
Specifically, we narrow our analysis to the significant tornado parameter (STP; T03) and its four constituent ingredients: 1) lowest 100-mb mean-layer (ML) CAPE; 2) MLLCL height; 3) 0−6-km bulk wind difference; 4) 0−1-km storm-relative helicity (SRH). The total number of grid-hour events (with accompanying near-storm environment data) was accumulated within each 40-km grid box by convective mode (Fig. 1). A 9-y sample is insufficient to capture the full variability of tornado occurrences by specific convective mode on a 40-km horizontal grid, given the rarity of tornadoes with specific storm types, and the inherent variability in the distribution. To address this concern, we accumulated all tornado events within a 120-km neighborhood centered on each grid point, effectively increasing the sample size and smoothing the distributions. Only grid neighborhoods containing at least ten tornado events for each convective mode category were considered. Additionally, data were contoured and smoothed via a kernel density estimate with an effective influence radius of 120 km, as in Brooks et al. (1998), Sobash et al. (2011) and Marsh et al. (2012).

3. Results

As discussed in section 2, sample-size limitations prevented a continuous analysis across the entire CONUS for each convective mode category. The general distribution of tornado events in the analysis reflects tornado climatology documented in previous work [e.g., the relatively lower frequency of events west of the Rockies and in Maine (Fig. 1a,b), after Kelly et al. (1978) and Brooks et al. (2003)]. An effect of our grid neighborhood procedure is the extension of values into the Gulf of Mexico and Atlantic Ocean in Fig. 1c,d, where tornado reports (and related convective modes) were not part of the initial sample. Moreover, the details of the kernel density plots cannot be taken literally in areas where events were not sampled (i.e., across international borders, coastlines, and the Rocky Mountains) during 2003–2011. The gradients in the kernel density estimate show artificially low values in areas with relatively few events, adjacent to areas with higher event frequency. Artifacts of our analysis procedure are illustrated by the sharp gradient in MLCAPE across southern Manitoba (Fig. 2e), the apparent decrease in MLLCL heights from east to west across the central Rockies (Fig. 4e), and the belt of lower 0–6-km BWD values outlining the international borders and Gulf and Atlantic coasts (Fig. 6e).

a. RM tornadoes

MLCAPE is typically larger across the Great Plains with tornadic RM (2000–4000 J kg^{-1} for the upper quartiles of the distributions shown in Fig. 2c,e), with consistently weaker MLCAPE along and east of the Appalachians. MLCAPE values with tornadic RM usually do not exceed 1500 J kg^{-1} east of the Mississippi River. Still, relatively low MLCAPE (10th percentile values of 100–500 J kg^{-1}) occurs occasionally in the Great Plains region. As such, tornadic RM can occur in a wide range of buoyancy across much of the CONUS east of the Rocky Mountains (Rasmussen and Blanchard 1998; T03; Craven and Brooks 2004).



* Smoothed using Kernel Density Estimation with a 2D Gaussian Kernel with bandwidth 120 kms

Figure 2: Kernel density estimation of a) 10th percentile, c) 50th percentile, and e) 90th percentile rank values of MLCAPE (J kg^{-1}) associated with all RM tornadoes, and the same percentile rank values associated with all QLCS tornadoes (b, d, and f, respectively) from the T12 sample.

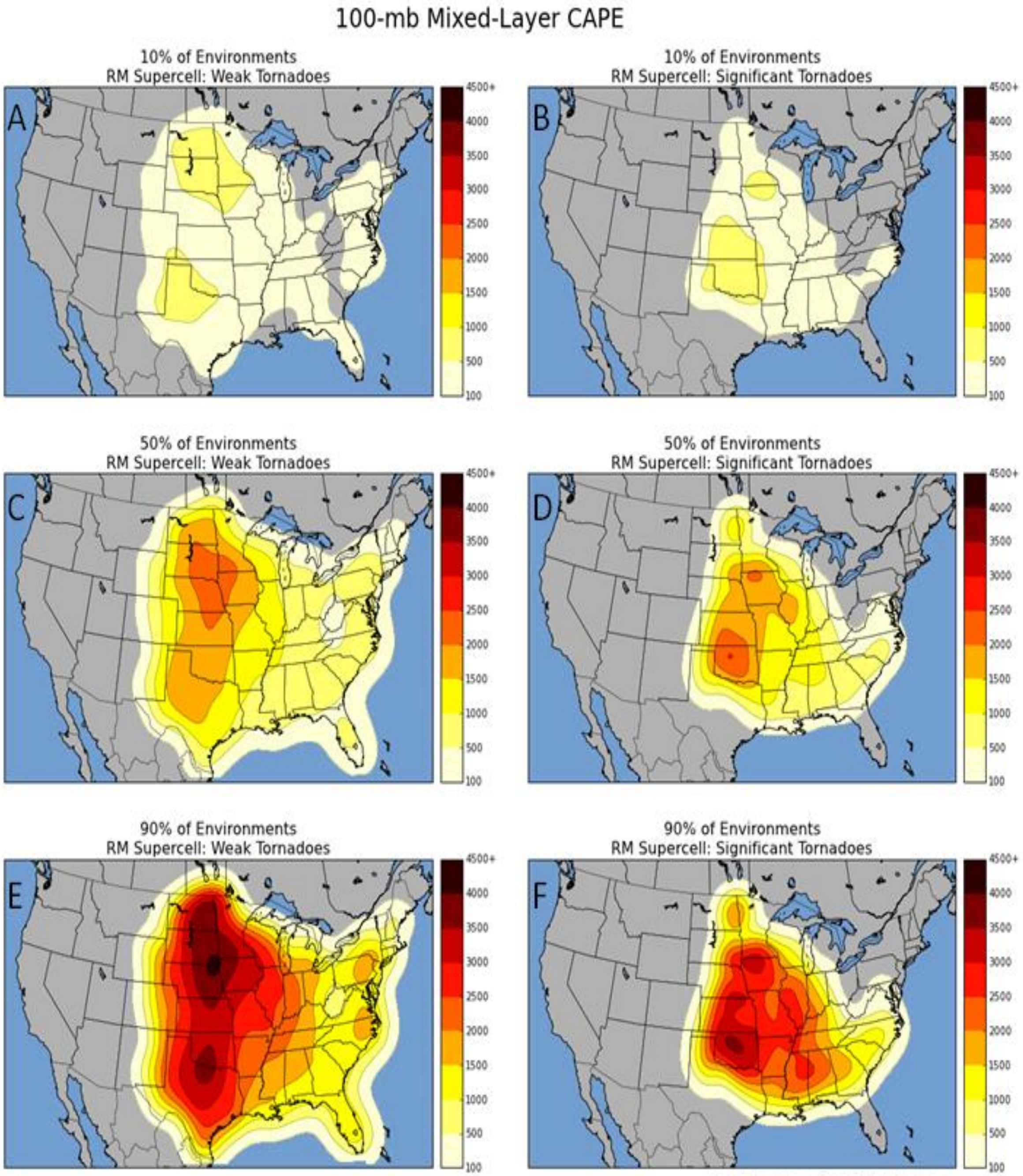


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Figure 3: Kernel density estimation of a) 10th percentile, c) 50th percentile, and e) 90th percentile rank values of MLCAPE (J kg^{-1}) associated with weak (EF0–EF1) RM tornadoes, and the same percentile rank values associated with all significant (≥ EF2) tornadoes (b, d, and f, respectively) from the T12 sample.

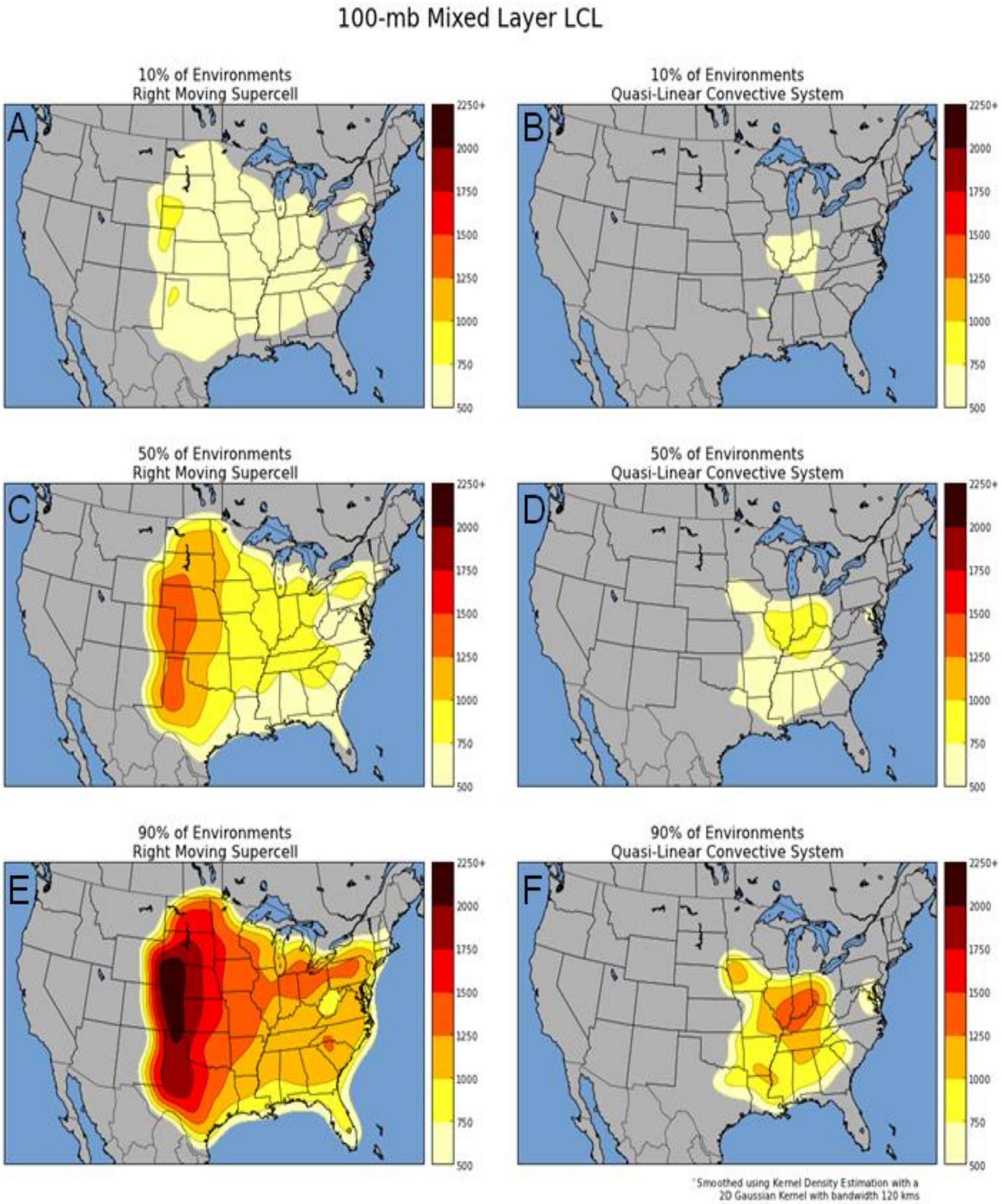
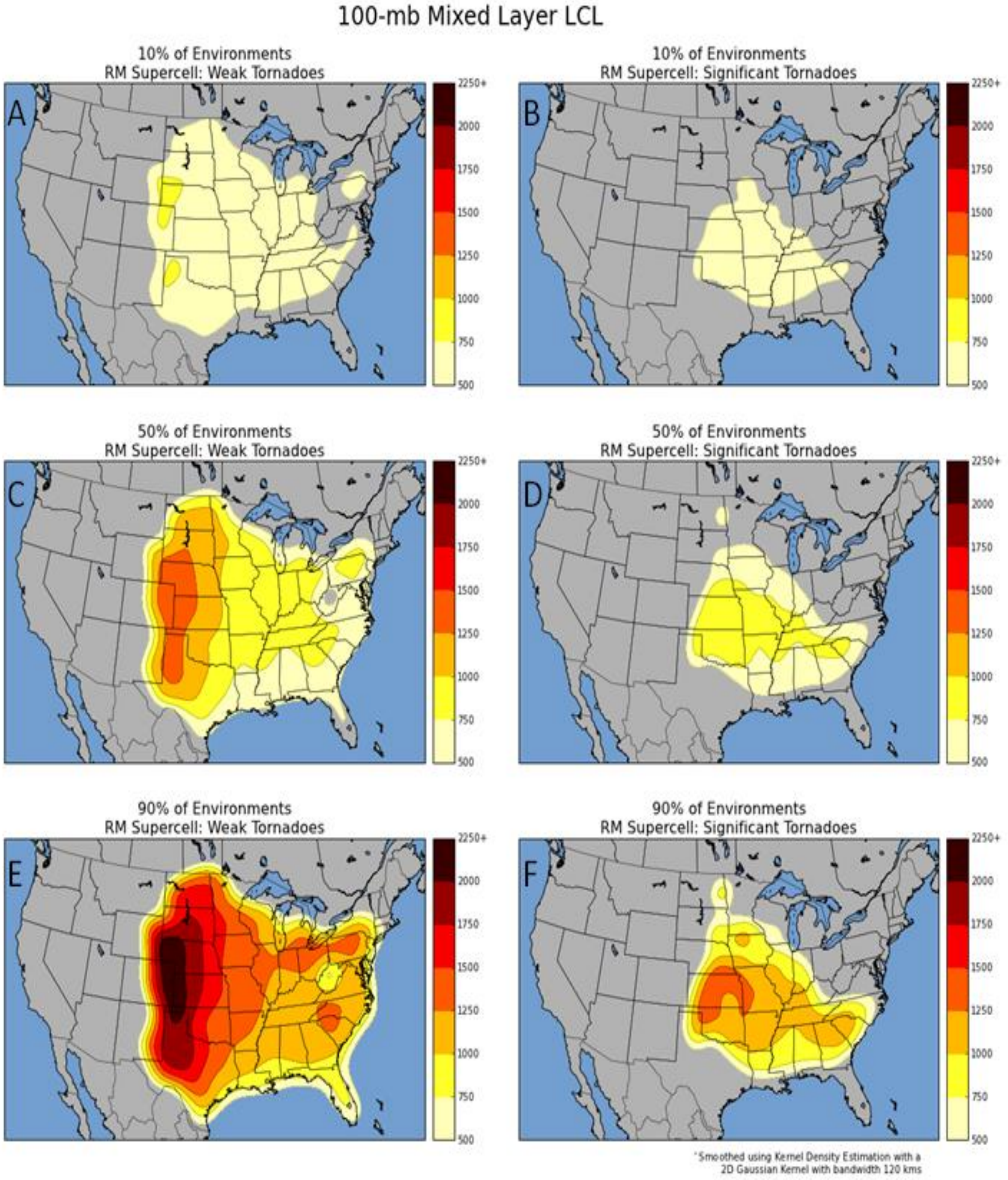


Figure 4: Same as Fig. 2, except for MLLCL height (m AGL).


100-mb Mixed Layer LCL

10% of Environments RM Supercell: Weak Tornadoes

10% of Environments RM Supercell: Significant Tornadoes

50% of Environments RM Supercell: Weak Tornadoes

50% of Environments RM Supercell: Significant Tornadoes

90% of Environments RM Supercell: Weak Tornadoes

90% of Environments RM Supercell: Significant Tornadoes

*Smoothed using Kernel Density Estimation with a 2D Gaussian Kernel with bandwidth 120 kms

Figure 5: Same as Fig. 3, except for MLLCL height (m AGL).

Weak RM tornadoes (damage rated EF0–EF1) were prevalent across much of the CONUS east of the Rocky Mountains, while significant RM tornadoes (damage rated ≥EF2) were more common in a smaller region from the central Great Plains the Tennessee Valley (Fig. 3). The magnitudes of MLCAPE are not appreciably different across the percentile rank distributions between RM that produced weak versus significant tornadoes.

MLLCL heights show a general tendency to be higher (i.e., >1500 m AGL) with tornadic RM across the region from the west Texas and eastern New Mexico border northward across the High Plains. Meanwhile, MLLCL heights are generally <1500 m AGL with the vast majority of tornadic RM across the Mississippi Valley and eastern states (Fig. 4a,c, e). MLLCL height is considered to be a limiting factor for significant tornadoes with RM (e.g., Markowski et al. 2002; Rasmussen 2003; T03). Indeed, significant RM tornadoes tend to occur in environments with substantially lower MLLCL heights across the eastern Great Plains [i.e., <1250–1500 m AGL (Fig. 5b,d,f)], compared to higher MLLCL heights with weak RM tornadoes across the High Plains (Fig. 5a, c,e).

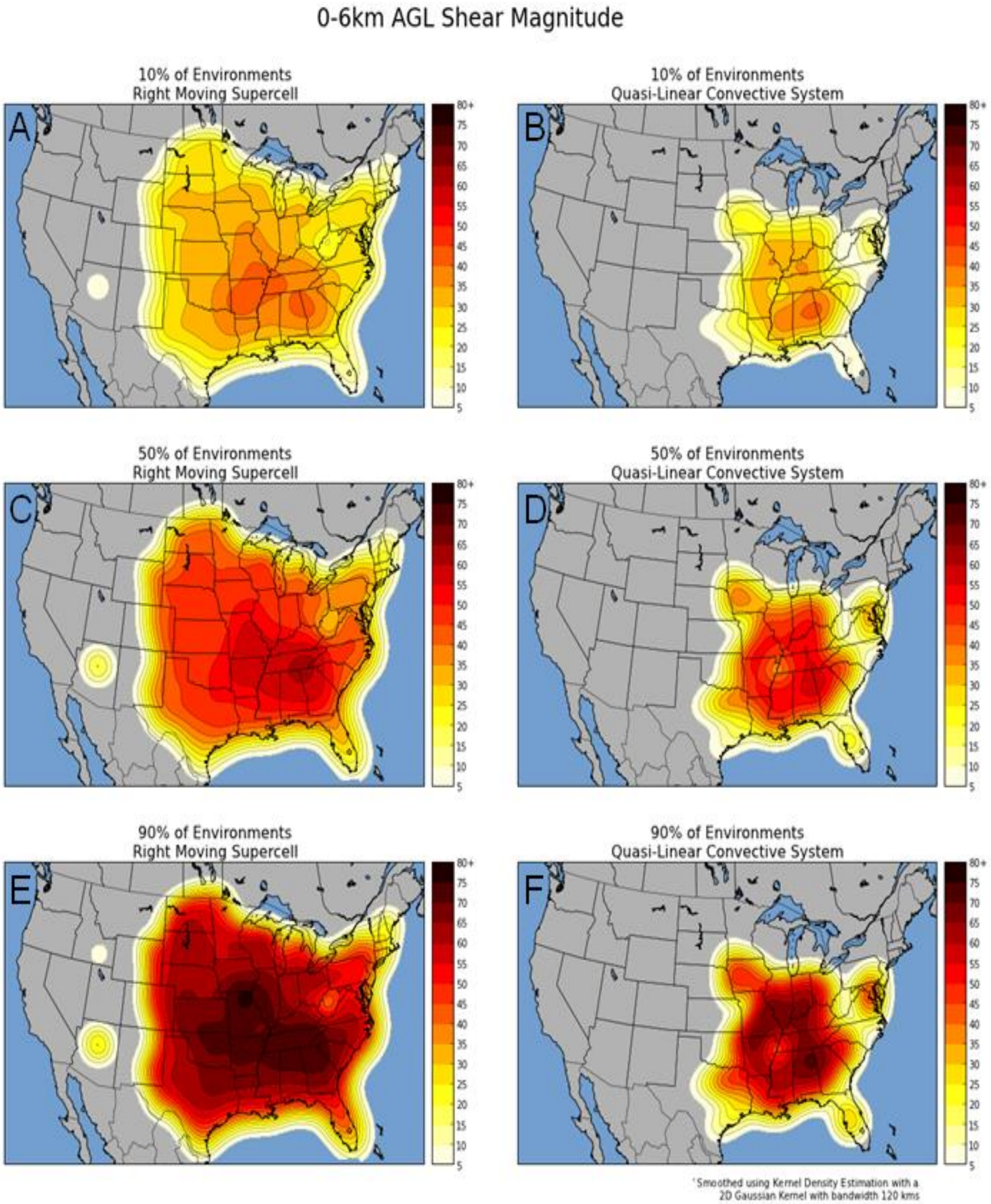
Not surprisingly, 0–6-km bulk wind difference (BWD) with tornadic RM falls in the range typically associated with supercells [roughly ≥35 kt (18 m s^{-1}) per T03], even in the lower end of the distribution (Fig. 6a,b). This measure of deep-layer vertical wind shear tends to be strongest across parts of the Mississippi and Tennessee Valleys (Fig. 6a,c,e), which overlaps a large part of the corridor where significant RM tornadoes are also most common (Fig. 7). Interestingly, 0–6-km BWD is not a good discriminator between significant RM tornadoes and weak RM tornadoes, especially in the eastern half of the Great Plains where both weak and significant tornadoes are common.

Low-level vertical wind shear, as represented by 0–1-km SRH in Fig. 8, shows a marked tendency to be largest across the lower Mississippi and Tennessee Valley regions, much like the distributions of 0–6-km BWD shown in Figs. 6 and 7. Weak tornadoes make up the majority of the low end of the 0–1-km SRH distribution shown in Fig. 8, where the area centered on Mississippi and Alabama is the only consistent area with SRH values considered sufficient for significant RM tornadoes. Meanwhile, 0–1-km SRH remains lower than 100 m^2 s^{-2} across much of the Great Plains at the 10th percentile with Plains RM weak tornadoes (Fig. 9). Somewhat surprisingly, 0–1-km SRH alone does not discriminate well between weak and significant RM tornadoes across the eastern portions of the Great Plains.

The STP highlights the apparent compensating effects of buoyancy and vertical shear within the parameter calculation itself, where the largest STP values correspond to the overlap of the larger MLCAPE values in the Great Plains with the stronger vertical shear across the Mississippi Valley and southeastern states (Fig. 10a,c,e). In general, the corridor of largest STP at the 90th percentile (Fig. 10f) extends from the central Plains to Mississippi and Alabama, which is the same corridor favored for significant RM tornadoes (Fig. 11) in the spring (T12). The STP more clearly discriminates between weak and significant RM tornadoes (especially across the eastern Great Plains), when compared to individual vertical shear parameters such as 0−1-km SRH and 0−6-km BWD, highlighting an advantage of the composite-parameter approach.

b. QLCS tornadoes

Buoyancy is clearly weaker in QLCS tornado environments versus tornadic RM environments, based on a comparison of Fig. 2a,c,e with Fig. 2b,d,f. The most pronounced differences are across the southeastern states where MLCAPE rarely exceeds 1000 J kg^{-1} with QLCS tornadoes, compared to the Great Plains where QLCS tornadoes are uncommon. Spatial variability is also larger with MLCAPE in QLCS environments (compared to RM environments), though much of this apparent variability could be due to a noticeably smaller sample size of QLCS tornadoes versus RM tornadoes (1168 vs. 7669, respectively). One exception is across Illinois and Indiana where the distributions of MLCAPE are more similar for RM and QLCS tornadoes, and sample sizes of each are also similar. The upper end of the MLCAPE distribution with QLCS tornadoes across Illinois and Indiana is dominated by spring and summer events, when buoyancy is largest [Fig. 15 in Smith et al. (2012); Figs. 16 and 17 in T12]. As discussed in T12, MLCAPE is a reasonable discriminator between tornadic RM and tornadic QLCS environments, especially in the winter across the southeastern states when buoyancy is weakest climatologically.



<u>Figure 6</u>: Same as Fig. 2, except for 0–6-km BWD (kt).

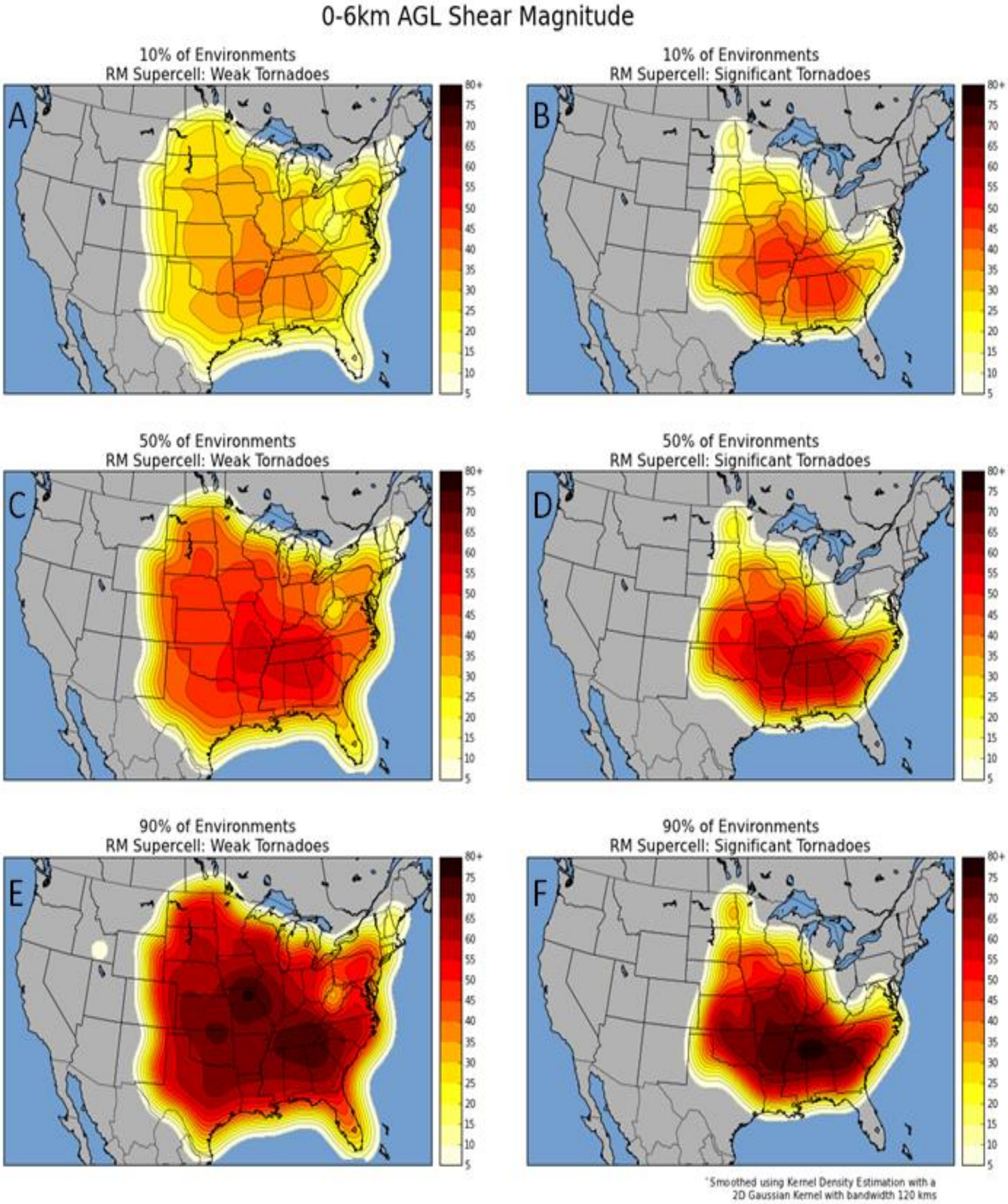


Figure 7: Same as Fig. 3, except for 0–6-km BWD (kt).

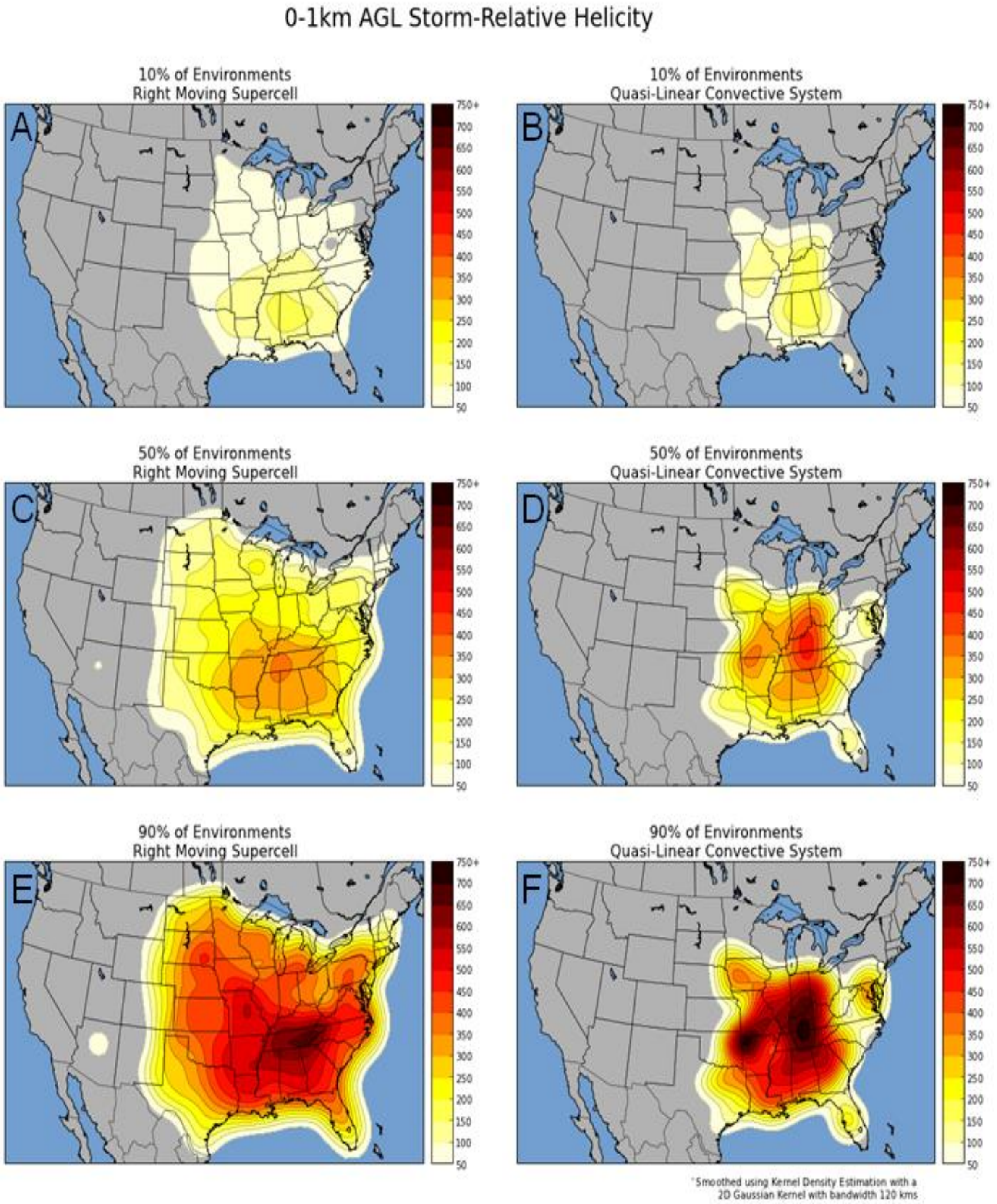


Figure 8: Same as Fig. 2, except for 0–1-km SRH (m^2 s^{-2}).

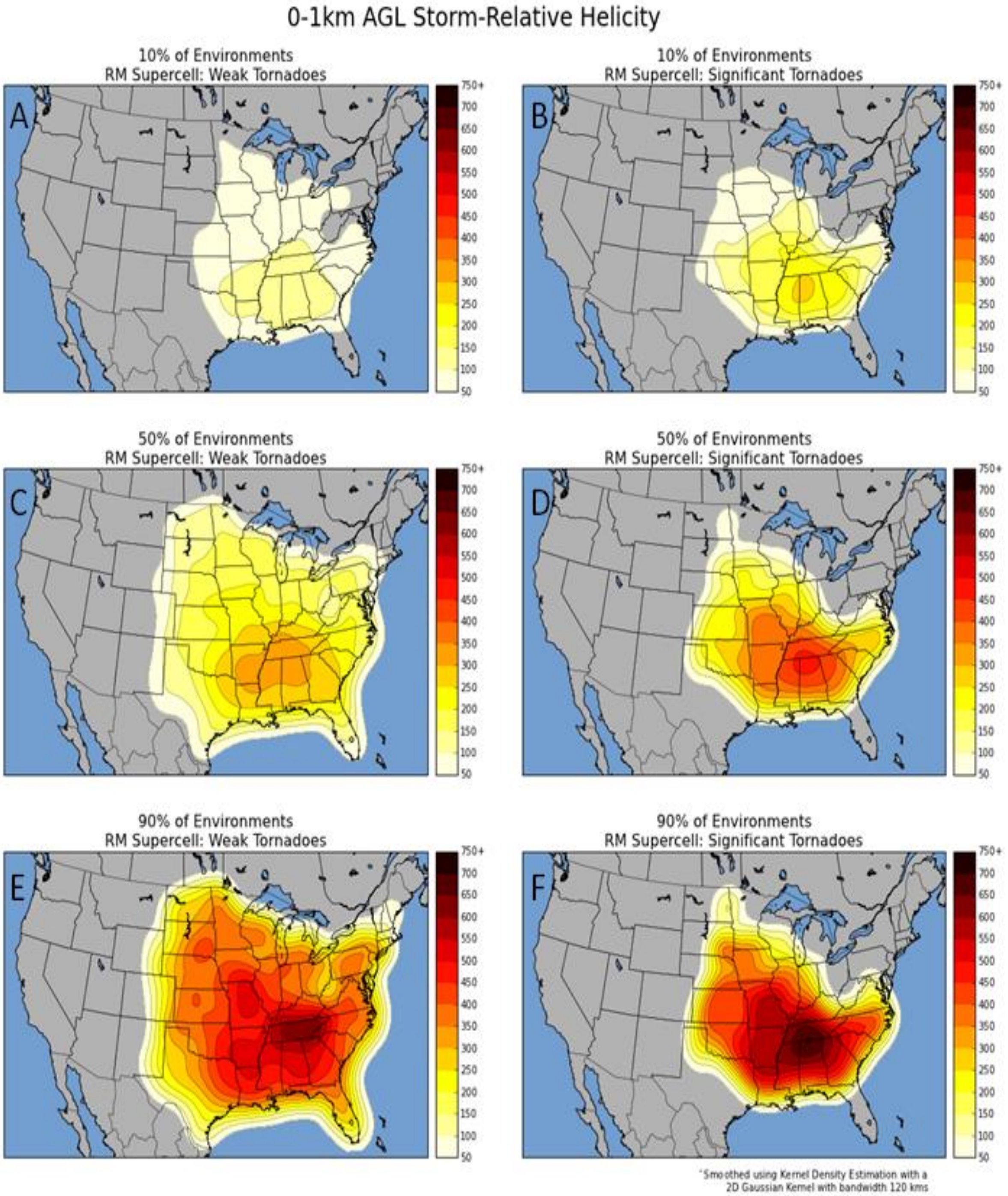


Figure 9: Same as Fig. 3, except for 0–1-km SRH (m^2 s^{-2}).

MLLCL heights rarely exceed 1500 m AGL in QLCS tornado environments, especially east of the Great Plains (Fig. 4b, d and f). The primary difference from RM tornado environments is the lack of QLCS tornado events across the High Plains.

The magnitude of 0–6-km BWD with QLCS tornadoes is quite similar to that of RM tornadoes (Fig. 6), where the majority of tornado cases with both convective modes fall into the part of the parameter space associated with supercells. Many factors can affect convective mode, including the magnitude and spatial patterns of low-level ascent, and the magnitude and orientation of deep-layer vertical shear vectors relative to surface boundaries that serve to focus thunderstorm initiation (e.g., Dial et al. 2010). Thus, more information than a single shear parameter is needed to anticipate convective mode.

Where both RM and QLCS tornadoes are relatively common (refer to the Mississippi and Tennessee Valley region in Fig. 8), 0–1-km SRH values are similar across the two convective modes and well into the range associated with tornadic RM (Rasmussen 2003; T03). The assumed rightward storm motion (Bunkers et al. 2000) in the SRH estimate is not necessarily applicable to linear convective systems. However, SRH does serve as a consistent means of comparing vertical shear environments since the storm motion estimate is based solely on the structure of the wind profile.

Overall, the STP is typically weaker in QLCS environments (Fig. 10), owing largely to weaker buoyancy compared to tornadic RM environments. The STP is designed to highlight significant tornadoes, and the majority of the tornadoes included in this analysis (90% of QLCS and 82% of RM) produced only weak (EF0–EF1) damage.

4. Discussion and summary

The spatial distributions of supercell-tornado parameters show distinct patterns that reflect the geography and synoptic climatology of each region. For example, MLCAPE is clearly greatest across the Great Plains in tornadic RM environments, with the largest values often 3000–4000 J kg^{-1} or larger. By comparison, MLCAPE is typically <2000 J kg^{-1} across the southeastern states in tornadic RM environments. Still, buoyancy can be large across the southeastern states in the more extreme events, such as the 27 April 2011 tornado outbreak across Mississippi and Alabama. MLCAPE for that event ranged from 2500–3500 J kg^{-1} for all of the Alabama grid-hour events, which is above the 90th percentile for significantly tornadic RM in this area (see Fig. 3f).

Likewise, MLLCL heights can vary substantially across the Great Plains in tornadic RM environments. The sample climatology shown in Fig. 4 clearly supports a wide variety of moisture environments across the Great Plains. MLLCL heights span a range from 500–2500 m AGL for tornadic RM, with greatest variability confined to the High Plains in weak RM tornado environments. The relatively frequent occurrence of weak tornadoes in high MLLCL environments across the High Plains could be related to non-meteorological factors such as the prevalence of dust to reveal weak tornado circulations, as well as less-restricted visibility. Otherwise, relatively few man-made structures are impacted by tornadoes across the High Plains, thus tornado damage ratings can be unrepresentative of actual tornado intensity (Doswell and Burgess 1988). Still, the High Plains environments with weak RM are also characterized by weaker low-level shear compared to areas farther east, and the weaker low-level shear and high MLLCL heights are unsupportive of significant tornadoes in a climatological sense (e.g., Markowski et al. 2002; T03).

Variability is much less in RM significant tornado environments from the eastern Plains to the Tennessee Valley, where MLLCL heights rarely exceed 1250 m AGL. This lower variability can be explained largely by lesser fluctuations in the magnitude of low-level moisture, especially across the Tennessee Valley and southeastern states. Here, low-level trajectories ranging from the southwest to the southeast all emanate from the upstream moisture source region of the Gulf of Mexico (e.g., Thompson et al. 1994). Hence, the warm sectors of synoptic cyclones are often relatively moist across the southeastern states, and LCL heights are relatively low. In contrast, low-level trajectories from the south and southeast are typically needed to draw richer moisture into the Great Plains, and these flow regimes are more common in the late spring and summer when warmer surface temperatures contribute to higher LCL heights.

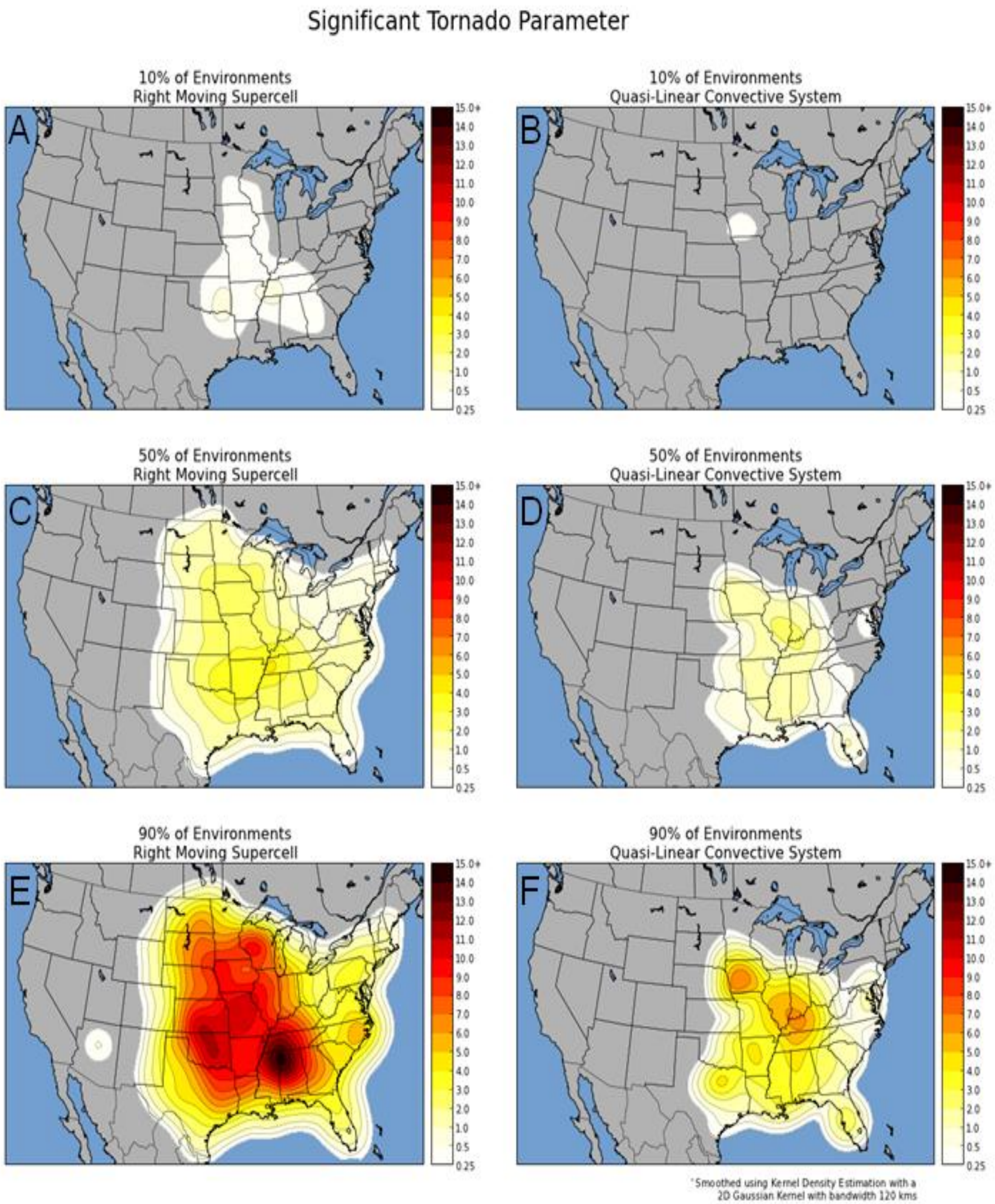
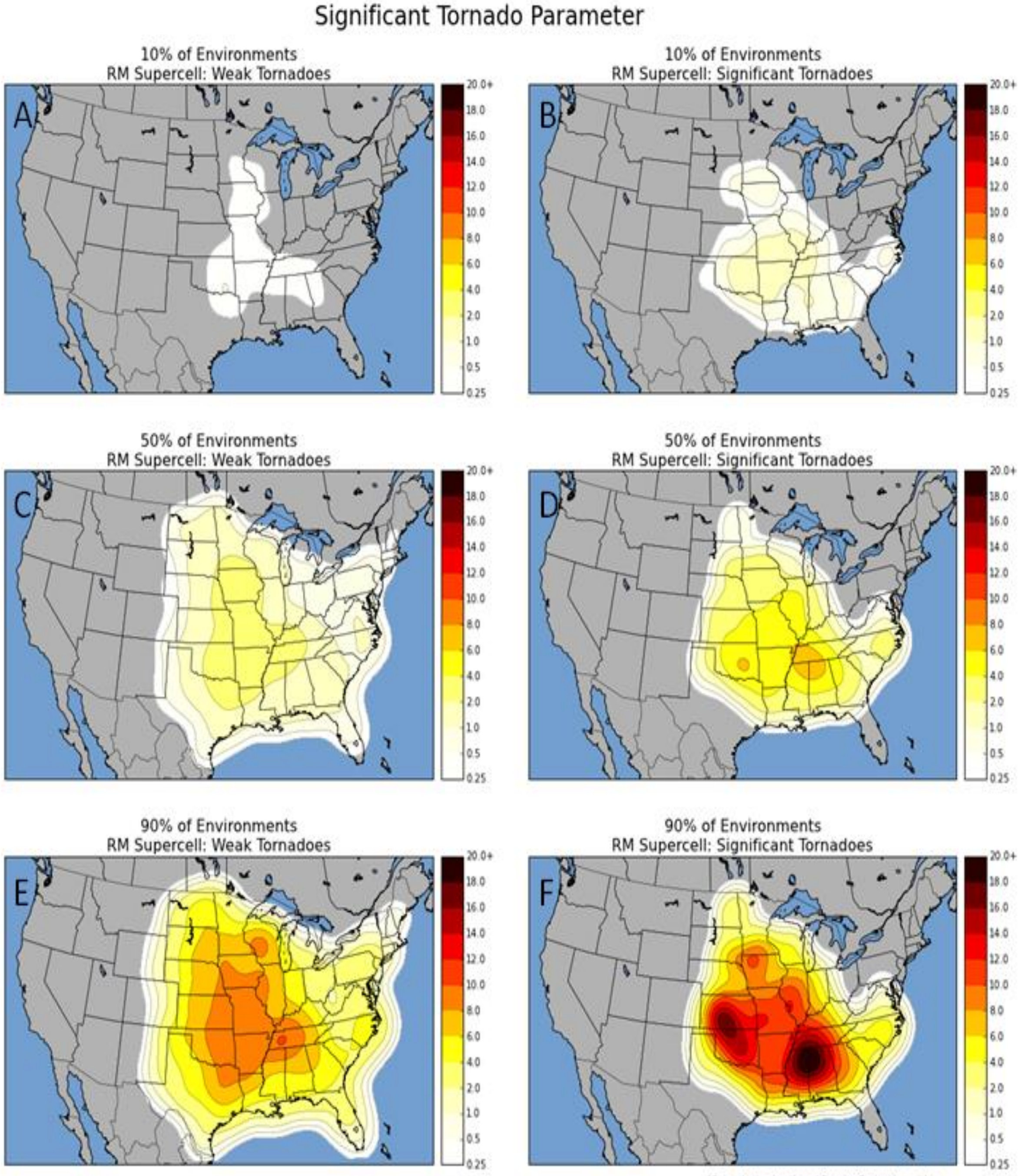


Figure 10: Same as Fig. 2, except for T03 version of STP (dimensionless).



*Smoothed using Kernel Density Estimation with a 2D Gaussian Kernel with bandwidth 120 kms

Figure 11: Same as Fig. 3, except for T03 version of STP (dimensionless).

Vertical wind shear is strongest in the significant RM tornado environments. Though measures of vertical wind shear have proven to be among the strongest discriminators between significantly tornadic and nontornadic RM (e.g., T03), parameters such as 0–1-km SRH, in isolation, may not always be the best discriminators between significant and weak RM tornadoes, or between RM tornadoes and QLCS tornadoes within a given region. Based on prior analyses and supported by results herein, buoyancy (or midlevel temperature lapse rates) may be one of the better discriminators between the significant RM tornadoes (Figs. 2 and 3) and QLCS tornadoes across the southeastern states. Likewise, low-level moisture (and hence MLLCL) is one of the better discriminators between significant and weak RM tornadoes across the Great Plains, where steep midlevel lapse rates and large buoyancy are more common. The tendency for compensating environmental ingredients is reflected in the STP distributions (Figs. 10 and 11) where extreme STP values are observed most consistently from the mid South to the central Great Plains, along the corridor of most frequent significant RM tornado occurrence.

The primary value in the analyses presented herein is the graphical representation of the spatial variation of several tornado-related environmental parameters. Such plots allow meteorologists to characterize efficiently the near-storm environment with consideration for regional climatology, by convective mode. Use of this information can reduce reliance on anecdotal evidence supporting "extreme" environments, or proximity sounding studies that may be dominated by events from a different region (e.g., T03). The analyses presented herein are limited primarily by the representativeness of our event sample from 2003–2011, and the degree to which the SPC environmental dataset represents the state of the atmosphere. Data from 2012 have been collected, though the background model system for the hourly SPC mesoanalyses switched from the RUC model to version 1 of the Rapid Refresh (Benjamin et al. 2007) model on 1 May 2012. Only small changes in the kernel density plots were noted when incorporating this new data, which suggests that our results are robust. Informal investigations and operational experience also suggest that the error characteristics of the Rapid Refresh (version 1) are different than the RUC model error characteristics noted by T03. The convective mode samples may be expanded to include additional years once version 2 of the Rapid Refresh model becomes operational, with its more similar error characteristics to the RUC based on informal investigations at SPC.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Charles A. Doswell III):

Initial Review:

Recommendation: Accept with minor revisions.

General comments: I have no major objections to this manuscript. The vast majority of my relatively few comments are minor. The only point I feel is important is that some of the conclusions are not justified based on what has been presented in the paper. If this can be fixed, and it should be relatively easy to do so, then I believe this would be a useful contribution by the authors. I would like to see the revised manuscript when it is submitted.

We thank Chuck Doswell for taking the time to examine the manuscript, and for his suggested improvements. Specifically, the request to provide more direct support for our claims regarding weak and significant tornado environments with right-moving supercells led to the inclusion of the five new figures, which matched a request from the other reviewer.

We want the reviewers to know that we also generated versions of all eleven figures that include data through 2012, which we completed after the original submission. The addition of 2012 tornado events is beneficial in that it boosts sample sizes. However, the background model basis for the SPC mesoanalysis system changed from the RUC to the [Rapid Refresh] (RAP) on 1 May 2012. Any of the environmental information from 1 May through 31 December 2012 (a little over 400 tornado events) was based on the RAP model, which appears to have error characteristics different from those documented by T03 for the RUC model. Our question for the reviewers is this: Is it worth adding the 2012 data to increase the sample sizes, at the expense of mixing background environmental data sources? The 2003–2012 figures are included in a separate document accompanying these responses.

Substantive comments: That CAPE is not a particularly useful variable for discriminating tornado environments because tornadic events occur over such a wide range of CAPE values (assuming it has some positive value—and acknowledging the exception of the distinction between RM and QLCS situations as discussed in T12), on its own, has been noted by several authors and it would be appropriate to cite at least some of them. If a listing of them is needed, I can provide one.

The Rasmussen and Blanchard (1998) and Craven and Brooks (2004) references have been added to the manuscript, and we can add additional references, if necessary.

Is [there] an apparent compensating effect between buoyancy and shear within the calculation of STP values, or is it a proposed compensating effect associated with some physical effect? The former is easy to see, the latter is evidently not defined herein.

The compensation is within the parameter calculation itself, as reflected in the revised wording.

Since there is no information provided in this paper regarding the spatial distributions of "significant" (EF2+, right?) RM or QLCS tornado distributions and their environments versus weak events, or versus nontornadic RM/QLCS events and their environments, any such conclusions cannot be justified on what is presented herein. If this (and similar) statements are to be made, evidence should presented to support such.

We have generated separate distributions for the ≥EF2 RM tornadoes and the EF0-EF1 RM tornadoes to allow direct comparisons of the environments. The number of ≥EF2 QLCS tornadoes was too small to justify any sort of meaningful kernel density estimates (only 119 total events for the CONUS 2003–2011).

All discussion of nontornadic supercells has been removed from text, though future work may include such cases.

[Minor comments omitted...]

Second Review:

Recommendation: Accept with minor revisions.

General remarks: Overall, the authors have responded adequately to my comments and those of Bill Gallus. Only a few minor points remain and I trust they will be dealt with appropriately by the authors. I now recommend publication and I don't need to see the manuscript again.

We thank the reviewer for his thoughtful comments and suggestions through the review process, and we believe the paper has been improved substantially as a result of this effort.

[Minor comments omitted...]

REVIEWER B (William A. Gallus):

Initial Review:

Recommendation: Accept with major revisions.

General comments: This manuscript examines convective modes associated with tornadoes during a 9-y period, making use of full volumetric WSR-88D data to do so. Variations are found to exist spatially in some supercell-related parameters as a function of storm type (RM versus QLCS). I believe this work is a natural and interesting extension of some earlier work done by some of these authors, but do have a few concerns regarding how material is presented, and thus recommend that the paper undergo major revisions before it can be accepted for publication.

We thank Bill Gallus for his thought-provoking questions, and especially for his request to add information in support of our claims in the paper. The addition of the weak (EF0–EF1) and significant (≥EF2) RM tornado environment comparisons strengthens our presentation and provides more meaningful information to the readers.

We want the reviewers to know that we also generated versions of all eleven figures that include data through 2012, which we completed after the original submission. The addition of 2012 tornado events is beneficial in that it boosts sample sizes. However, the background model basis for the SPC mesoanalysis system changed from the RUC to the RAP on 1 May 2012. Any of the environmental information from 1 May through 31 December 2012 (a little over 400 tornado events) was based on the RAP model, which appears to have error characteristics different from those documented by T03 for the RUC model. Our question for the reviewers is this: Is it worth adding the 2012 data to increase the sample sizes, at the expense of mixing background environmental data sources? The 2003–2012 figures are included in a separate document accompanying these responses.

Specifically, I have three major concerns, and then a few other less serious ones.

Major comments: At several places in the paper, you differentiate between EF0/EF1 and EF2–EF5 tornadoes. Yet, you never present any analyses that are a function of these two intensity categories. I believe in most instances, you are referring to previously published works, but I was often left wondering or wanting to see what your own analysis would have showed regarding differences spatially as a function of tornado intensity. For instance, your last paragraph on p. 3 mentions that high MLLCL heights limit significant tornadoes. It would be very interesting to see how your own MLLCL plot (Fig. 3) would look if restricted to just EF0-EF1 tornadoes, and then also shown for EF2 or stronger. I realize sample size would be a more serious concern when subdividing your sample, but since you discuss the relation of MLLCL to intensity, it seems you should attempt to do this analysis.

We now provide specific figures separating EF0–1 and EF2+ RM tornado environments, in support of the original claims.

There are other instances where you again mention tornado intensity, pointing out that most of the tornadoes at a particular portion of the spectrum of parameter values are EF0–EF1, but you never show a plot that would help the reader to see this. More importantly, since most casualties (and damage?) happen with significant tornadoes, it seems at a minimum it would be useful to see the distribution of parameter values for that subset. I know I'd like to see each figure repeated for the two categories, but that would greatly lengthen the paper, so I recognize that may not be possible. But, perhaps a few new figures could be added for just those parameters where a significant difference is present in the EF0–EF1 sample compared to the EF2–EF5? You seem to imply that significant differences are present for parameters like MLLCL and 0–1km SRH.

A new set of five figures shows side-by-side comparisons of weak (EF0–EF1) and significant (EF2+) RM tornadoes, for the same environmental parameters examined in the original figures.

Again, at the end of section 3, you start discussing fractions of tornadoes that are EF0–EF1 versus stronger, so this is further evidence it might be good to let readers see some of the differences in the parameter distributions spatially for different intensities of tornadoes (my suggestion is to use the non-significant and significant as the two you explore).

In the conclusions section, you again start to discuss differences between different intensities of tornadoes, when your paper is not really about this and provides no figures to justify such discussion. You make a claim on page 8 about how buoyancy does a good job of discriminating between significant RM events and nontornadic RM or QLCS tornadoes. However, you don't differentiate the intensity of the RM events in the paper, nor the QLCS events, and I am guessing you are assuming all QLCS events are non-significant. Is that true? I know it is more rare to have significant QLCS tornadoes than significant RM ones, but they do happen.

Our entire sample includes only 119 EF2+ QLCS tornadoes. Thus, the sample size is too small to generate any meaningful kernel density spatial plots.

One thing I really would have liked to see is more discussion of possible reasons for the differences showing up. Some particularly interesting differences in my opinion are the variations in MLLCL for RM, and in MLCAPE for QLCS tornadoes. Why, for instance, would MLCAPE values typically be so much lower in the southeast than in places further north? In the discussion of QLCS MLCAPE on p. 5, you end by talking about how MLCAPE is a reasonable discriminator especially in the winter in the southeast, but the information in Fig. 2 shows at least as much difference, if not more, in MLCAPE values over places like Missouri, Arkansas and the eastern Great Plains as is showing up in the southeast. Why would you not say “especially in these areas” as well? If the important word in your statement is “winter”, then you need to let us know that you are providing information not available to the reader in Fig. 2. For MLLCL, you do provide some deeper discussion in the conclusions section, talking about trajectories from a broader range of directions supplying moisture to the SE and thus leading to lower MLLCLs than in the Plains. However, one is still left with a question of how tornadoes happen in the High Plains with such dry boundary layers. That might have been discussed in Markowski et al. (2002) or Rasmussen (2003) and T03, but it would be good to repeat it here. The trajectory discussion only explains why high MLLCLs are more common in the Plains than the SE. It does not explain why tornadoes apparently happen in the Plains with high MLLCLs but not in other regions.

The lower MLCAPE values with QLCS tornadoes in the southeast, compared to larger MLCAPE values with IA/IL/IN QLCS tornadoes, appear to be largely the result of seasonal variations in buoyancy. Buoyancy is clearly larger by late spring and summer when the QLCS tornado occurrences are most *common across IA/IL/IN, whereas MLCAPE is weaker during the winter and early spring when most QLCS tornadoes occur in the southeast (based on Figs. 16 and 17 from T12). Similar discussion has been added to the first paragraph of subsection b on p. 8.*

The High Plains tornado environments are characterized by larger MLCAPE compared to the other regions, and steeper lapse rates [inferred in this work, and documented in other work like Lanicci and Warner (1991), Banacos et al. (2010), etc.]. We can speculate on the reasons for the preponderance of weak tornadoes across the high Plains, such as a prevalence of dust to reveal weak tornado circulations, as well as unrestricted visibility and spotter/chaser presence to compensate for lack of population density. Another possible explanation includes the tendency for most storms to occur across the high Plains during the warm season when deep-layer and low-level shear are weaker compared to the lower Plains and eastern states in the transition seasons. Some of this discussion above has now been added to the text.

I agree with your concluding paragraph, and in fact, would have liked to see you perhaps include in your summary a table where you offer some forecasting guidance. I was left with the impression the paper was only reporting the bare minimum of facts about the analyses, when there is such a great potential for it to go further toward helping forecasters. For instance, it looks to me like you could say that in the eastern Great Plains, you need high MLCAPE to get RM tornadoes, but can have QLCS ones with much lower MLCAPE. In IL/IN and parts of the SE, forecasters should know that the amount of MLCAPE does not work to differentiate these two types of tornadoes. You could perhaps have a bullet list of forecast rules based on your figures. Obviously if you do a more thorough job of showing results for intensity differences in tornadoes, some of the forecasting rules could also relate to tornado intensity.

I also had a few minor concerns which follow:

In section 2, how exactly did you use the radar data to determine mode? Am I correct you looked at just two modes? It would be nice to state that fact more explicitly, perhaps by mentioning what all modes were used in Smith et al. (2012) and then state you are only looking at two—RM and QLCS. This is especially important since so many different modes have been defined in different recent studies. There is no real consensus on what modes should be used in classifying storms.

Yes, we only considered the RM and QLCS tornadoes. All of the supercells (discrete, cluster, and line) were included in one group to maximize sample size and the extent of spatial distributions of the environmental parameters associated with the tornadoes. It would be possible to break up the three classes of supercells, though this would also greatly increase the number of figures needed to display the data. As it stands, we went with all RM vs. all QLCS, and weaktor RM vs. sigtor RM, to keep the number of figures and the analysis relatively uncluttered.

[Minor comments omitted…]

Second Review:

Recommendation: Accept with minor revisions.

General comments: The manuscript has been improved significantly by the inclusion of the new figures, and I am generally happy with it as it stands. I do still have a few minor comments for consideration.

Substantive comments: Regarding your major question about whether or not to include the 2012 data, I'm afraid I don't know what to suggest here. It looks to me from the fields I examined closely that it is not making a huge impact on the results. I would find it acceptable for you to leave the paper as it is without the 2012 data, but add some statements in the discussion/summary pointing out that you did study the impact of adding 2012 data, but because of changes in the background model, thought it best not to include the events in the sample, but found that the same trends are present and the fields do not change appreciably, which suggests your results are fairly robust.

We have chosen to retain the 2003–2011 data since the RAP model replaced the RUC on 1 May 2012, and its error characteristics appeared to be somewhat different than the RUC based on informal/anecdotal evidence. Moreover, the current version of the RAP is scheduled to be replaced with a second version of the RAP by 2014, and parallel runs of RAP v2 show error characteristics close to those of the previous RUC system. [Text was added to section 4.]

[Minor comments omitted…]