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ENVIRONMENTAL FEATURES DISCRIMINATING BETWEEN HIGH SHEAR/LOW CAPE SEVERE CONVECTION AND NULLS

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1. INTRODUCTION

Over the past two decades, several studies (e.g., Schneider et al. 2006; Schneider and Dean 2008; Guyer and Dean 2010) have noted the frequency of severe convection associated with large 0-6 km shear and marginal convective available potential energy (CAPE), particularly in the mid-Atlantic and southeastern United States (Lane 2008; Konarik and Nelson 2008). High shear (i.e., 0-6 km shear ≥ 18 m s^{-1}), low CAPE (≤ 500 J kg^{-1}; hereafter, HSLC) environments are responsible for a considerable fraction of severe wind and tornado reports across the southeast and mid-Atlantic, including a substantial number of significant (EF2 or greater on the Enhanced Fujita scale) tornadoes (Guyer and Dean 2010). HSLC environments are more common than those characterized by high CAPE and high shear, leading to a greater number of false alarm hours and lower likelihood of detection (Schneider and Dean 2008). Furthermore, a higher percentage of low CAPE tornadoes occur during the cool season or overnight relative to their high CAPE counterparts (Guyer and Dean 2010), implying that forecasters and the public may suffer from reduced situational awareness during periods when HSLC convection could occur (Ashley et al. 2008; Brotzge et al. 2011).

Despite the acknowledged significance of severe HSLC convection, few studies have focused on improving warning and forecasting operations of these events. For the most part, these studies have investigated radar signatures commonly associated with HSLC events in an attempt to improve probability of detection of severe convection and lead time of warnings (e.g., McAvoy et al. 2000; Grumm and Glazewski 2004; Lane and Moore 2006; Schneider and Sharp 2007). Only a handful of studies have investigated HSLC environmental conditions in extensive detail (e.g., Cope 2004; Wasula et al. 2008), and the only climatology focusing on a component of the HSLC severe convection problem was provided by Guyer and Dean (2010), which purely explored tornadoes in low CAPE environments. Thus, a comprehensive assessment of environmental features critical in discriminating between HSLC severe and non-severe convection has not been performed until now.

Modeling studies by McCaul (1991) and McCaul and Weisman (1996, 2001) explored the development of convection in marginally unstable environments. In general, it was found that the intensity of this convection was sensitive to instability in the low-levels—measured by 0-3 km CAPE and lapse rates, a suggestion corroborated through a climatology of significant tornadoes in the Greenville-Spartanburg, SC (GSP) county warning area (CWA) by Lane (2008). However, it is important to note that these modeling studies have focused on miniature supercells within tropical cyclone environments. While some tropical cyclone events are indeed HSLC, and storm characteristics have many similarities (e.g., spatial scale of convection and associated rotation, etc.), tropical cyclone miniature supercells represent only a fraction of HSLC events. For the purposes of this study, we are focused on HSLC severe convection events associated with mid-latitude cyclones, which can occur in the form of miniature supercells, quasi-linear convective systems (QLCSs), or other, less organized modes.

This paper is organized in the following manner. Section 2 will provide an overview of the data and methods of our study. Section 3 will provide a climatology of HSLC severe convection in the mid-Atlantic and southeastern U.S., including the evaluation of environmental parameters' ability to discriminate between significant events and non-severe events. Herein, we will also assess the skill of existing composite forecasting parameters during HSLC events and propose a composite parameter designed specifically for use in HSLC events. In section 4, we will briefly describe future plans for idealized simulations of HSLC events. Finally, section 5 will provide a conclusion and discussion of our results.

2. DATA AND METHODS

2.1 *Development Events*

Collaborators at National Weather Service (NWS) Weather Forecast Offices (WFOs) in the southeast and mid-Atlantic[†] compiled a list of HSLC events that occurred across the region between January 2006 and April 2011. While not all-inclusive, the case list was

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verified to include the majority of HSLC significant events—particularly tornadoes—for the given spatial and temporal domains. The total number of severe reports for the given days was 6,245. For each severe report in the list of events, the Storm Prediction Center (SPC) provided us with a relational database composed of archived surface objective analysis (SFCOA) data, known operationally as the SPC Mesoanalysis.

The database consisted of 84 different environmental parameters on a 40-km grid at hourly intervals. For analyses, we use the nearest grid point to a report at the preceding hour. Through inspection, it was noted that not all of the events in the database met our HSLC criteria. For example, an HSLC event in Sterling, VA may have coincided with a non-HSLC event in Charleston, SC. In order to remove unwanted events from our database, we inspected each event CWA-by-CWA to determine which CWAs' reports were primarily HSLC. We considered an event to be HSLC for a given CWA if more than half of that CWA's reports for a given day met our HSLC criteria. If these criteria were not met, the CWA's reports for that particular event were excluded from our database. Following this quality control procedure, 3,315 severe reports remained in our database.

Finally, in an attempt to curb biases due to large individual events, we decided to keep only one report per CWA per hour in our database. Here, we simply took the first report that occurred within a CWA for a given hour, with precedence to tornado reports, then wind reports, and finally hail reports (i.e., a hail report would only be kept if there were no wind or tornado reports in that CWA during that hour). Following this second filtering, 943 severe reports remained. 80 of these reports were significant severe reports, which were used for the majority of the analysis discussed in Section 2.4.

2.2 *Development Nulls*

A null was subjectively defined as a severe thunderstorm or tornado warning issued by a WFO when no severe events occurred in that respective CWA during a convective day (1200 UTC-1200 UTC). For our purposes, we considered warnings issued only between October and May from 2006 to 2010.

Data for the nulls were also derived from archived SFCOA fields. However, the null database was created by interpolating the values from surrounding grid points to the latitude/longitude point of the null warning. In testing, interpolation led to only small differences, on average, to the nearest neighbor method (not shown). After a quality control measure to remove the majority of non-HSLC events (a few marginal HSLC nulls were maintained to support consistency with the events database), 114 nulls remained in the null dataset.

2.3 *Verification Dataset*

To test our results from the development dataset, we collected SFCOA data for all significant reports and all nulls (as defined in Section 2.2) across the U.S. from 2006-2011 (nulls began in Oct. 2006). For the verification dataset, data for both the reports and nulls were gathered using the nearest grid point and the preceding hour. The methods described in Section 2.4 were again employed using the verification dataset to assess the applicability of our preliminary results outside of the southeast and mid-Atlantic in addition to reevaluating the performance of our techniques.

2.4 *Methods*

In order to analyze the skill of environmental parameters discriminating between HSLC severe convection and nulls, we completed a comprehensive statistical analysis focusing on the ability of individual parameters to discriminate between significant severe HSLC events and non-severe HSLC events. Only significant severe events were included in this analysis after discussions with NWS collaborators at WFOs and the SPC along with the consideration of uncertainty of severe reports noted in previous studies (e.g., Trapp et al. 2006). For this analysis, we primarily utilized the true skill statistic (TSS; Wilks 1995), given by

$$TSS = (ad-bc)/[(a+c)(b+d)], \qquad (1)$$

where a is a correct forecast, b is a false alarm, c is a miss, and d is a correct null. To a close approximation, the TSS can be represented as the difference between the probability of detection and false alarm rate (*not* false alarm *ratio,* which is typically used for warning skill assessment). This skill parameter gives weight to correct null forecasts and also provides consistency with Thompson et al. (2004), who used TSS in determining the optimal value for the Significant Tornado Parameter (STP).

For each parameter in the relational database, we assessed its optimal TSS at discriminating between the 80 HSLC significant severe events (in our one report per CWA per hour ("ORPC") dataset) against the 114 HSLC nulls. This was accomplished by calculating the TSS for a wide range of thresholds and determining the highest TSS for each parameter.

Following the assessment of each individual parameter, we created a composite parameter by taking the product of the three conditionally most skillful parameters. All of the reports above the most skillful parameter's optimal value (i.e., value at which its TSS was maximized) were utilized to conduct a second round of TSS tests in order to identify the second conditionally most skillful parameter. This was designed to reduce false alarms, which outnumbered the misses. Finally, a last series of TSS tests using all reports with the first and second parameters both above their optimal values determined the third conditionally most skillful parameter. These three parameters were then combined, using their optimal values as approximate normalization values.

Because the majority of HSLC significant severe events and nulls over the past six years were included in our original dataset, it was impossible to assemble a verification dataset using events only from the southeast and mid-Atlantic that was large enough to test our findings. As a result, we also utilized Monte Carlo simulations (Wilks 1995), which are designed to artificially create subsets of data through repeated random sampling of a dataset. Using the Monte Carlo method, we ran 100,000 realizations of TSS tests, each with 30 randomly selected significant severe events and 30 randomly selected nulls. This increased the confidence in our findings using the development dataset.

3. ENVIRONMENTAL PARAMETER CLIMATOLOGY

3.1 *Annual and Diurnal Distributions*

The annual and diurnal trends of HSLC severe events and nulls across our collaborating CWAs are shown in Fig. 1. We restricted our identification of nulls to the months of October through May; i.e., no summertime nulls were collected in our development dataset. This seems to be a reasonable omission for our comparisons, as no significant severe events occurred between June and September, though there were some non-significant severe reports. There is a clear peak in severe and significant severe reports in the spring, particularly in March and April, while the null distribution is approximately uniform throughout the non-summer months. Diurnally, all subsets show a fairly noisy trend, though a late afternoon through evening enhancement is visible within the severe reports (especially the significant severe reports in late afternoon), along with a relative lull in the morning. Nulls show no clear diurnal trend.

3.2 *Environmental Parameter Skills*

The ten most discriminatory parameters between all HSLC significant events and all HSLC nulls are listed in Table 1 with their associated TSS and optimal value. This particular list only includes parameters in the original relational database provided by the SPC. The top ten is composed of shear magnitudes, lapse rates, composite parameters, and the zonal components of various wind and shear measurements.

The skill of the zonal components of the wind and shear measurements is likely not generalizable due to the variance in wind and shear orientation from event to event. However, the orientation of shear and wind vectors relative to boundaries *could* play a role in the storm morphology and associated hazards, as suggested by previous studies (e.g., Bluestein and Weisman 2000; French and Parker 2008; Dial et al. 2010). This will be explored further in future work.

The STP and the Vorticity Generation Parameter (VGP) perform well in this assessment, though it is worth noting that their optimal values (0.25 and 0.07, respectively) are well below the commonly accepted optimal values of 1.0 for the STP (Thompson et al. 2004) and 0.2 for the VGP (Rasmussen and Blanchard 1998). However, the authors acknowledge that these values were meant to represent environments favorable for tornadoes (particularly, significant tornadoes) and not all significant severe events. This will be explored in more detail shortly.

The effective shear stands out among the individual parameters as the best performer, though the 0-3 km lapse rate has a comparable TSS. The latter term has been suggested as an important contributor to severe weather in GSP (Lane 2008), and based on this study, it is a good discriminator between HSLC significant severe weather and nulls throughout the region. The importance of low-level lapse rate was also noted by McCaul and Weisman (2001) in their simulations. Effective shear (Thompson et al. 2007) was developed to more accurately depict the representative shear layer for environments in which shallow or elevated convection was expected. Given that the majority of our dataset consists of HSLC convection, which tends to be vertically compressed (Reilly 2004; Lane and Moore 2006), the effective shear would be expected to perform more skillfully than any fixed layer shear, which is confirmed by our results.

3.3 *Development of a HSLC Composite Parameter*

Given that the effective shear (hereafter, ESHR) was the most skillful parameter overall, it was used as the base for the development of a composite parameter designed specifically for discriminating HSLC significant severe convection against non-severe HSLC convection. The iterative method described in Section 2.3 was employed in order to determine the next two conditionally most skillful parameters. Through this analysis, it was determined that the most skillful conditional parameters were the 700-500 mb lapse rate (LR75) and the 0-3 km lapse rate (LLLR).

We developed a composite parameter by utilizing the product of these three parameters, each initially normalized by its respective optimal value. While the product of the parameters is not necessarily the best formulation of the composite parameter, it is the best we have identified thus far. Following testing, we adjusted the ESHR normalization value in order to achieve an optimal value of one for the entire parameter. This parameter, referred to as the Severe Hazards in Environments with Reduced Buoyancy parameter – Effective shear version (SHERBE), is given by:

$$SHERBE = (ESHR/26 \text{ m s}^{-1}) * (LR75/5.8 \text{ K km}^{-1}) * (LLLR/5.2 \text{ K km}^{-1}). \quad (2)$$

Given that ESHR is dependent on CAPE, and considering that some of the significant events in our development dataset occurred with analyzed CAPE of 0 J kg^{-1}, analyzed ESHR may be suspect in some HSLC cases. Thus, we also evaluated the use of fixed-layer shear magnitudes in order to maximize the skill of the parameter (hence the “effective shear version” notation on the previous parameter). Through TSS calculations, it was determined that using the 0-3 km shear magnitude (S3MG) rather than ESHR improved the parameter’s skill, at least for our development dataset.

Thus, the Severe Hazards in Environments with Reduced Buoyancy parameter (SHERB) is defined as

$$SHERB = (\mathrm{S3MG}/25\ \mathrm{m\ s^{-1}}) * (LR75/5.8\ \mathrm{K\ km^{-1}}) * (LLLR/5.2\ \mathrm{K\ km^{-1}}). \quad (3)$$

Using the 0-6 km shear magnitude also provided a similar maximum TSS; however, through Monte Carlo simulations, it was determined that a parameter utilizing the 0-6 km layer was not as robust as either the S3MG or ESHR version.

Fig. 2 shows a comparison of TSS between the SHERBE, the SHERB, and other existing composite parameters, including the STP, the Supercell Composite Parameter (SCP), the VGP, and the Energy-Helicity Index (EHI). There are two clear messages associated with Fig. 2. First, the SHERB and SHERBE have comparable TSSs, and these maxima are well above the maxima for the existing composite parameters. Secondly, while the existing composite parameters exhibit skill, note again that the optimal values for these parameters are below commonly suggested values.

The authors note that some of the existing composite parameters were designed to conditionally determine the threat for significant tornadoes, not *all* significant events. However, even when assessing their skill at discriminating significant tornadoes from nulls, the SHERB and SHERBE outperform the four existing parameters, though the gap has closed considerably, as shown in Fig. 3. Further, the optimal values of the parameters remain low. The only parameter, to the authors' knowledge, designed to diagnose regions favorable for any significant severe weather is the Craven-Brooks Significant Severe parameter, which was not shown in Fig. 2. Its optimal TSS was 0.243 at a value of 7000.

Fig. 4 shows box-and-whisker plots of the SHERB for significant, non-significant but severe, and non-severe HSLC convection. Note that the 25th percentile of the significant events and the 75th percentile of the non-severe events are located at a SHERB value of approximately one. Thus, the majority of HSLC significant events occur above the SHERB threshold, while less than one quarter of the nulls are above the given threshold. The distributions for the SHERBE, though not shown, are comparable.

3.4 *Monte Carlo Simulations*

For each realization of Monte Carlo simulations, 30 randomly selected events and 30 randomly selected nulls were compared through the tests described in Section 2.4. The Monte Carlo simulations largely served to corroborate our previous findings, though minor differences were noted. For example, though ESHR was the most skillful parameter in our original computations, the LLLR was the most skillful individual parameter using the Monte Carlo simulations. Regardless of the differences in individual parameter skill, the SHERB and SHERBE remained the most skillful composite parameters, with average TSSs of 0.625 and 0.591, respectively.

3.5 *Verification Dataset*

The above results were tested using the verification dataset described in Section 2.3. Here, we used a strict cut-off of 500 J kg^{-1} and 18 m s^{-1} to define HSLC events (i.e., we did not use the criterion for HSLC events described in Section 2.1). For our region, comparable trends were observed in terms of composite parameter skills. The SHERB and SHERBE outperformed all existing composite parameters in discriminating all significant events and from nulls, though the TSSs were somewhat lower—0.465 for the SHERB and 0.497 for the SHERBE. Likewise, the SHERB and SHERBE outperform all other composite parameters in our region when discriminating between HSLC significant tornadoes and nulls.

Preliminary evaluation of the skills of individual parameters suggests that 0-3 km and 700-500 hPa lapse rates may not be as discriminatory within our region using the verification dataset, as shown in Table 2. However, the 850-500 hPa lapse rate is very skillful. ESHR remains the most skillful parameter in our region.

Across the entire U.S., the SHERB and SHERBE do not perform as admirably, as shown in Fig. 5. We suspected that much of the decline in performance was a result of regional variability. Fig. 6 shows the most skillful composite parameter by region in discriminating HSLC significant events and nulls. This map demonstrates that, although there are some regions in which the SHERB and SHERBE are outperformed by existing composite parameters, one of the two parameters is the most skillful in many areas. Further analysis is necessary to understand the details surrounding the regional variability, and this topic will be the focus of continuing work. It is also possible that methodology differences—using interpolation in the development null dataset, ORPC in the development events dataset, or a strict cut-off in shear and CAPE for the test dataset—may have contributed to some of the skill differences we have noted. Continuing work will assess the relative importance of these factors.

4. IDEALIZED SIMULATIONS

The second phase of this project will utilize idealized model simulations in an attempt to answer remaining questions regarding the dynamics of HSLC severe convection. Composite soundings for differing convective modes (e.g., discrete supercells, linear non-supercells, supercells embedded within lines, etc.), created through synthesis of archived Rapid Update Cycle fields for our HSLC significant severe events, will be used to initialize Cloud Model 1 (CM1; Bryan and Fritsch 2002). We intend to test the sensitivities of HSLC convection to the thermodynamic profile, the hodograph shape and orientation relative to a preexisting cold pool, and multiple initialization techniques. Additionally, we hope to understand the development of tornado-like vortices within HSLC convection, both in QLCSs and discrete miniature supercells.

Thus far, we have successfully simulated supercells using a slightly modified composite discrete supercell sounding and a cold pool initialization. Further investigation of these simulations is necessary before any conclusions can be made.

5. DISCUSSION AND CONCLUSIONS

Severe convection occurring in environments with marginal instability but large amounts of deep-layer shear remains a challenge in forecasting and warning operations. However, through the comparison of environmental parameter distributions between HSLC significant severe events and non-severe convection, we have identified key parameters that discriminate between the two subsets. Further, we have developed two composite parameters that exhibit an increase in skill over all existing composite parameters in diagnosing areas favorable for HSLC significant severe weather in the southeast and mid-Atlantic.

There are a few caveats to using the SHERB and SHERBE. First, it should be noted that neither parameter is designed to forecast the onset of convection. Each parameter was designed using datasets in which convection was ongoing—either significant severe convection or non-severe convection. Therefore, it is ultimately up to the forecaster to determine whether or not convection will occur, then use the diagnostic SHERB and SHERBE values accordingly. Also, since the parameters were designed only using the significant severe and null datasets, the non-significant severe events were not considered. As shown by Fig. 4, the distributions of these parameters for non-significant severe events lie in between the significant severe events and the nulls. Thus, there is a higher probability that a non-significant severe event will occur below the threshold (i.e., be missed by the parameters). However, the ultimate goal of the parameter is to ensure high probability of detection of significant severe events and to limit false alarms of non-severe events, both of which it does successfully. The authors acknowledge that there are likely situations in which the SHERB and SHERBE will struggle, as is anticipated for every parameter (after all, no parameter will ever be—nor should be considered—a “magic bullet”). We are continuing to test variations of the parameters in order to maximize the skill for future diagnostic use.

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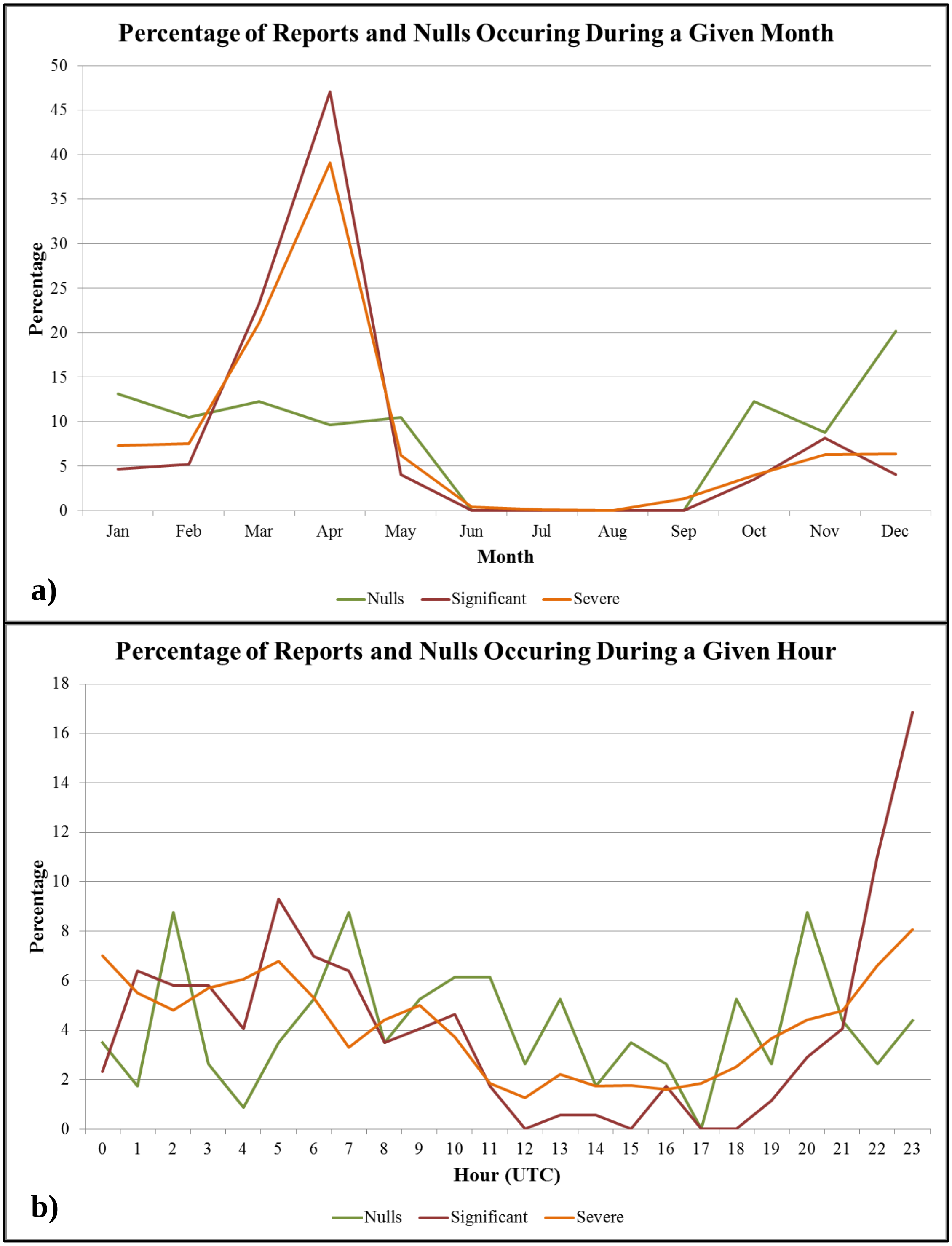

Figure 1. a) Annual distribution of HSLC severe convection, significant severe convection, and nulls for our temporal and spatial domains using the development dataset; b) As in a, but diurnal distributions, rather than annual distributions.

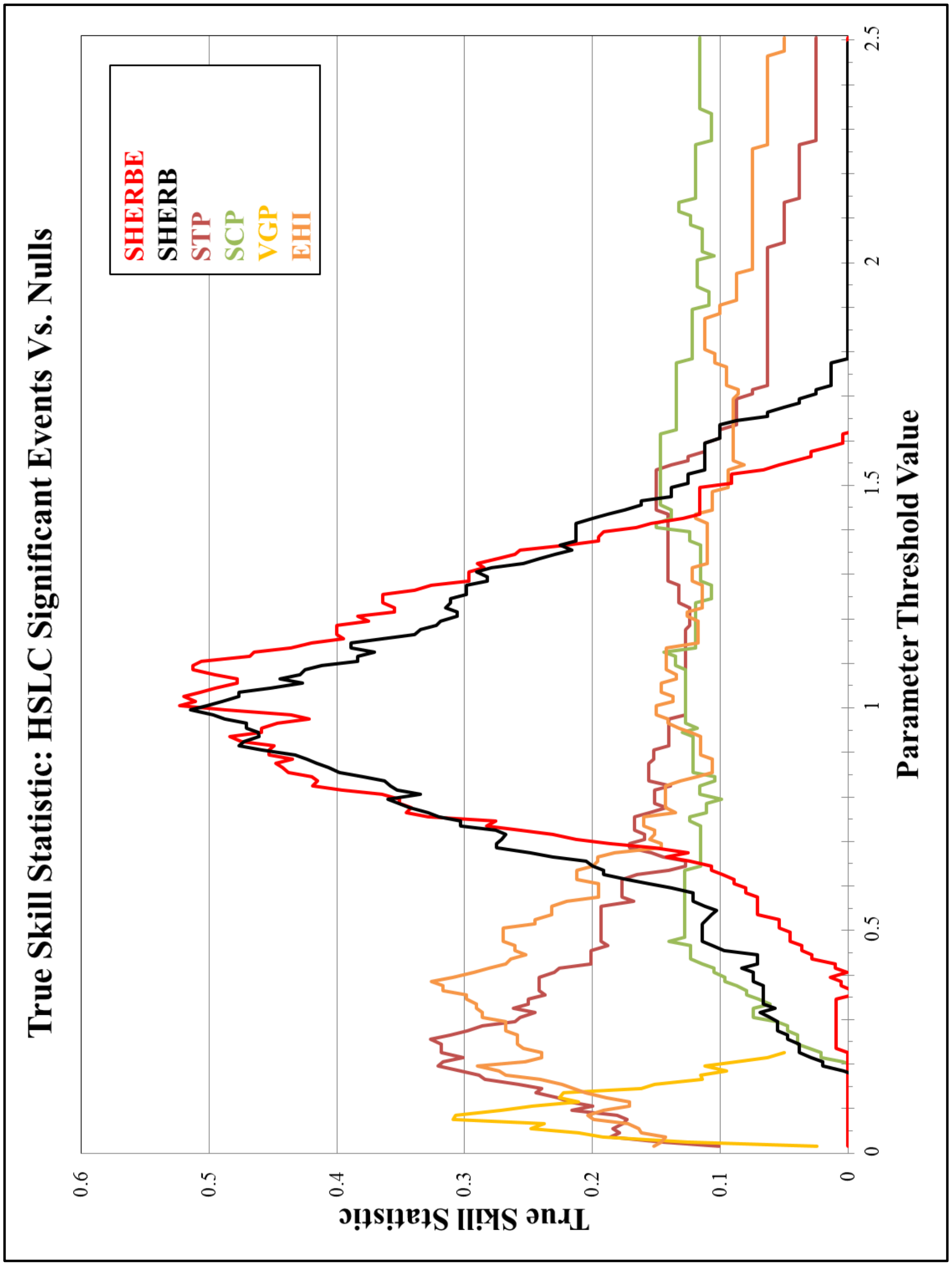

Figure 2. TSS for given composite parameters in discriminating between HSLC significant events and nulls using the development dataset.

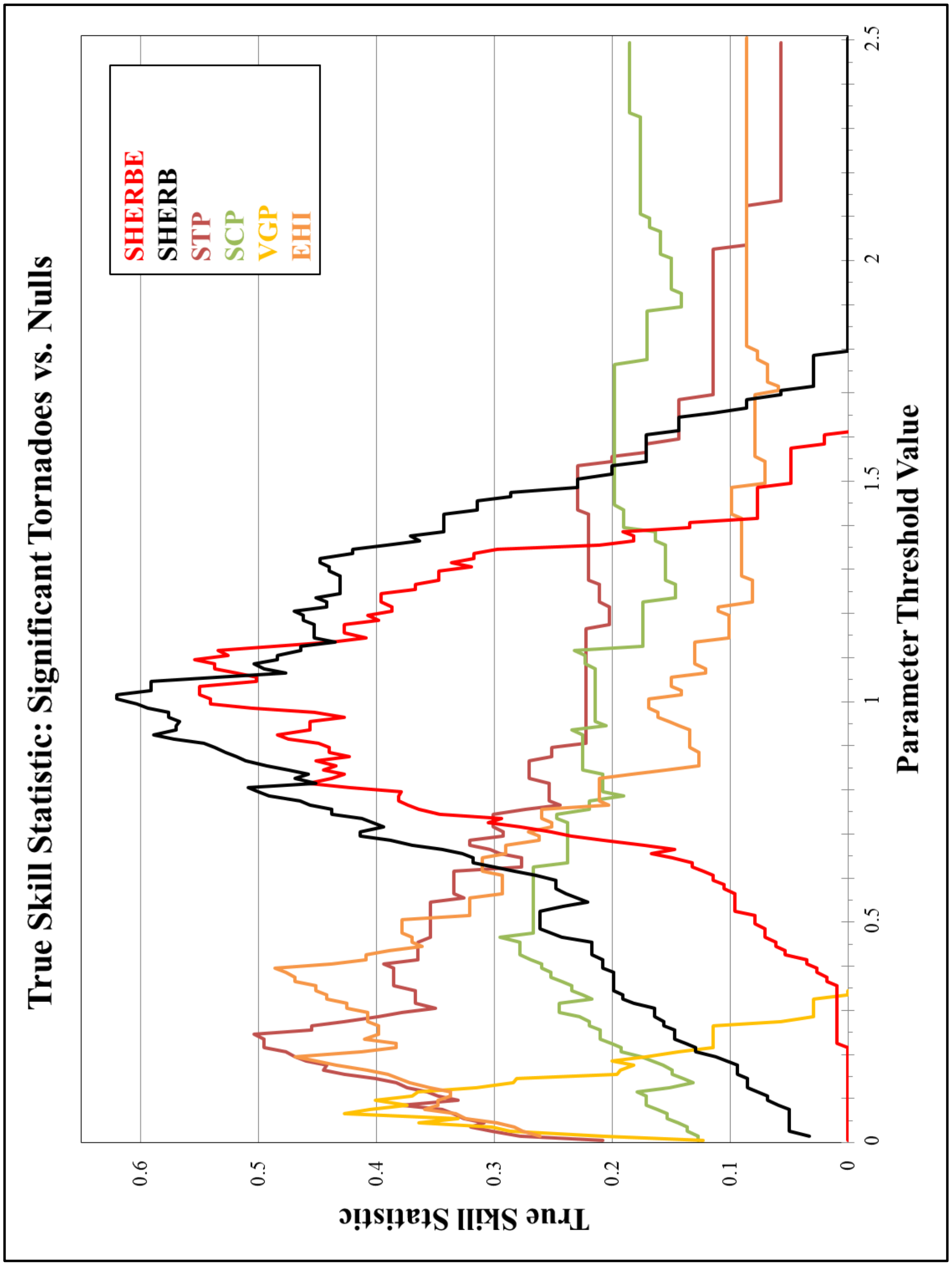

Figure 3. As in Fig. 2, but for significant tornadoes against nulls.

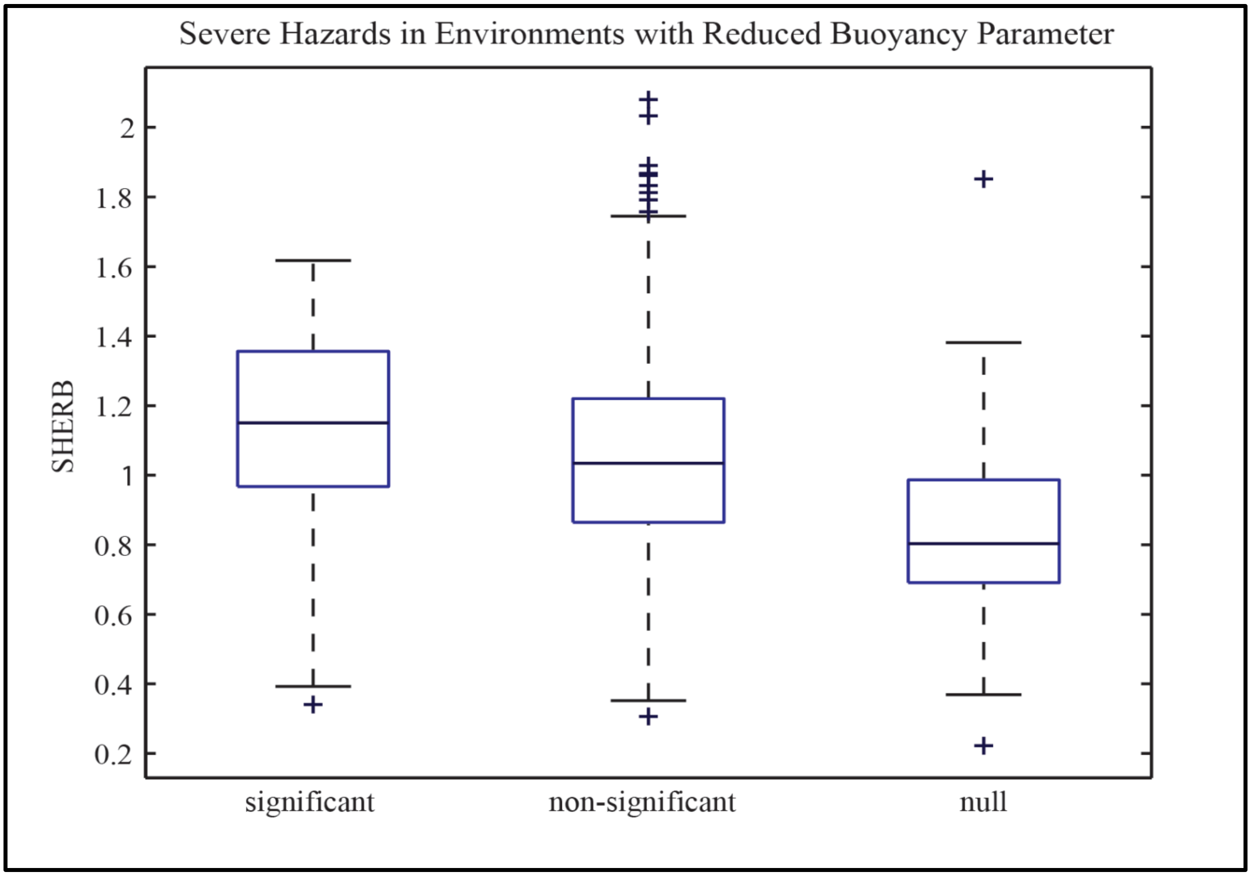

Figure 4. Distributions of the SHERB for significant severe, non-significant severe, and non-severe (null) HSLC convection for the development dataset.

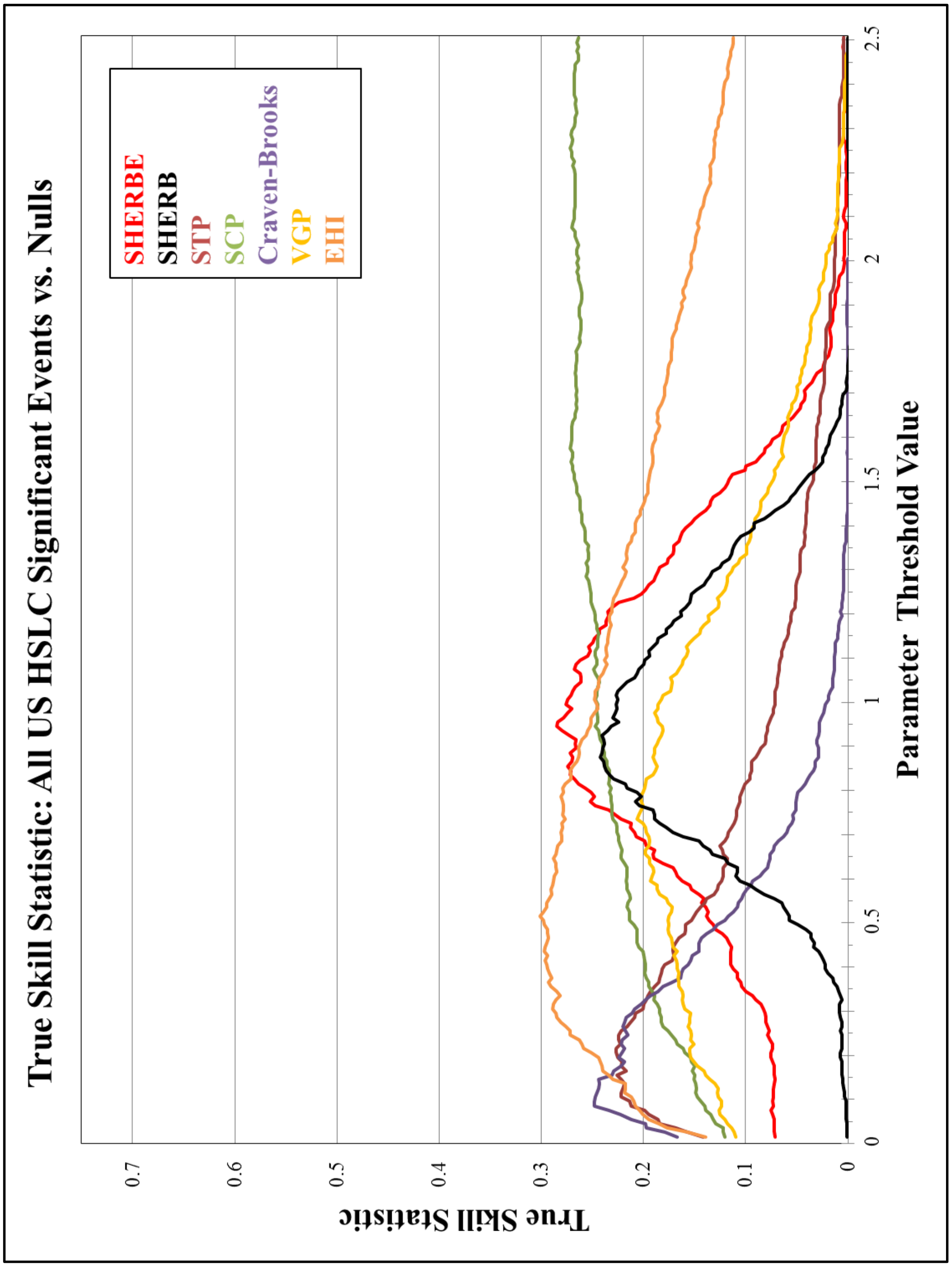

Figure 5. As in Fig. 2, but for verification dataset. Also included is the Craven-Brooks Significant Severe parameter (value has been divided by 50000). The VGP has been multiplied by 10 in order for easier comparison to other parameters.

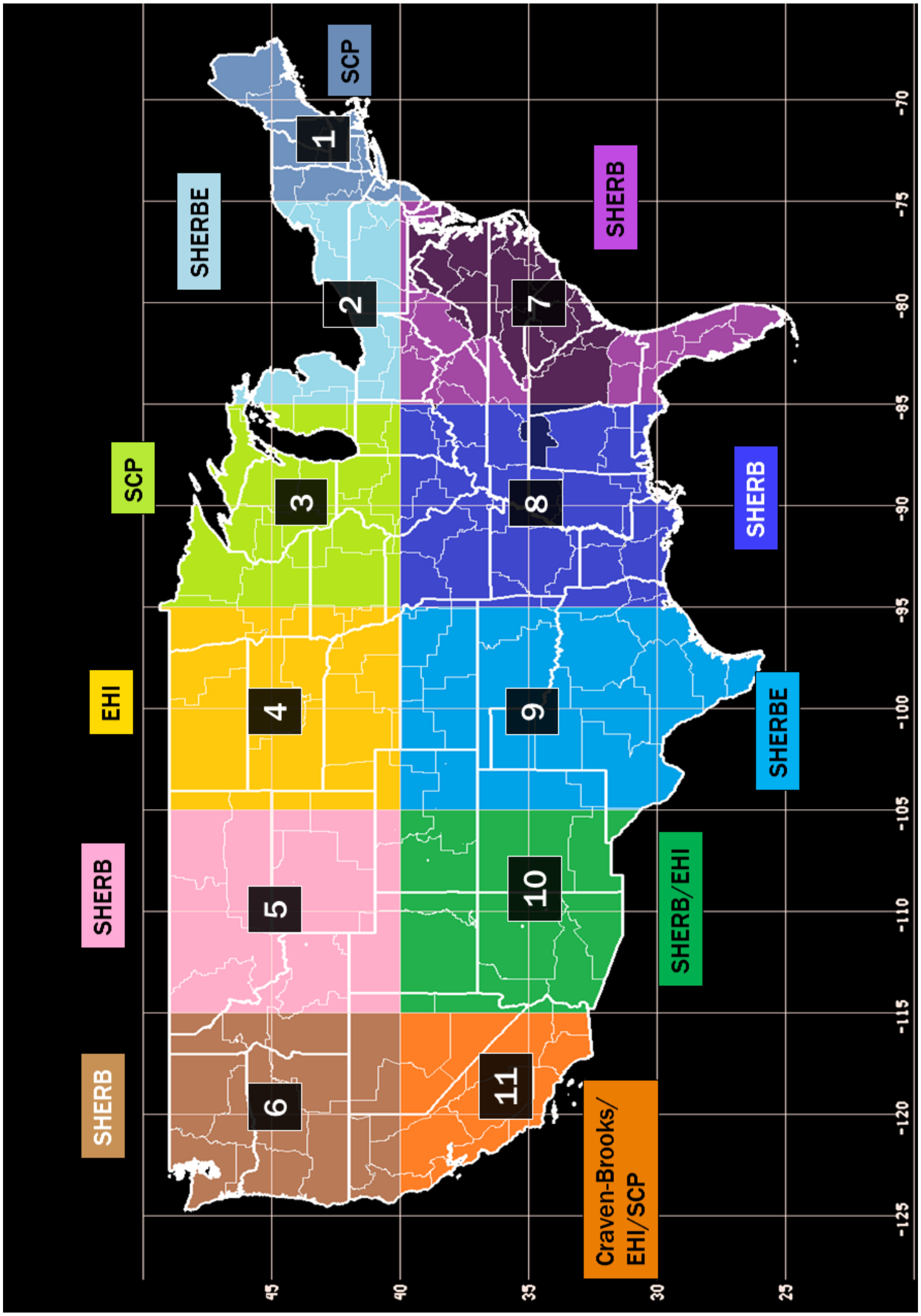

Figure 6. Best performing composite parameter by region in discriminating HSLC significant events from nulls.

Table 1. Ten Best Parameters at Discriminating Between HSLC Significant Events and Nulls within our Development Dataset

Parameter	*True Skill Statistic*	*Optimal Value*
Effective Shear	0.373	22.64 m s^{-1}
0-3 km Lapse Rate	0.364	5.2 K km^{-1}
Significant Tornado Parameter	0.327	0.25
Vorticity Generation Parameter	0.314	0.07
850-500 hPa Lapse Rate	0.306	5.7 K km^{-1}
U Component of the Effective Shear	0.304	19.03 m s^{-1}
700-500 hPa Lapse Rate	0.300	5.5 K km^{-1}
U Component of the Bunkers Storm Motion	0.300	18 m s^{-1}
0-6 km Shear Magnitude	0.297	26.75 m s^{-1}
U Component of the Cloud Bearing Layer Wind	0.286	19.55 m s^{-1}

Table 2. Ten Best Parameters at Discriminating Between HSLC Significant Events and Nulls within our Verification Dataset in Our Collaborating Domain

Parameter	*True Skill Statistic*	*Optimal Value*
Effective Shear	0.377	24.69 m s^{-1}
850-500 hPa Lapse Rate	0.360	6.0 K km^{-1}
Vorticity Generation Parameter	0.353	0.06
Downdraft CAPE	0.350	400 J kg^{-1}
100 hPa MLCAPE	0.336	75 J kg^{-1}
U Component of the Effective Shear	0.333	23.66 m s^{-1}
Significant Tornado Parameter	0.325	0.20
100 hPa Mixed Parcel Lifted Index	0.324	-0.2 K
SBCAPE	0.305	50 J kg^{-1}
0-6 km Shear Magnitude	0.289	32.41 m s^{-1}