9.1 High-shear, low-CAPE environments: What we know and where to go next

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1. Introduction

As noted by numerous operational case studies (e.g., Cope 2004; Lane and Moore 2006; Clark 2009), environments associated with low instability and strong deep-layer wind shear vector magnitudes [high-shear, low-CAPE (HSLC) environments] pose a unique challenge to forecasters due to their compact spatial dimensions (e.g., McCaul 1987; Davies 1990; Kennedy et al. 1993; Davis and Parker 2014), rapid intensification of rotation (e.g., Cope 2004), relatively low ratio between severe weather reports and environmental hours (e.g., Dean et al,. 2009), and prevalence during the cool season and overnight (Sherburn and Parker 2014a). However, literature on severe HSLC environments remains sparse, leading to numerous gaps in the knowledge base, particularly related to the dynamics and predictability of severe HSLC convection. This work serves to provide a review of our current knowledge of HSLC environments and examine the questions yet to be answered.

2. Typical Features

a. Environmental characteristics

The terms "high shear" and "low CAPE" have been used for a variety of deep-layer shear vector magnitude and CAPE thresholds over the last fifteen years. Prior to Guyer and Dean (2010), "low CAPE" traditionally referred to mixed-layer (ML) CAPE ≤ 1000 J kg^{-1} (e.g., Schneider et al. 2006). More recent work has focused on even lower values of CAPE, with Guyer and Dean (2010) introducing the threshold of 500 J kg^{-1}. Subsequent climatological studies by Davis and Parker (2014) and Sherburn and Parker (2014a) also utilized 500 J kg^{-1}, though they considered surface-based (SB) CAPE. Additional criteria based upon most unstable (MU) CAPE, low-level shear, and lifted condensation levels (LCLs) have also been included in various studies (e.g., Schneider et al. 2006, Sherburn and Parker 2014a). Environments associated with tropical cyclone tornadoes are also notably HSLC (e.g., McCaul 1987; McCaul 1991), though our focus is on HSLC convection associated with extratropical cyclones.

Severe HSLC environments are typically characterized by strong synoptic and mesoscale forcing, with potent upper-level and surface cyclones, attendant cold fronts, and upper-level divergence (e.g., McAvoy et al. 2000; Cope 2004; Lane and Moore 2006; Wasula et al. 2008), as shown in Figure 1. Additionally, moisture is abundant in the low-levels and often throughout much of the troposphere, contributing to low LCLs. Though instability is limited, it is often (but not necessarily) focused in the low levels, leading to enhanced values of 0-3 km CAPE (e.g., Lane 2008). In addition to strong deep-layer shear vector magnitude, low-level winds and shear are intense, with low-level jets (LLJs) commonly reaching 25-30 m s^{-1} (e.g., Lane and Moore 2006). Lightning can be limited or nonexistent in these environments, owing to the lack of instability within the clouds' mixed-phase region (van den Broeke et al. 2005).

b. Radar presentation and signatures

The most common convective modes in HSLC environments are quasi-linear convective systems (QLCSs) and mini-supercells, the latter of which exhibit the structure of classic high CAPE supercells but on scales as much as half of an order of magnitude smaller. Kennedy et al. (1993) provided the first single-Doppler analysis of a mini-supercell within an HSLC environment, noting a mesocyclone largely confined to the lowest 3 km with echo top heights of 6 km or less (Figure 2). More recently, Davis and Parker (2014) found through a radar climatology of HSLC tornadic and non-tornadic vortices that mini-supercell mesocyclones have a median depth of ~2-4 km. Additionally, Davis and Parker noted a typical base-scan diameter of ~2 km, confirming that HSLC convection has a smaller horizontal *and* vertical footprint than higher CAPE convection, as illustrated by Figure 3. HSLC QLCS mesovortices were shown to be of a comparable depth and diameter. As a result, even the base radar scan may overshoot rotation, particularly at long ranges from the radar (Davis and Parker 2014).

A study by McAvoy et al. (2000) formally introduced the "broken-S" signature, which has been identified in multiple case studies (e.g., Lee and Jones 1998; Clark 2011) and bears a striking resemblance to the "precipitation cores" and "gap regions" noted to occur within narrow cold-frontal rainbands by Hobbs and Persson (1982). The broken-S signature occurs within QLCSs (and is not unique to HSLC cases; e.g., Grumm and Glazewski 2004) and is characterized by an S-shaped bulge in reflectivity, followed by a break in reflectivity near the bulge (Figure 4). Tornadoes can occur coincident with or shortly after this break in reflectivity in the lowest radar tilts (e.g., Lane and Moore 2006), implying that it is likely a consequence of or collocated with intensifying rotation. Though the broken-S signature has a non-zero false alarm rate, it does have operational utility, given that it tends to occur in a top-down manner; a break in reflectivity aloft appears

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first, followed by a break in reflectivity in lower levels (Davis 2013). This *could* provide some lead time that is otherwise difficult to manage within HSLC environments (Lane and Moore 2006), though Davis and Parker (2014) found little lead time associated with broken-S signatures close to the radar. “Classical” supercell and QLCS radar reflectivity signatures—such as hook echoes, rear inflow notches, and gust front cusps—were also investigated by Davis and Parker (2014), but little practical skill or lead time were noted.

3. Operational Challenges

a. Spatial and temporal dimensions

As mentioned above, one of the primary challenges involving HSLC convection is its small spatial dimensions. This especially poses a problem during warning operations, given that reflectivity structures and rotational signatures can be poorly resolved or even missed, particularly at distances farther from radar (Lane and Moore 2006; Davis and Parker 2014). Additionally, rotation is often transient and rapidly evolving in HSLC convection, leading to little or no lead time prior to tornadogenesis (e.g., Cope 2004). Figure 5 shows the shallow nature and rapid enhancement of tornadic HSLC vortices close to the radar (Davis and Parker 2014). Farther from radar, the signal becomes more muddled, with only modest differences between tornadic and non-tornadic vortices on the mean (Davis and Parker 2014).

b. Frequency and timing

Though relatively common, HSLC environments produce severe hazards a disproportionately low percentage of the time (Dean et al. 2009), leading to high false alarm rates and low probability of detection for Storm Prediction Center tornado watches (Figure 6). Additionally, severe HSLC convection can occur at all times of the year and day, as illustrated by Figure 7 (Sherburn and Parker 2014). However, severe environments during the cool season and overnight are preferentially HSLC due to climatology (e.g., Vescio and Thompson 1998; Hanstrum et al. 2002; Guyer et al. 2006; Thompson et al. 2010; Kis and Straka 2010). This poses a unique challenge for both local and national forecasters: many HSLC outbreaks occur at non-traditional times when situational awareness is low, leading to relatively high normalized fatality totals (Ashley et al. 2008) and poor warning skill (Brotzge et al. 2011) during the cool season and overnight.

c. Limitations of forecast parameters

Traditional forecasting parameters, including composite parameters such as the Significant Tornado Parameter (STP; Thompson et al. 2003; Thompson et al. 2004; Thompson et al. 2012), Energy Helicity Index (EHI; e.g., Davies 1993), and Vorticity Generation Parameter (VGP; e.g., Rasmussen and Blanchard 1998), include CAPE as a primary constituent. Guyer and Dean (2010) found that the median value of STP (including CIN) within their low CAPE significant tornado dataset was 0.2, with 75% of these cases having a value of 0.6 or lower. High CAPE significant tornadoes, on the other hand, occurred within environments where the STP was at or above the conventional threshold of 1 (e.g., Thompson et al. 2012) 75% of the time, as shown by Figure 8. These findings were corroborated by Sherburn and Parker (2014), who found that the skill scores of traditional composite parameters (including STP, EHI, VGP, and others) at discriminating between significant severe and non-severe HSLC convection were maximized at values lower than conventionally recommended (e.g., on the SPC mesoanalysis page; Figure 9).

d. Predictability

Colloquially, models have been noted to perform poorly in HSLC events, particularly when it comes to representing the limited instability that is available. Coniglio (2012) showed that this was a concern in higher CAPE environments with Rapid Update Cycle (RUC) analyses and 1-h forecasts and the SPC’s mesoanalysis (Bothwell et al. 2002), as typical errors in CAPE when comparing observed VORTEX2 soundings to RUC and SPC mesoanalysis fields ranged from 100-300 J kg^{-1}. Perhaps a more negligible error in higher CAPE environments, these values represent a substantial fraction of our low CAPE threshold. Additionally, Sherburn and Parker (2014) noted in their development dataset that several significant severe reports occurred within environments characterized by 0 J kg^{-1} of diagnosed MUCAPE (via the SPC mesoanalysis). A rigorous examination of the predictability of HSLC events using operational models will be a subject of future work.

4. Operational Advancements

Considering the challenge of shallow convection, Thompson et al. (2007) introduced effective-layer parameters, including the effective bulk wind difference (commonly known as the effective shear). The effective shear is based upon storm depth rather than using fixed layers, ideally providing a representative shear layer regardless of the convection’s vertical extent. This parameter is now included in the STP rather than the 0-6 km shear vector magnitude. However, in vanishingly low CAPE situations, the effective shear will trend towards zero (e.g., Sherburn and Parker 2014a); as a result, effective shear must be used with caution when diagnosed or forecast CAPE is very low.

To address the limitations in traditional composite parameters, Sherburn and Parker (2014a) utilized a statistical approach to determine skillful combinations of individual environmental parameters within a dataset of HSLC convection across the Southeast and Mid-Atlantic. They found that a product of low- and mid-level lapse rates with various shear and wind constituents (termed the Severe Hazards in Environments with Reduced Buoyancy parameter, or "SHERB") resulted in higher skill in discriminating between HSLC significantly severe and non-severe convection than any existing composite parameter (Figure 9). However, the SHERB is subject to some operational caveats, namely its false alarm area in locations where convection is not expected (Sherburn and Parker 2014a).

5. Missing Pieces

a. Synoptic and mesoscale processes and evolution

Despite numerous case studies of HSLC severe events in conference proceedings and through collaborative research (i.e., the Collaborative Science, Technology, and Applied Research program, or CSTAR), little detail is known regarding the evolution of the environment preceding HSLC convection or the impacts of synoptic and mesoscale processes on the severity of that convection. However, several potential key attributes of the antecedent environment have been noted across these case studies.

Mid-level dry intrusions, which have been correlated with increased tornado risk in tropical cyclones (Curtis 2004; Edwards et al. 2010), were observed in case studies of severe HSLC convection by Lane and Moore (2006), Wasula et al. (2008), Evans (2010), and Gatzen et al. (2011), amongst others. These dry intrusions, often associated with a cold front aloft (e.g., Hobbs et al. 1990) or an upper-level jet streak, could contribute to in-situ production of buoyancy through potential instability, further enhancing lift in an already strongly-forced environment (Gatzen et al. 2011), or help to destabilize the low-levels through diminishing cloud cover (Wasula et al. 2008). Additionally, near-surface dry air can contribute to stronger cold pools, which may be necessary to balance higher values of environmental shear, subsequently maintaining updrafts (Rotunno et al. 1988; Evans 2010). While Sherburn (2013) studied the impacts of dry air on idealized HSLC convection, rigorous quantitative investigations of the impact of dry air on HSLC convection within more realistic cases including synoptic-scale forcing have yet to be undertaken. Furthermore, Barker (2006) identified "reflectivity tags" coincident with tornadogenesis in several events, arguing these were manifestations of interactions with upper-level jet streaks or gravity waves, neither of which has been directly examined with respect to its influence on HSLC convection.

Severe HSLC convection is typically associated with either a strong synoptic-scale cold front or system-scale outflow boundaries (e.g., McAvoy et al. 2000; Cope 2004; Lane and Moore 2006; Wasula et al. 2008; Clark 2009; Clark 2011). However, the relative impacts of these two forcing mechanisms on the subsequent evolution and severity of convection is unknown. Additionally, our knowledge regarding the role of shear vector orientation relative to either synoptic-scale or mesoscale boundaries—both in deep and shallow layers—remains limited, though this has been explored in higher-CAPE environments (e.g., Bluestein and Weisman 2000; French and Parker 2008; Dial et al. 2010). While McCaul and Weisman (2001) investigated the influence of differing shear profiles on convective evolution in HSLC environments, these simulations were initialized using warm bubbles, which would not represent the dynamics associated with either a cold front or system-generated outflow boundary.

The evolution of environments in the hours leading up to HSLC convection likely plays a role in their severity. Evans (2010) found that 12-h 500 hPa height falls tended to be greater for HSLC events with more severe reports. Further, the strong LLJs usually observed within HSLC environments imply rapid low-level moisture transport, warm air advection, and forcing for ascent (e.g., Latimer and Kula 2010). Some of these features (namely, low-level moisture transport via 850 hPa moisture convergence) were corroborated through recent work by Sherburn and Parker (2014b, this conference) using reanalysis fields. However, no work to the authors' knowledge has thoroughly examined the evolution of the pre-storm environment, particularly with observations.

b. Numerical weather prediction performance

Based upon observations (e.g., Davis and Parker 2014), typical scales of mesocyclones and mesovortices within HSLC environments are only marginally resolvable or unresolvable by even the highest resolution operational models. Recent work (e.g., Flournoy et al. 2014, this conference; King and Parker 2014, this conference) has indicated that at least 1-km grid spacing may be necessary to resolve the details of HSLC cellular convection and rotation therein, in addition to structural details of HSLC convective lines. Therefore, HSLC convection may be poorly represented by even convection-allowing models due to its compressed spatial scales. Additionally, as noted previously, HSLC environments tend to be rapidly evolving in advance of severe convection. The extent to which models accurately represent the antecedent environment and its evolution are unknown.

c. Convective-scale dynamics

Few numerical studies have investigated HSLC convection (e.g., McCaul and Weisman 1996; McCaul and Weisman 2001; Sherburn 2013). As a result, many fundamental questions regarding HSLC convection—particularly involving its development, maintenance and decay, strength, and tornado production—remain unanswered.

McCaul and Weisman (1996) simulated supercells within environments that were characterized by CAPE near 600 J kg^{-1}. Within these supercells, the dynamic component of the vertical perturbation pressure gradient acceleration was dominant in forcing updrafts with velocities maximized near 10 m s^{-1}. However, the degree to which dynamic forcing for ascent can overcome a lack in buoyancy has yet to be addressed, particularly in cases where convection transitions from a high-CAPE to low-CAPE environment [e.g., as discussed by Davis (2013)], is unknown.

Subsequent work by McCaul and Weisman (2001) revealed that the vertical distribution of CAPE within marginally unstable environments was critical, as convection in environments where CAPE was focused in the lowest 2.5 km was both more intense (in terms of updraft velocities) and longer-lived than other configurations. This was later corroborated by case studies and climatological studies (e.g., Lane 2008), which found that values of 0-3 km CAPE tend to be higher in HSLC significant tornado events. Whether or not there is an “ideal” vertical distribution of CAPE to promote severe HSLC convection has not been determined.

Sherburn (2013) ran several simulations of convection within HSLC environments, with grid spacings as low as 125 m. Using a cold block initialization, convection first developed linearly before evolving into clusters and cells. Multiple low-level vortices were observed, seeming to form via the mechanism described by Atkins and St. Laurent (2009). Over time, transient supercells with weakly to moderately rotating updrafts became the dominant mode, and some low-level vortices extended upward to the mid-levels (i.e., approximately 2 km), likely forming and strengthening as a result of the tilting and subsequent stretching of storm-generated baroclinic vorticity localized to outflow surges within these supercellular features. Given the different environmental characteristics of HSLC convection compared to the more typically studied high-CAPE, high-shear convection, it would be worth investigating the source of this vorticity (i.e., following the techniques of Dahl et al. 2014); in particular, does the barotropic component of vorticity (i.e., reorganization of ambient vorticity) play a non-negligible role in creating near-surface vortices within HSLC environments?

6. Ongoing and Future Research

As of August 2014, work has started on a new CSTAR project focused entirely on improving the understanding and forecasting of HSLC convection. In particular, the project will focus on five key areas: a) process studies utilizing idealized models, including the development of a radar emulator; b) environmental evolution and pre-conditioning; c) operational numerical weather prediction resolution and sensitivities; d) predictability using ensembles and dynamical-statistical downscaling; and e) operational assessment of forecasting parameters.

a. Process studies utilizing idealized models

- Sensitivity tests and more sophisticated process studies will be undertaken using the Bryan Cloud Model (CM1; Bryan and Fritsch 2002) to calculate vortex budgets within HSLC near-surface mesovortices and tornado-like vortices and quantitatively examine the relative magnitudes of dynamic and buoyant vertical perturbation pressure gradient accelerations in a variety of environments.
- Radar emulator (e.g., as in May et al. 2007) studies will allow for a 3D analysis of idealized HSLC convection at a minute-by-minute time step immediately preceding vortexgenesis, potentially allowing for the identification of radar reflectivity or velocity precursors that had been previously unobserved.

b. Environmental evolution and pre-conditioning

- Ongoing work seeks to quantify the impact of rapid environmental evolution ahead of severe HSLC convective events through idealized and real case simulations, in addition to supplemental observations.

c. Operational numerical weather prediction resolution and sensitivities

- Future work seeks to determine the optimal numerical weather prediction configuration that will allow for resolution of relevant features while remaining operationally feasible.

d. Predictability using ensembles and dynamical-statistical downscaling

- Future work will seek to address the observed deficiencies in operational models through statistically-driven bias correction while evaluating the performance of ensemble forecasting systems and their ability to increase forecaster confidence regarding the potentially severity of HSLC convection.

e. Operational assessment of forecasting parameters

- An ongoing collaborative effort between researchers at North Carolina State University and forecasters at regional WFOs seeks to determine the operational utility of the SHERB parameter (Sherburn and Parker 2014) and how it can be improved upon in the future while investigating the possibility that a new combination of variables will lead to a more skillful composite parameter.

7. Conclusions

High-shear, low-CAPE (HSLC) environments remain a considerable challenge for operational forecasters at the Storm Prediction Center and local weather forecast offices, particularly across the Mid-Atlantic, Ohio Valley, and Southeast. Many gaps in our knowledge of HSLC events remain, ranging from predictability to mesoscale evolution in the hours preceding an HSLC event to the dynamics associated with HSLC tornadogenesis. Ongoing and future work seeks to address remaining questions associated with these environments through numerical model simulations, increased observations of the environment in proximity to severe HSLC convection, and collaborative investigation between the National Weather Service and educational institutions.

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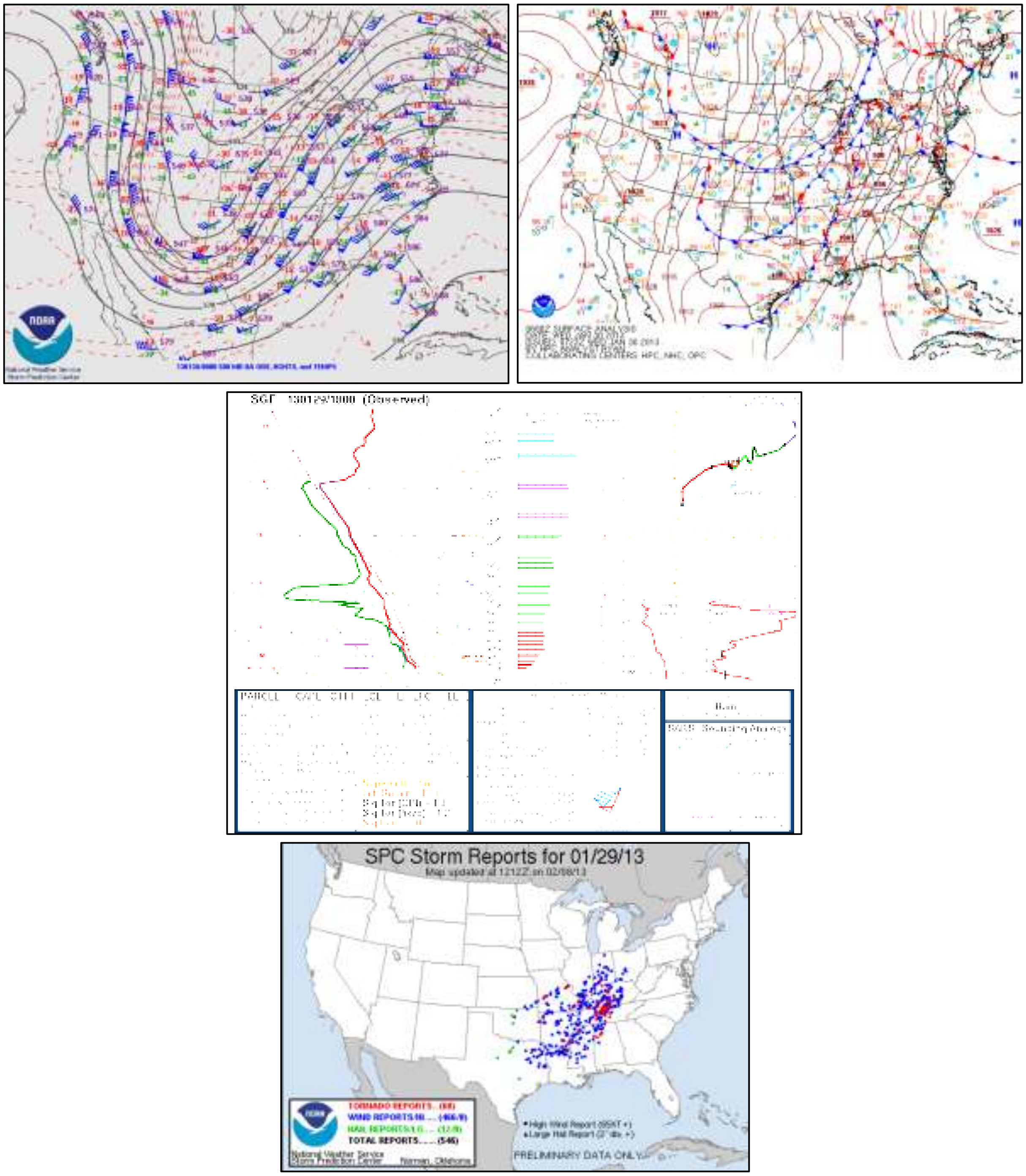

Figure 1. Upper-level and surface maps with a representative sounding from a severe HSLC convective event on January 29, 2013:
(top left, credit Storm Prediction Center) 500 hPa observations, wind barbs (kt), and objectively analyzed geopotential height contours (dam) from 0000 UTC 30 January 2013
(top right, credit Weather Prediction Center) surface observations and subjectively analyzed surface pressure systems, surface fronts, and mean sea level pressure (hPa) from 0600 UTC 30 January 2013
(middle, credit Storm Prediction Center) observed Springfield, MO (SGF) sounding from 1800 UTC 29 January 2013
(bottom, credit Storm Prediction Center) preliminary storm reports for 29 January 2013

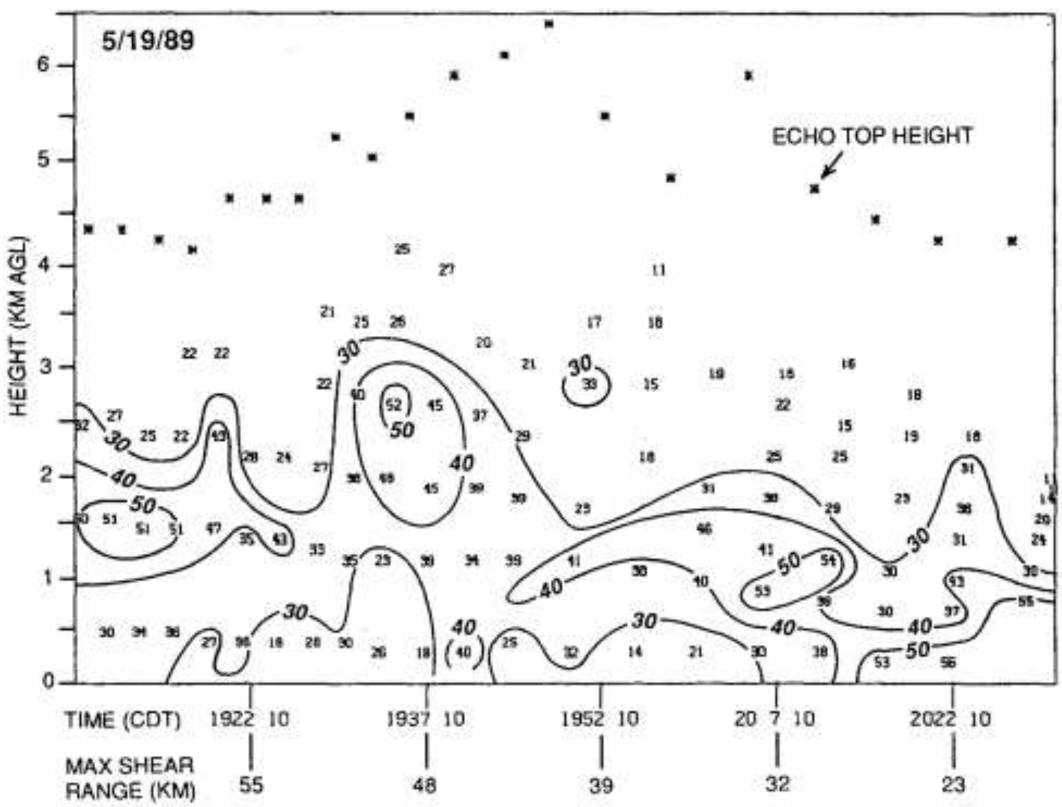

FIG. 11. Time–height plot of maximum radial velocity shear between adjacent-beam range gates. Shears have been normalized to a range of 25 km, units are 10^{-3} s^{-1}. The range normalization was accomplished by multiplying the raw shear values calculated from the basic gate data by the quantity [gate range (km)/25]. Heights are in kilometers AGL; the elevation of the radar site is 230 m. Echo-top heights are indicated by asterisks.

Figure 2. From Kennedy et al. (1993; their Fig. 11), vertical cross section through a mini-supercell of maximum radial velocity shear (10^{-3} s^{-1}). Additional information is provided in the caption.

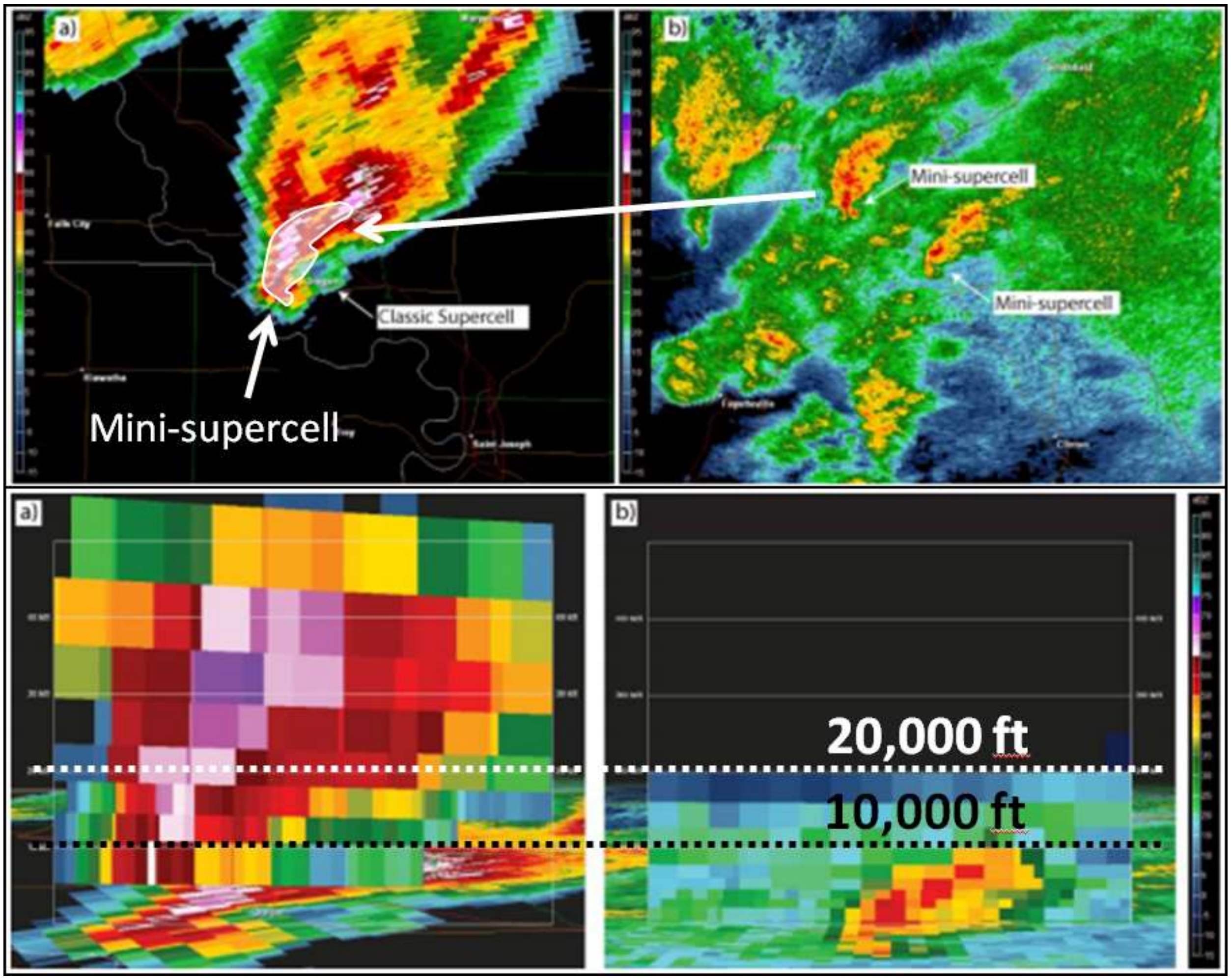

Figure 3. Four-panel plot showing a horizontal (top) and vertical (bottom) comparison between a classic high-CAPE supercell (left) and an HSLC mini-supercell (right). Figure from Davis (2013), with some annotations added by authors.

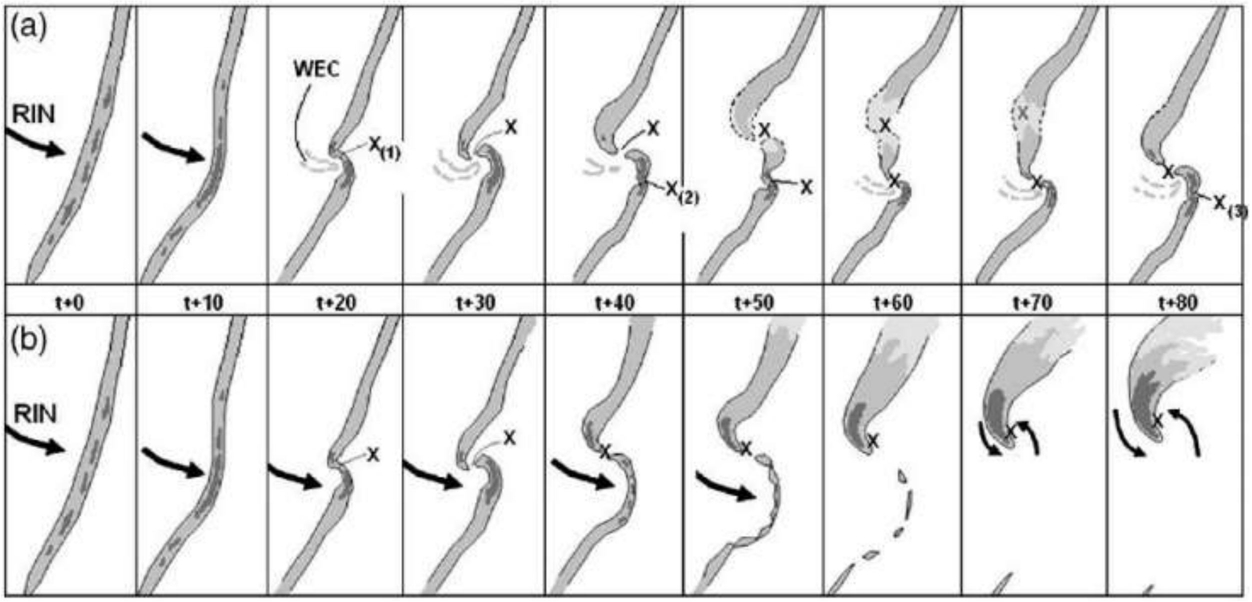

Figure 4. From Clark (2011), conceptual models of two different evolutions of the broken-S signature: a rear inflow notch (RIN) and weak echo channel (WEC) are noted, with evolution a) corresponding to a cyclic broken-S process and b) corresponding to the development of a supercellular-like feature as the southern segment dissipates.

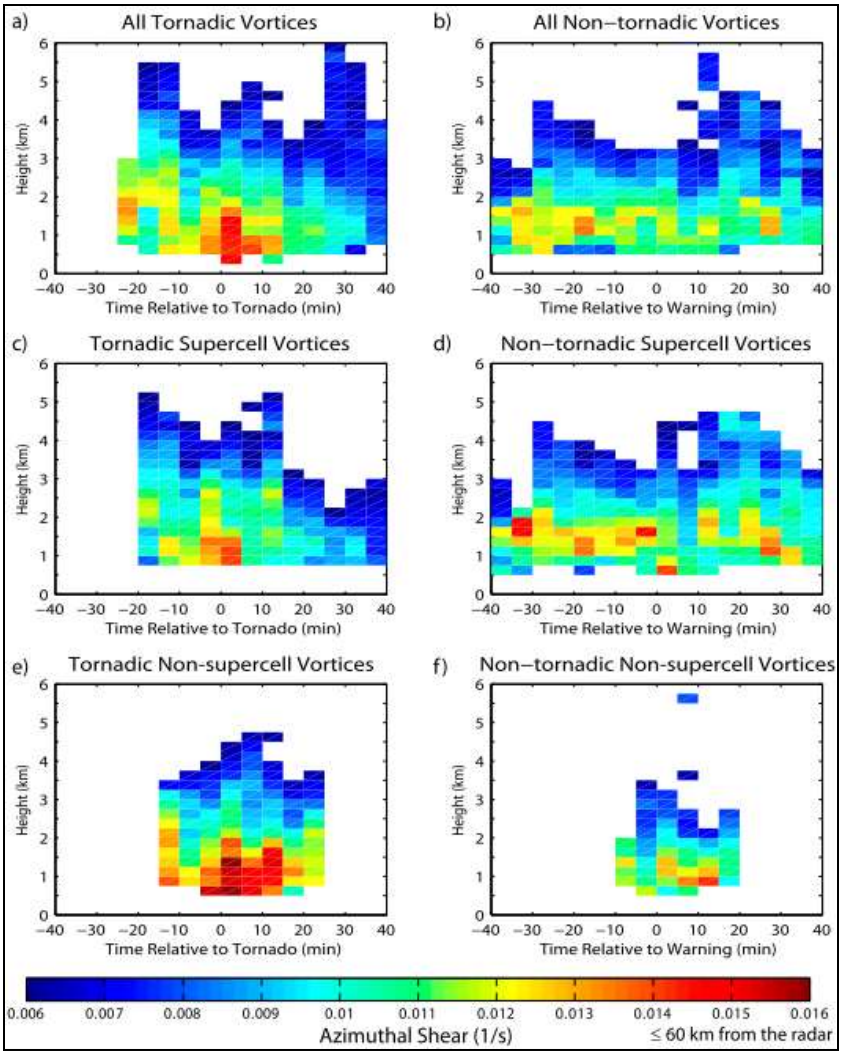

Figure 5. From Davis and Parker (2014), a) time-height plot of azimuthal shear (s^{-1}) for all tornadic vortices occurring within 60 km of the radar, with 0 min on the x-axis corresponding to the time of tornado occurrence; b) as in a), but for non-tornadic vortices; here, 0 min on the x-axis corresponds to the time that a tornado warning was issued; c) as in a), but only for tornadoes associated with supercells; d) as in b), but only for non-tornadic vortices associated with supercells; e) as in c), but for non-supercell tornadic vortices; f) as in d), but for non-supercell, non-tornadic vortices

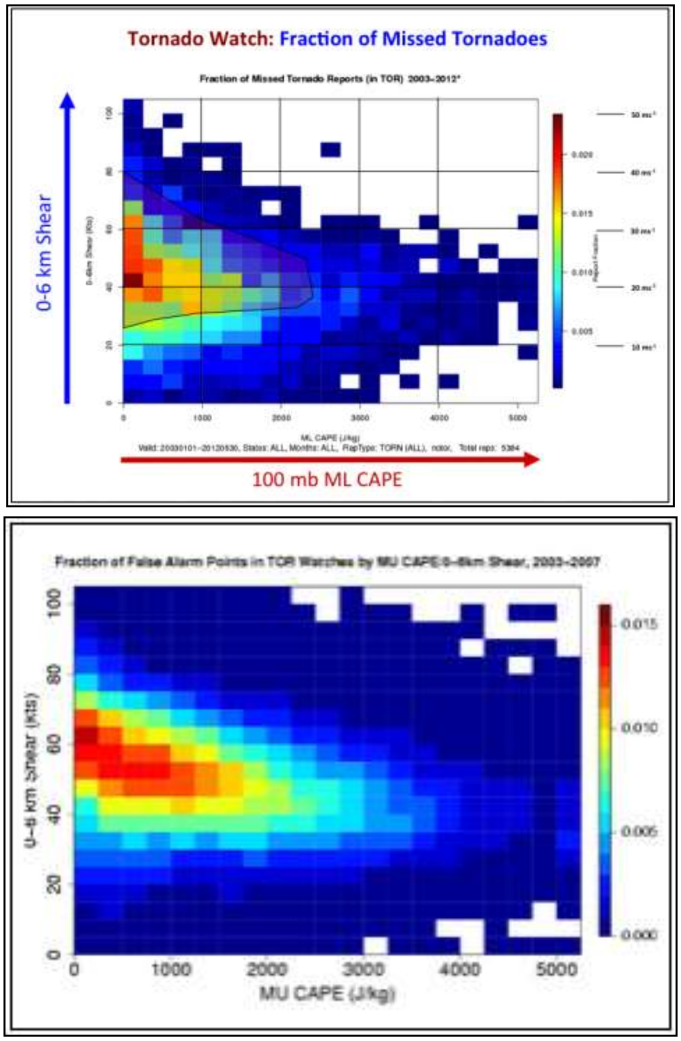

Figure 6. *(top)* From Dean and Schneider (2012), the fraction of all tornado reports missed by a tornado watch within a given MLCAPE and 0-6 km shear regime; *(bottom)* from Dean and Schneider (2008), the fraction of all false alarm points within tornado watches occurring within a given MUCAPE and 0-6 km shear regime

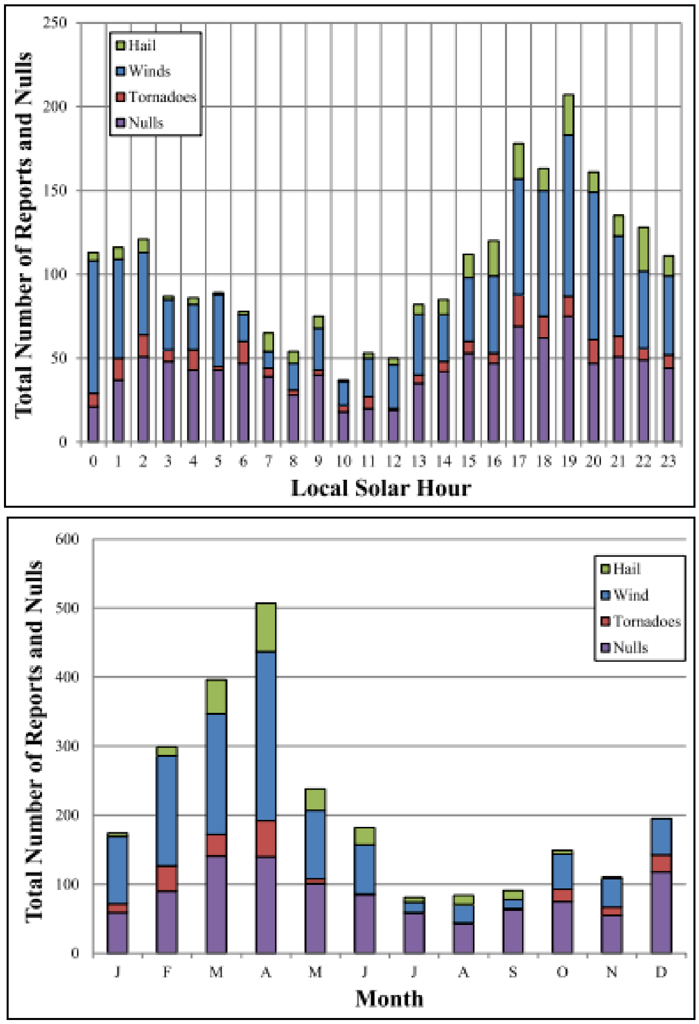

Figure 7. From Sherburn and Parker (2014a), the diurnal *(top)* and annual *(bottom)* cycles of all HSLC (in this case, defined as SBCAPE ≤ 500 J kg^{-1}, MUCAPE ≤ 1000 J kg^{-1}, and 0-6 km bulk wind difference ≥ 18 m s^{-1}) significant severe reports and nulls (i.e., unverified warnings) between 2006 and 2011

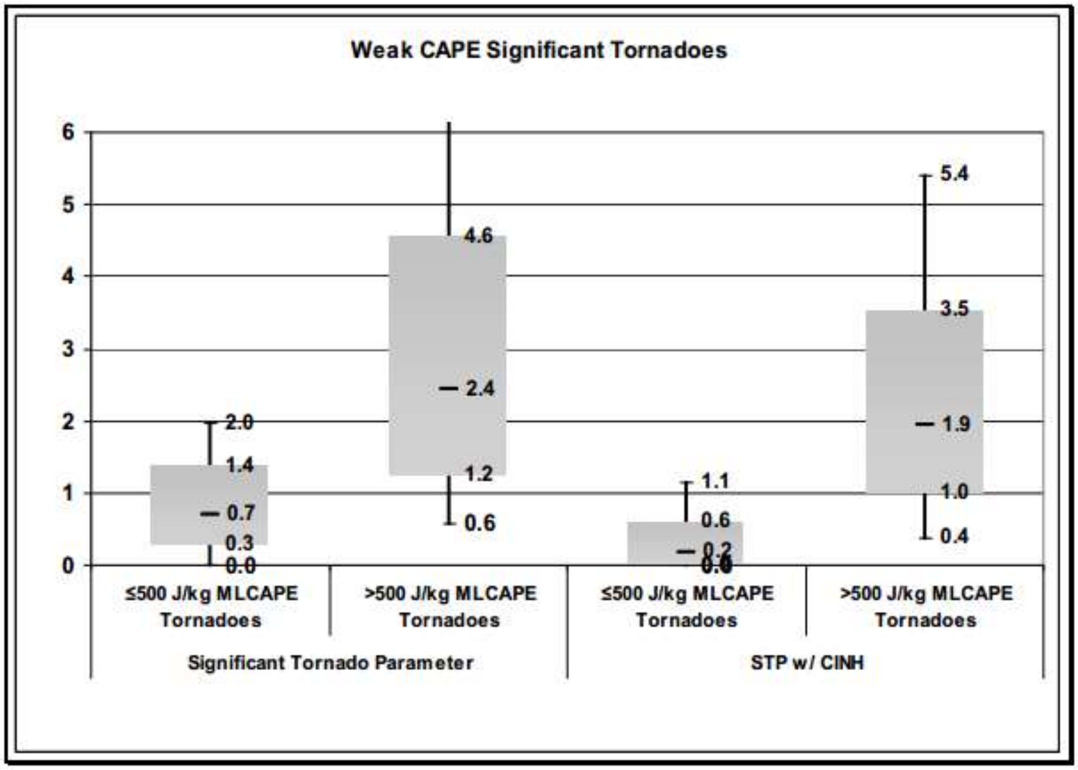

Figure 8. From Guyer and Dean (2010), distributions of the Significant Tornado Parameter (both including CIN, on the right, and not including CIN) for all significant tornadoes occurring within environments characterized by MLCAPE ≤ 500 J kg^{-1} (left of each parameter) and MLCAPE ≥ 500 J kg^{-1} (right of each parameter) between 2003 and 2009

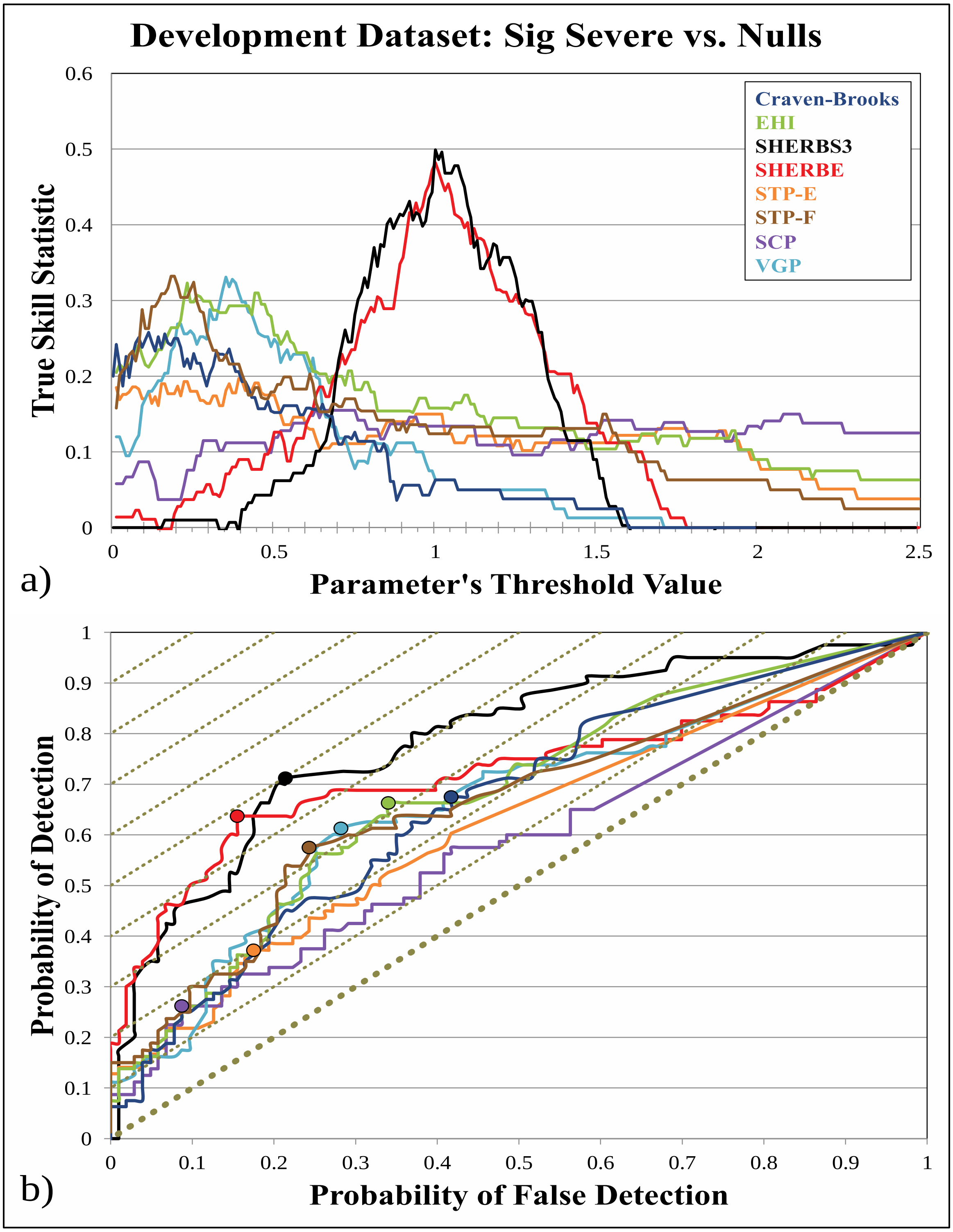

Figure 9. From Sherburn and Parker (2014a), a) true skill statistic (TSS) at discriminating between HSLC significant severe reports and nulls for the given composite parameters at varying parameter threshold values; b) corresponding ROC curves, with the dotted diagonal lines showing lines of constant TSS, increasing towards the top left