1.1 ENVIRONMENTS OF DERECHO-PRODUCING AND NON-DERECHO-PRODUCING MESOSCALE CONVECTIVE SYSTEMS IN THE UNITED STATES

Andrew R. Wade*
University of Oklahoma, Cooperative Institute for Severe and High-Impact Weather Research and Operations (CIWRO), Norman, OK

Brian J. Squitieri
NOAA/NWS/NCEP Storm Prediction Center, Norman, OK

Israel L. Jirak
NOAA/NWS/NCEP Storm Prediction Center, Norman, OK

Lydia A. Burroughs
University of Oklahoma, Norman, OK

Taylor R. King
University of Oklahoma, Norman, OK

Parker R. Alvstad
University of Oklahoma, Norman, OK

1. INTRODUCTION

Derechos (e.g., Johns and Hirt 1987, Coniglio and Stensrud 2004, Corfidi et al. 2016, Squitieri et al. 2025a, hereafter S25a) are widespread severe windstorms, characterized by families of destructive downbursts containing significant severe gusts, associated with extratropical, cold pool-driven mesoscale convective systems (MCSs). Derechos have disproportionate societal impacts (Ashley and Mote 2005) and can be challenging to forecast, especially in weakly forced synoptic settings (Ribeiro et al. 2024a, b).

The literature on derecho environments remains inconclusive on two key points. The first is how the environments of derechos meeting very high criteria for severe wind production, as in S25a, differ from environments of less extreme MCSs. The second is which layers of bulk shear are most useful in forecasting MCS severity and derecho potential.

Corresponding author: Andrew R. Wade, andrew.wade@noaa.gov

The latter question regarding vertical shear profiles is in its fourth decade of debate following Rotunno et al. (1988, hereafter RKW). RKW demonstrated how the interacting circulations associated with environmental shear ahead of the cold pool and baroclinity near the leading edge of the cold pool govern updraft tilt, with an optimal cold pool–shear balance promoting vertical updrafts in the convective line. Weisman and Rotunno (2004) revisited this idea and reinforced it with simulations in which horizontally periodic squall lines were most intense with shear confined to the 0–5-km layer above ground level (AGL). However, Lafore and Moncrieff (1989), Moncrieff and Liu (1999), and Coniglio et al. (2006) explored other effects of shear above the height of the cold pool, noting a deep overturning circulation at the convective line and greater vertical displacement of inflow parcels with larger upper-level shear.

Much of the evidence for a close relationship between low-level shear and MCS intensity is derived from idealized simulations and analytical models. Observational studies have more often emphasized shear over deeper layers. Evans and Doswell (2001) found that some derechos occurred with smaller low-level shear than RKW would predict. In observed soundings analyzed by Cohen et al. (2007), layers extending up to 10 km AGL were most skillful at discriminating between weak, severe, and derecho-producing MCSs. Coniglio et al. (2012) showed that the intensity of the 8 May 2009 "Super Derecho" may have been modulated by deep shear, with modest and variable low-level line-normal shear during much of the event. More recently, Mauri and Gallus (2021) found somewhat greater differences in deep-layer shear than low-level shear among high-intensity, low-intensity, and nonsevere wind-producing nocturnal MCSs. Gallus and Duhachek (2022) followed by extending the study to diurnal MCSs, and found that deep-layer shear distinguished among the three categories better than low-level shear.

The present study joins this debate with a unique dataset of proximity environments of intense derechos and moderately severe non-derechos.

2. DATA AND METHODS

2.1 *Derechos and non-derechos*

From 2003 through 2024 inclusive, the stringent S25a criteria applied to the Wade et al. (2023, hereafter W23) MCS dataset with detailed manual quality control identified 74 derechos. Of these, two were omitted from this study as cool-season outlier cases with unusually strong forcing. Two more were excluded as unusually difficult to track in any representative way across multiple MCS segments and "handoffs." One more was dropped due to limited radar coverage over the Rocky Mountains and parts of the adjacent High Plains. This yielded 69 derechos. In the Wade et al. (2025) classification of synoptic patterns, 49 of these fall into the ridge/northwest flow and zonal flow patterns, and 20 fall into the warm-season trough pattern. Derechos in the latter pattern often tend toward serial characteristics, i.e., longer convective lines containing multiple bowing segments and/or embedded supercells. Given the morphological differences and the greater difficulty of forecasting derechos in the weakly forced patterns (Ribeiro et al. 2024a, b), this study for now excludes the 20 derechos downstream of troughs, and focuses on the 49 in northwest and zonal flow.

Finding non-derechos is somewhat more arbitrary. If this set consisted of marginally organized multicells with at most a few wind reports, many variables would likely appear artificially skillful in identifying derecho environments compared to these. In the other direction, long-lived and significantly severe MCS wind events falling only one or two reports or measurements short of S25a derecho criteria may not physically differ from the derechos at all, given the chance and inconsistencies involved in wind reporting. The non-derecho set avoids both of these extremes by targeting persistent, moderately severe MCSs. The W23 dataset was filtered for MCSs occurring from May to September, producing at least 20 severe wind reports of any kind and 0–4 significant severe wind reports, and having a wind swath length of at least 400 km. (A few MCSs were retained despite reaching 20 reports via contributions from neighboring cells or segments algorithmically attached to the main MCS.) So far, 42 such non-derechos have been evaluated, manually tracked, and added to the dataset.

2.2 *Manual tracking of MCSs*

W23's algorithmic tracking contains some timestep-to-timestep inconsistencies, and its motion estimate relies on centroids rather than leading-edge features like bow apices. For detailed analysis, manual recording of these features' locations at each hour of MCS life (Fig. 1) is preferable. Relatively disorganized subsevere periods in early or late life were not tracked. Tracking began with the work of Burroughs et al. (2025), and the present study expands their sample and analysis. For variables requiring a storm motion, such as storm-relative winds or layer-lifting CAPE, the motion at each hour was defined from the previous hour to the subsequent hour, except at the first and last hours, when hourly motions were used.

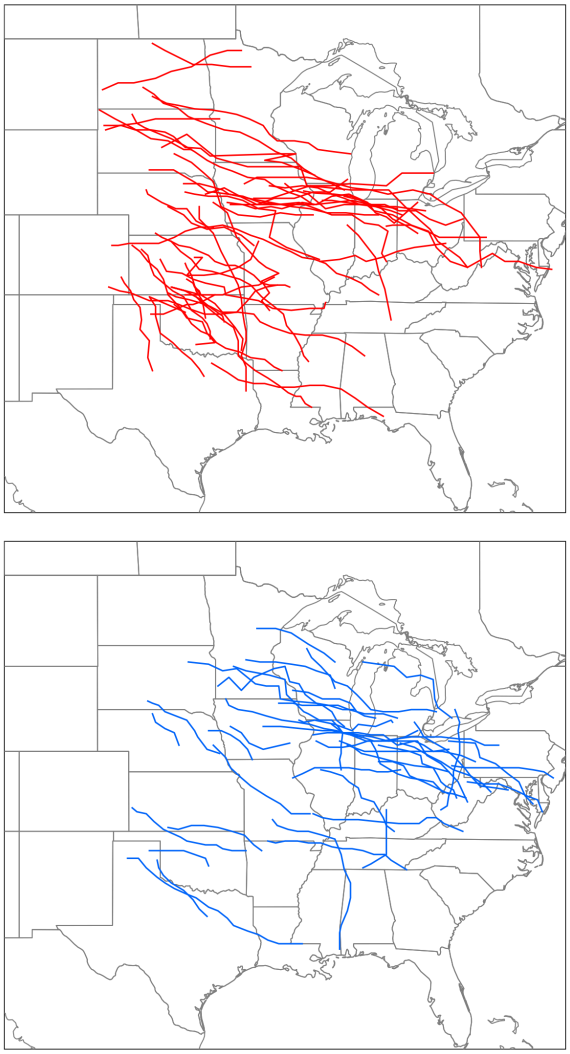

Fig. 1. Manual tracks of (top) 49 derecho-producing MCSs in the northwest and zonal flow patterns, and (bottom) 42 non-derecho-producing MCSs.

2.3 ***Proximity environmental data***

The NOAA/National Weather Service Storm Prediction Center (SPC) maintains a local archive (2003–present) of Rapid Update Cycle (RUC)/Rapid Refresh (RAP) model analyses, as well as the surface objective analysis (SFCOA; Bothwell et al. 2002) and derived fields based on these analyses. SFCOA's hourly output and 40-km grid spacing can target proximity environments (e.g., Potvin et al. 2010) more precisely than purely observational data. For each manually identified MCS location, a vertical profile valid 1 h prior to MCS arrival was created using SFCOA as the lowest level and RUC/RAP pressure-level data (on 25-hPa intervals in most cases) above. SHARPpy (Blumberg et al. 2017) was used to calculate all parameters. For the vertical integrations in the layer-lifting framework discussed in section 3.4, profiles were interpolated to 50-m vertical levels.

Each MCS's lifetime was segmented into thirds, representing early, middle, and late stages. Some hours were classified as belonging to two stages for cases with a number of hours not divisible by 3. In the following distributions of parameters by stage, a single value represents each MCS, averaged across all hours within that stage. This prevents overrepresentation of longer-lived MCSs by including all hours individually. The composite environments use a similar approach.

We are particularly interested in parameters that discriminate between derechos and non-derechos early in MCS life. Many derechos reach peak significant severe wind production in the first few hours (Squitieri et al. 2025b), and these early-life environments determine the initial cold pool and convective line structures that will interact with later inflow environments. All three stages are nevertheless shown since temporal trends in certain variables may add some information.

For each variable shown in sections 3.1–3.4, statistical significance *t*-tests were applied to the derecho and non-derecho distributions in each life stage. *p*-values of 0.05 or below are noted above their distributions. We emphasize that this does not imply practical significance. Some results are very unlikely to be of any operational utility despite $p < 0.05$. Values are provided for comparison among the variables. Tests were not applied across different life stages, which may be a topic for future work.

3. RESULTS

3.1 *Thermodynamic parameters*

Differences in mixed-layer convective available potential energy (MLCAPE; Fig. 2) and most unstable CAPE (MUCAPE; Fig. 3) between derecho and non-derecho environments are fairly small. Derechos are more likely than non-derechos to occur with substantial mixed-layer convective inhibition (MLCIN; Fig. 4). This is at first glance a physically counterintuitive result and is discussed further in section 4.

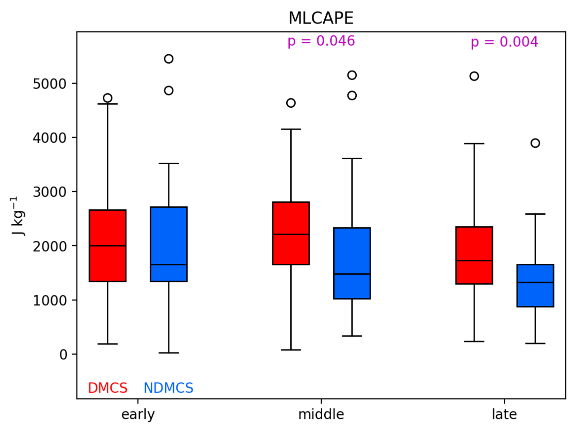

Fig. 2. Boxplots of MLCAPE in derecho (red) and non-derecho (blue) proximity environments by life stages. *p*-values ≤ 0.05 are noted above their respective pairs of distributions.

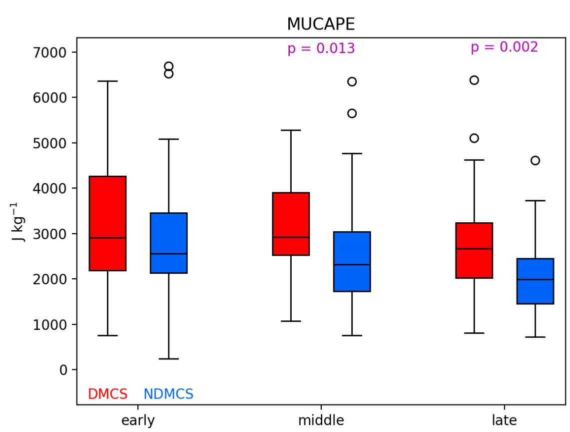

Fig. 3. As in Fig. 2, but for MUCAPE.

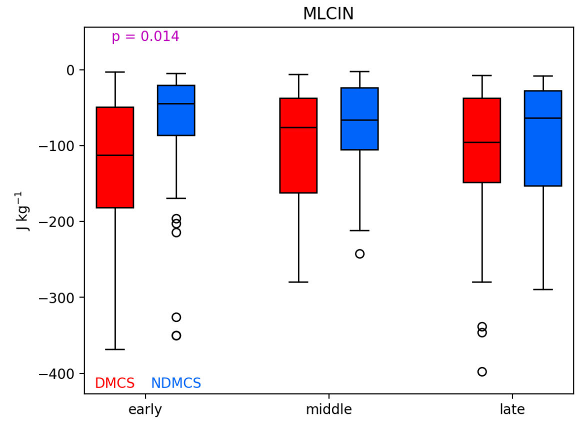

Fig. 4. As in Figs. 2–3, but for MLCIN.

Downdraft CAPE (DCAPE; Fig. 5) exhibits a statistically significant, but practically rather small, difference between derechos and non-derechos in early life. Subjectively, DCAPE is high across both samples and all life stages, with most values exceeding 1000 J kg^{-1}.

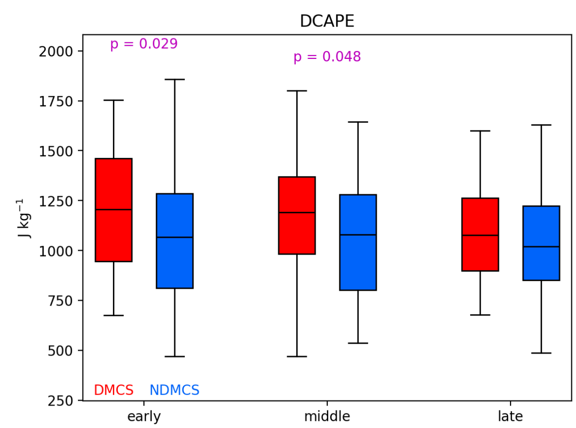

Fig. 5. As in Figs. 2–4, but for DCAPE.

3.2 *Kinematic parameters*

Bulk shear layers of 0–1, 0–3, 0–6, and 1–9 km AGL are evaluated in Figs. 6–9. The 0–3-km and 0–6-km layers appear often in severe storms studies, including investigations of RKW and other MCS-shear interactions. The less common 1–9-km layer proved to be the most skillful for distinguishing between smaller samples of derechos and non-derechos in the earlier version of this work (Burroughs et al. 2025). Here, 0–1-km and 0–3-km shear do not significantly differ between derechos and non-derechos. Shear over the deeper 0–6-km and 1–9-km layers, however, differs to an extent that is both statistically significant and practically relevant.

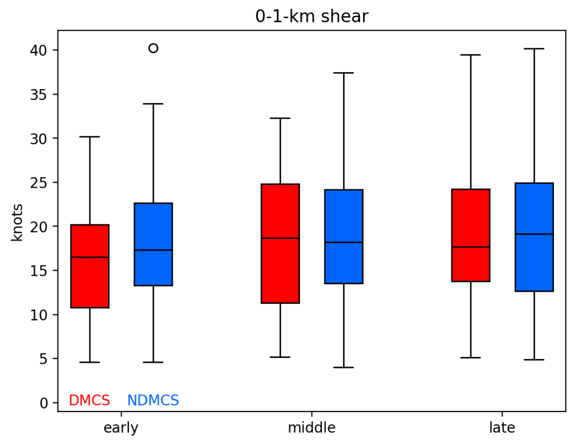

Fig. 6. As in Figs. 2–5, but for 0–1-km AGL bulk shear.

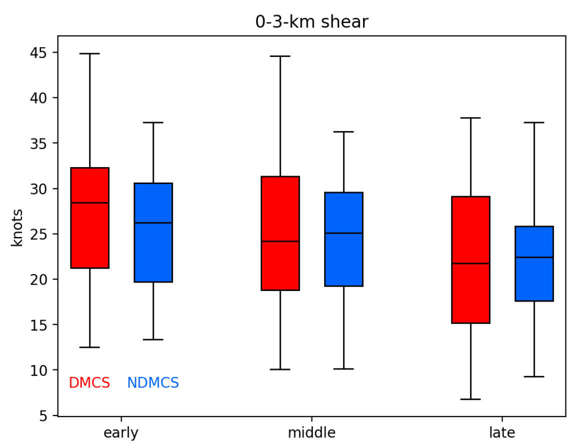

Fig. 7. As in Figs. 2–6, but for 0–3-km AGL bulk shear.

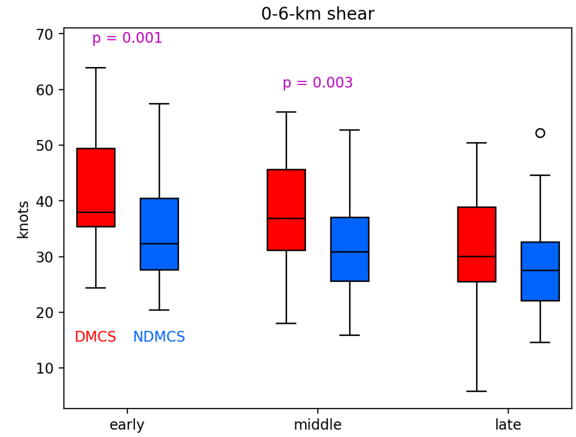

Fig. 8. As in Figs. 2–7, but for 0–6-km AGL bulk shear.

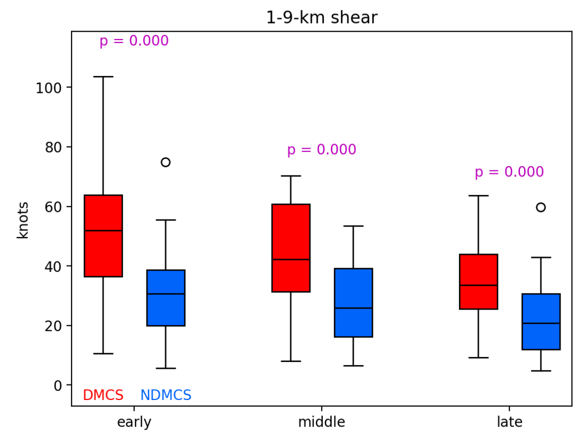

Fig. 9. As in Figs. 2–8, but for 1–9-km AGL bulk shear.

Evans and Doswell (2001) noted that derecho environments were characterized by large 0–2-km AGL MCS-relative winds. This relationship also holds in the current dataset (Fig. 10) using the manually calculated MCS motions. Most of this difference is in the zonal component; the meridional component does not differ at a statistically significant level.

3.3 *Combined parameters*

The derecho composite parameter arose from the work of Evans and Doswell (2001) and is available in SPC's mesoscale analysis. It combines MUCAPE, DCAPE, 0–6-km bulk

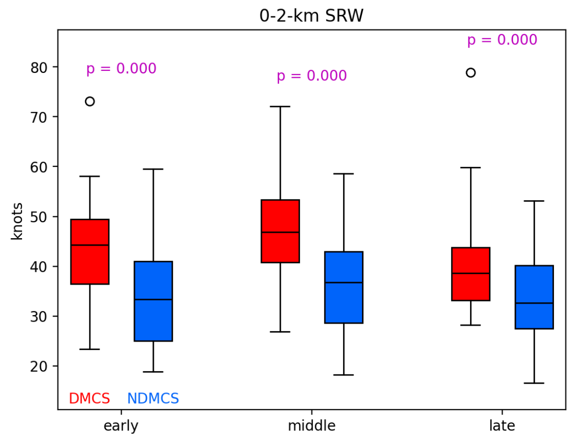

Fig. 10. As in Figs. 2–9, but for 0–2-km AGL storm-relative wind.

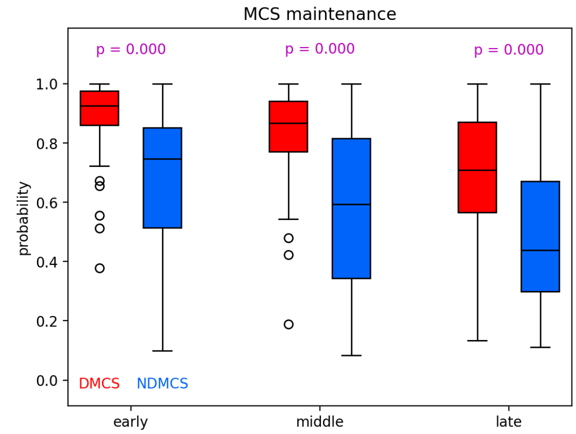

Fig. 12. As in Figs. 2–11, but for MMP.

shear, and 0–6-km mean wind speed. It may discriminate between derechos and non-derechos in middle and late life in this dataset (Fig. 11), but the relationship is not especially strong, perhaps owing in part to differences in derecho definitions and criteria compared to the present study. Distributions of the MCS maintenance probability (MMP; Coniglio et al. 2007) exhibit greater differences, especially earlier in life (Fig. 12). The SHARPpy formulation of MMP combines MUCAPE, 3–8-km lapse rate, 3–12-km mean wind speed, and the maximum bulk shear over varying deep layers.

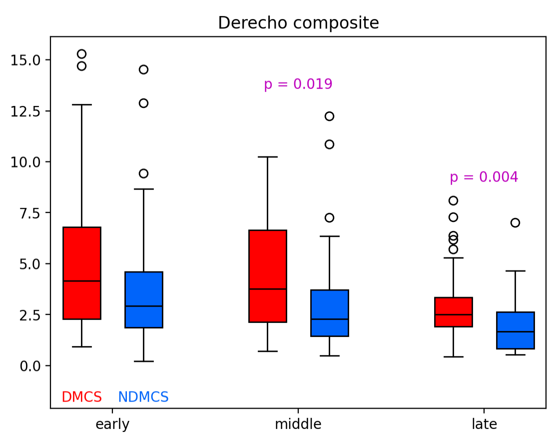

Fig. 11. As in Figs. 2–10, but for the derecho composite parameter.

3.4 ***Layer-lifting variables***

Alfaro (2017) proposed a “layer-lifting model of convection” for evaluating MCS environments, given the nature of deep, slab-like ascent forced by the advancing cold pools of mature MCSs. Three variables in this framework were tested on the present dataset: the shear-layer inflow fraction (Alfaro 2017 Eq. 6), integrated CAPE (Alfaro 2017 Eq. 7), and layer-lifting CAPE (Alfaro 2017 Eq. 8.). The inflow fraction (Fig. 13) was calculated here with the upper bound of the numerator integral at 3 km AGL, as best discriminated between mature and dissipating MCSs in Alfaro and Coniglio (2018). While that temporal trend is evident in this dataset, it does not distinguish derechos from non-derechos. Integrated CAPE (Fig. 14) and layer-lifting CAPE (Fig. 15) also tend to be smallest approaching MCS demise, when statistically significant differences appear, but the distributions still overlap considerably.

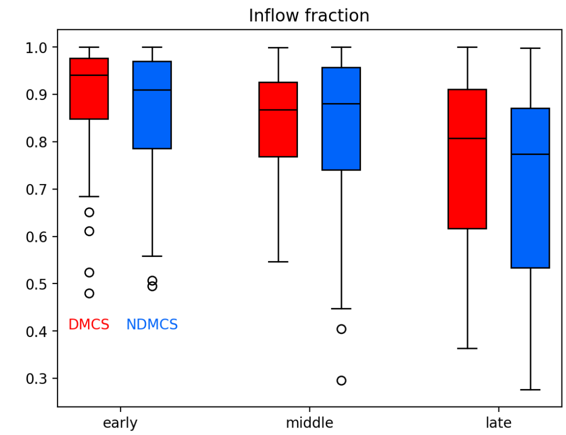

Fig. 13. As in Figs. 2–12, but for the 0–3-km AGL inflow fraction.

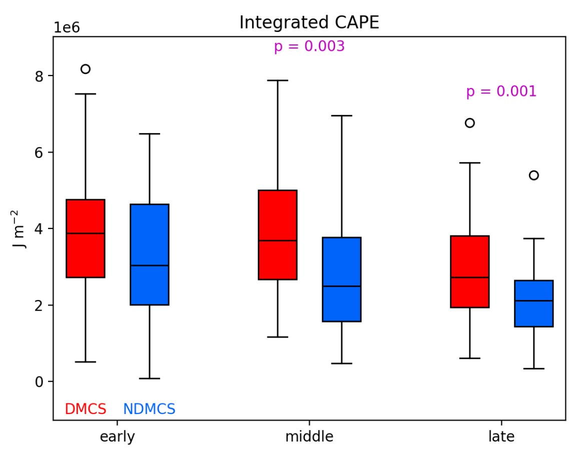

Fig. 14. As in Figs. 2–13, but for integrated CAPE.

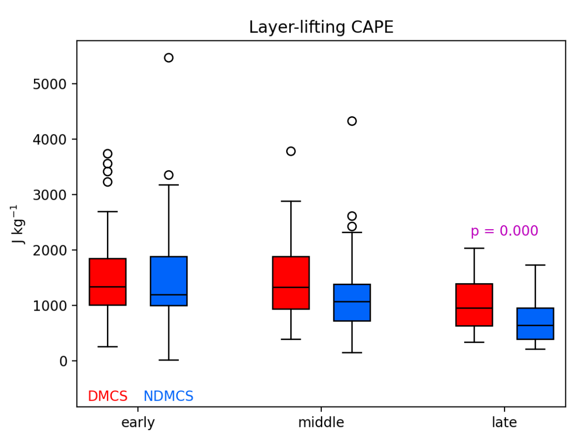

Fig. 15. As in Figs. 2–14, but for layer-lifting CAPE.

3.5 *Composite profiles*

Mean hodographs (Fig. 16) associated with derechos and non-derechos both curve clockwise in the lowest 1 km, but the mean derecho hodograph is somewhat more sharply kinked around 500 m, while the non-derecho hodograph curves more gently. Derecho hodographs tend to be longer aloft, from about 3 km all the way to the tropopause.

Mean thermodynamic profiles for both derechos and non-derechos were created, but are not shown here because they contain high MUCIN unrepresentative of their constituent profiles. In fact, in a simple idealized configuration of Cloud Model 1 (Bryan and Fritsch 2002), the mean derecho profile did not permit deep convection at all. (The non-derecho profile was not tried.) This misleading result probably arises from averaging widely varying low-level stability profiles. Some individual derecho environments are classically surface-based with well-mixed boundary layers, but many, as seen in the MLCIN distributions, are not. These range from shallow nocturnal inversions to deep stable layers north of synoptic boundaries. While each of these profiles individually may contain a modestly inhibited parcel at some pronounced maximum of equivalent potential temperature, their mean consists of broadly warm and stable low levels with no such supportive maximum. Alternative compositing techniques will have to be pursued, perhaps normalizing elevated profiles to the height of the most unstable parcel. Low levels of the composite hodographs above should be viewed cautiously in light of this result, since they may also reflect the unrepresentative combination of many stability profiles.

4. CONCLUSIONS

By a wide margin, the greatest differences in any single environmental variable between S25a derechos and non-derechos are in deep layers (0–6-km and especially 1–9-km) of bulk shear. The 0–3-km layer sometimes favored for RKW-like assessments of system balance

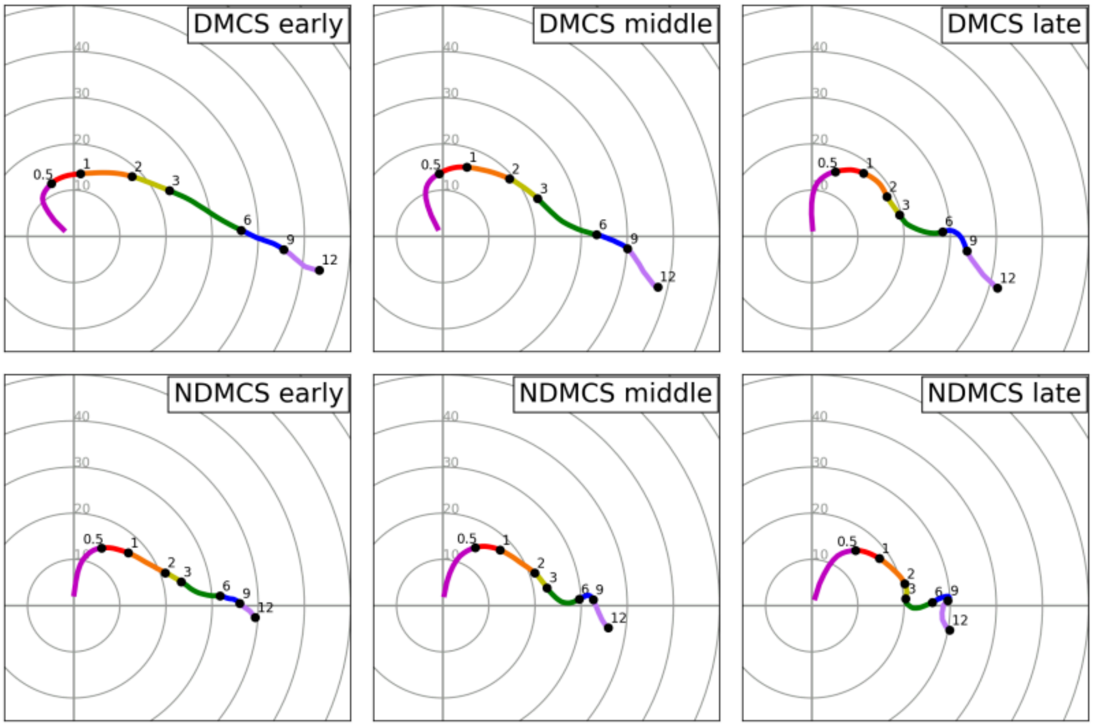

Fig. 16. Mean hodographs (knots) for (top, left to right) early, middle and late stages of derecho-producing MCSs, and (bottom, left to right) early, middle, and late stages of non-derecho-producing MCSs. Markers on hodographs are in km AGL and segments are colored by altitude.

cannot distinguish at all between derecho-producing MCSs and moderately severe ones. Low-level storm-relative inflow also tends to be greater for derechos than for non-derechos. Mean ground-relative hodographs in early and middle life indicate that this is not purely a function of system forward speed: derechos' 0–2-km environmental winds are more backed. However, the dependence on observed system motion poses an obstacle to using storm-relative inflow in forecasting.

Most point thermodynamic variables are of little or no use for distinguishing between derechos and severe non-derechos. Even DCAPE exhibits a practically small, though statistically significant, difference. Regarding the curiously large MLCIN associated with derechos compared to non-derechos, it seems physically unlikely that low-level stability directly favors widespread significant severe wind near the surface, all else being equal. Rather, this probably indicates the most common synoptic location of supportive deep-layer shear: poleward of a surface boundary. This is directly compatible with the conceptual model of Johns (1993, his Fig. 3) and the synoptic composites of Wade et al. (2025, their Figs. 5, 7, and 8). Speculatively, it may be that the combination of ingredients just to the cool side of a surface boundary—large deep-layer shear, moderate low-level stability, and perhaps focused ascent associated with warm advection (e.g., Jirak and Cotton 2007, Wade et al. 2025)—is more favorable for derecho production than smaller shear, minimal MLCIN, and nebulous forcing farther equatorward.

Among parameters incorporating both kinematic and thermodynamic fields, MMP discriminates surprisingly well between derechos and non-derechos. While the observed decrease in MMP from early to late life also reflects its intended purpose, its “off-label” utility for identifying derecho environments likely lies in its best-layer shear formulation. In SHARPpy, MMP’s shear term uses the maximum bulk shear in any layer with a bottom from 0–1 km and a top from 6–10 km. This encompasses the 1–9-km layer suggested by Burroughs et al. (2025) and reinforced here with the larger sample, while adding flexibility for varying tropopause depths, equilibrium levels, and/or buoyancy distributions. We plan to evaluate variations of this term separately in future work.

REFERENCES

Alfaro, D. A., 2017: Low-tropospheric shear in the structure of squall lines: Impacts on latent heating under layer-lifting ascent. *J. Atmos. Sci.*, **74**, 229–248, https://doi.org/10.1175/JAS-D-16-0168.1.

Alfaro, D. A., and M. C. Coniglio, 2018: Discrimination of mature and dissipating severe-wind-producing MCSs with layer-lifting indices. *Wea. Forecasting*, **33**, 3–21, https://doi.org/10.1175/WAF-D-17-0088.1.

Ashley, W. S., and T. L. Mote, 2005: Derecho hazards in the United States. *Bull. Amer. Meteor. Soc.*, **86**, 1577–1592, https://doi.org/10.1175/BAMS-86-11-1577.

Blumberg, W. G., K. T. Halbert, T. A. Supinie, P. T. Marsh, R. L. Thompson, and J. A. Hart, 2017: SHARPpy: an open source sounding analysis toolkit for the atmospheric sciences." *Bull. Amer. Meteor. Soc.*, **98**, 1625–1636, https://doi.org/10.1175/BAMS-D-15-00309.1.

Bothwell, P., J. Hart, and R. Thompson, 2002: An integrated three-dimensional objective analysis scheme in use at the Storm Prediction Center. *Preprints, 21st Conf. on Severe Local Storms/19th Conf. on Weather Analysis and Forecasting/15th Conf. on Numerical Weather Prediction.*, San Antonio, TX, Amer. Meteor. Soc., JP3.1, https://ams.confex.com/ams/pdfpapers/47482.pdf.

Bryan, G. H., and J. M. Fritsch, 2002: A benchmark simulation for moist nonhydrostatic numerical models. *Mon. Wea. Rev.*, **130**, 2917–2928, https://doi.org/10.1175/1520-0493(2002)130<2917:ABSFMN>2.0.CO;2.

Burroughs, L. A., T. R. King, and P. Alvstad, 2025: The impacts of wind shear on derecho development and maintenance. *24th Student Conference*, New Orleans, LA, Amer. Meteor. Soc., S220, https://ams.confex.com/ams/105ANNUAL/meetingapp.cgi/Paper/458831.

Cohen, A. E., M. C. Coniglio, S. F. Corfidi, and S. J. Corfidi, 2007: Discrimination of mesoscale convective system environments using sounding observations. *Wea. Forecasting*, **22**, 1045–1062, https://doi.org/10.1175/WAF1040.1.

Coniglio, M. C., and D. J. Stensrud, 2004: Interpreting the climatology of derechos. *Wea. Forecasting*, **19**, 595–605, https://doi.org/10.1175/1520-0434(2004)019<0595:ITCOD>2.0.CO;2.

Coniglio, M. C., D. J. Stensrud, and L. J. Wicker, 2006: Effects of upper-level shear on the structure and maintenance of strong quasi-linear mesoscale convective systems. *J. Atmos. Sci.*, **63**, 1231–1252, https://doi.org/10.1175/JAS3681.1.

Coniglio, M. C., H. E. Brooks, S. J. Weiss, and S. F. Corfidi, 2007: Forecasting the maintenance of quasi-linear mesoscale convective systems. *Wea. Forecasting*, **22**, 556–570, https://doi.org/10.1175/WAF1006.1.

Coniglio, M. C., S. F. Corfidi, and J. S. Kain, 2012: Views on applying RKW theory: An illustration using the 8 May 2009 derecho-producing convective system. *Mon. Wea. Rev.*, **140**, 1023–1043, https://doi.org/10.1175/MWR-D-11-00026.1.

Corfidi, S. F., M. C. Coniglio, A. E. Cohen, and C. M. Mead, 2016: A proposed revision to the definition of “derecho.” *Bull. Amer. Meteor. Soc.*, **97**, 935–949, https://doi.org/10.1175/BAMS-D-14-00254.1.

Evans, J. S., and C. A. Doswell III, 2001: Examination of derecho environments using proximity soundings. *Wea. Forecasting*, **16**, 329–342, https://doi.org/10.1175/1520-0434(2001)016<0329:EODEUP>2.0.CO;2.

Gallus, W. A., and A. C. Duhachek, 2022: Differences in near-storm parameters useful for forecasting intensity of nocturnal and diurnal bow echo winds. *Wea. Forecasting*, **37**, 2331–2347, https://doi.org/10.1175/WAF-D-21-0213.1.

Jirak, I. L., and W. R. Cotton, 2007: Observational analysis of the predictability of mesoscale convective systems. *Wea. Forecasting*, **22**, 813–838, https://doi.org/10.1175/WAF1012.1.

Johns, R. H., 1993: Meteorological conditions associated with bow echo development in convective storms. *Wea. Forecasting*, **8**, 294–299, https://doi.org/10.1175/1520-0434(1993)008<0294:MCAWBE>2.0.CO;2.

Johns, R. H., and W. D. Hirt, 1987: Derechos: Widespread convectively induced windstorms. *Wea. Forecasting*, **2**, 32–49, https://doi.org/10.1175/1520-0434(1987)002<0032:DWCIW>2.0.CO;2.

Lafore, J.-P., and M. W. Moncrieff, 1989: A numerical investigation of the organization and interaction of the convective and stratiform regions of tropical squall lines. *J. Atmos. Sci.*, **46**, 521–544, https://doi.org/10.1175/1520-0469(1989)046<0521:ANIOTO>2.0.CO;2.

Mauri, E. L., and W. A. Gallus Jr., 2021: Differences between severe and nonsevere warm-season, nocturnal bow echo environments. *Wea. Forecasting*, **36**, 53–74, https://doi.org/10.1175/WAF-D-20-0137.1.

Moncrieff, M. W., and Liu, C., 1999: Convection initiation by density currents: Role of convergence, shear, and dynamical organization. *Mon. Wea. Rev.*, **127 ,** 2455–2464, https://doi.org/10.1175/1520-0493(1999)127%3C2455:CIBDCR%3E2.0.CO;2.

Potvin, C. K., K. L. Elmore, and S. J. Weiss, 2010: Assessing the impacts of proximity sounding criteria on the climatology of significant tornado environments. *Wea. Forecasting*, **25**, 921–930, https://doi.org/10.1175/2010WAF2222368.1.

Ribeiro, B. Z., S. J. Weiss, and L. F. Bosart, 2024a: Short- and medium-range predictability of warm-season derechos. Part I: Operational predictability and composites. *Wea. Forecasting*, **39**, 1869–1887, https://doi.org/10.1175/WAF-D-23-0172.1.

Ribeiro, B. Z., S. J. Weiss, and L. F. Bosart, 2024b: Short- and medium-range predictability of warm-season derechos. Part II: Convection-allowing ensemble forecasts. *Wea. Forecasting*, **39**, 1889–1905, https://doi.org/10.1175/WAF-D-24-0052.1.

Rotunno, R., J. B. Klemp, and M. L. Weisman, 1988: A theory for strong, long-lived squall lines. *J. Atmos. Sci.*, **45**, 463–485, https://doi.org/10.1175/1520-0469(1988)045<0463:ATFSLL>2.0.CO;2.

Squitieri, B. J., A. R. Wade, and I. L. Jirak, 2025a: On a modified definition of a derecho. Part I: Construction of the definition and quantitative criteria for identifying future derechos over the contiguous United States. *Bull. Amer. Meteor. Soc.*, **106**, E84–E110, https://doi.org/10.1175/BAMS-D-24-0015.1.

Squitieri, B. J., A. R. Wade, and I. L. Jirak, 2025b: On a modified definition of a derecho. Part II: An updated spatial climatology of derechos across the contiguous United States. *Bull. Amer. Meteor. Soc.*, **106**, EOR, https://doi.org/10.1175/BAMS-D-24-0140.1.

Wade, A. R., B. J. Squitieri, and I. L. Jirak, 2023: 26-year climatology of severe wind-producing mesoscale convective systems in the United States. *32nd Conf. Weather Analysis and Forecasting,* Madison, WI, Amer. Meteor. Soc, 1.5, https://www.spc.noaa.gov/publications/wade/mcsclimo.pdf.

Wade, A. R., B. J. Squitieri, and I. L. Jirak, 2025: Synoptic characteristics of derechos and other widespread significant severe wind events. *Wea. Forecasting*, in revision.

Weisman, M. L., and R. Rotunno, 2004: “A theory for strong long-lived squall lines” revisited. *J. Atmos. Sci.*, **61**, 361–382, https://doi.org/10.1175/1520-0469(2004)061<0361:ATFSLS>2.0.CO;2.