Pre-Convective HSLC-Supercell Environmental Analysis from a Boundary-Layer Profiling Perspective

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ABSTRACT

Complex atmospheric environments in the southeastern United States cause obstacles in forecasting and awareness in severe weather prone locations. High-shear, low CAPE (HSLC) environments play a large role in complicating numerical weather prediction, operational forecasting, and warning processes. This can limit accuracy and further contribute to severe events in these regions becoming high impact events. One of the main explanations behind our lack of understanding about HSLC environments is due to the observation gap in the boundary layer. In efforts to address this gap, there have been developments of ground-based profiling platforms. Relevant data is reviewed from the mobile unit *CLAMPS* which provides high resolution profiles of temperature, moisture, and wind, similarly to radiosondes, but at much finer temporal scale. This case study analyzes the pre-convection environment before a discrete supercell passes over the unit to investigate the detailed environmental cues that lie within the boundary layer. This analysis also determined the amount of influence for each known factor in discrete mode convection, along with confirming previous results of another study regarding the rapid destabilization process thought to be important in the southeastern United States.

I. Introduction

The convective environment retains substantial complexity within the southeastern United States region characterized by high shear and low convection available potential energy, or CAPE (HSLC). This type of environment possesses variability in literature; an average interpretation is an environment that exhibits SBCAPE ≤ 1000 J kg^{-1} and shear from 0-3 km (i.e., King et al. 2017). HSLC environments are highly associated with large-scale forces with lifting for convection initiation associated with potent upper-level troughs, surface cyclones, and cold fronts (e.g., McAvoy et al. 2000; Cope 2004; Lane and Moore 2006; Wasula et al. 2008). Notorious conditions for 'traditional' U.S plains convection to produce severe weather differ from this class of weather setting. More 'traditional' environments are characterized by larger instability (SBCAPE<<1000 J kg^{-1}) and generally are in place for several hours. HSLC environments can evolve rapidly, with destabilization of the convective boundary layer (CBL) on the sub-hourly time scale.

Recently, studies have aimed to further the investigation of the environment of the southeast environment of the United States. Verification of the Origins of Rotation in Tornadoes Experiment-Southeast (VORTEX-SE) sought to bring many institutions and their researchers (including meteorologically-focused and social science focused scientists) to research storms, the conditions that produce severe weather, and the impacts these severe events on people. VORTEX-SE deployed various instruments across Alabama and neighboring southeastern states and recorded impactful events over the course of many years from 2016-2019.

No pre-convection environment is exactly the same. Multiple observation locations in a diversity of positions can exhibit the setting's unique properties. In complicated environments especially, understanding the physical process behind particular features and factors observed is important. Unknown processes and driving forces can be the reason why intricate environments are difficult to thoroughly understand. Bodies of water, topography, and soil properties and heterogeneity are some possible variables that can drive processes in pre-convection environments but are difficult to observe and separate from other processes completely to continue building upon current knowledge.

In order to learn new things, and begin to separate processes in complex environment, specialized observations are needed. When exploring the boundary layer section of the atmosphere, profiling is the best approach in collecting the highest-resolution data in the lower atmosphere. The existing observation network is often insufficient (in vertical-, horizontal-, and temporal- resolution) to fully characterize phenomena of interest, especially for the PBL (Wagner et al. 2019). Specifically, mobile remote sensing profiling facilities can alleviate other weather instrument limitations by providing detailed analyses of the evolution of kinematic and thermodynamic structure and stability of the lower troposphere in close proximity to events of interest in near real time (Wagner et al. 2019).

Several institutions have deployed specialized instrumentation to measure boundary-layer properties. The NOAA National Severe Storms Lab (NSSL) specifically built a new platform–a second iteration of the Collaborative Lower Atmospheric Mobile Profiling System (CLAMPS; Wagner et al. 2019)–to support VORTEX-SE objectives. CLAMPS provides state-of-the-art high vertical resolution profile properties at rapid time intervals. These data enable new perspectives and research opportunities.

Initial work has established definitive variations of the pre-convection environment across different convective modes using VORTEX-SE boundary layer profile observation datasets from multiple years of deployment (Pardun et al. 2021). The pre-convection boundary layer evolution was reviewed for linear, discrete, and mixed-mode storms. From this work, several cases of differing modes were compared and contrasted in regard to their environmental progression prior to each storm occurrence. Lapse rate was found to have the most influence in destabilizing discrete convective mode environments from a surface-based CAPE (SBCAPE) composite perspective (Pardun et al. 2021). Applicable conclusions made in the present work will be tested against this finding.

Convection that is characterized as discrete are areas of above-threshold reflectivity that generally contain a single dominant updraft (Smith et al. 2012). Studies have shown that discrete convective modes are more likely to become severe and produce tornadoes than other modes (Smith et al. 2012). In light of this, comprehensive case studies looking into the surrounding pre-convective environment for this particular type of convection may be found very useful for many applications.

The goal of this study is to examine pre-storm observations depicting the environment that reinforces supercell convection in the southeast U.S. Additionally, this research is an opportunity to evaluate hypothesized discrete mode behavior from the longitudinal work of Pardun et al. (2021) for a specific case.

II. Data & Methods

Most analysis herein relies on CLAMPS observation data. Two CLAMPS facilities are jointly operated by the University of Oklahoma and National Oceanic and Atmospheric Administration (NOAA) National Severe Storms Laboratory. Generally identical systems, CLAMPS is a portable boundary layer profiling unit in a trailer platform hosting multiple boundary-layer profiling instruments inside. CLAMPS-2 was funded by NOAA specifically as a part of the VORTEX-SE project (i.e., Wagner et al. 2019).

The instrumentation that retrieved the desired information were the atmospheric emitted radiance interferometer (AERI), microwave radiometer (MWR), and Doppler lidar. The AERI and MWR both make spectral radiance measurements in the infrared and microwave, respectively, which are used in an inverse radiative transform based physical retrieval. This retrieval is used to create temperature and water vapor profiles and estimates cloud properties and trace-gas concentrations. The resulting thermodynamic profiles are high-resolution near the surface, with decreasing resolution with height, and are available every few minutes, which is excellent for research (i.e., Wagner et al. 2019). The Doppler Lidar (DL) takes measurements along different azimuth and elevation directions using a 3D scanner to trace atmospheric motion. The DL can exploit the frequency shift of aerosol particles in motion to determine range and velocities of meteorological scatterers; hence, it can determine the profiles of the vertical and horizontal wind (e.g., Wagner et al. 2019). CLAMPS observation data for 2017 VORTEX-SE cases are available on the NCAR EOL Data Repository (https://www.eol.ucar.edu/field_projects/vortex-se).

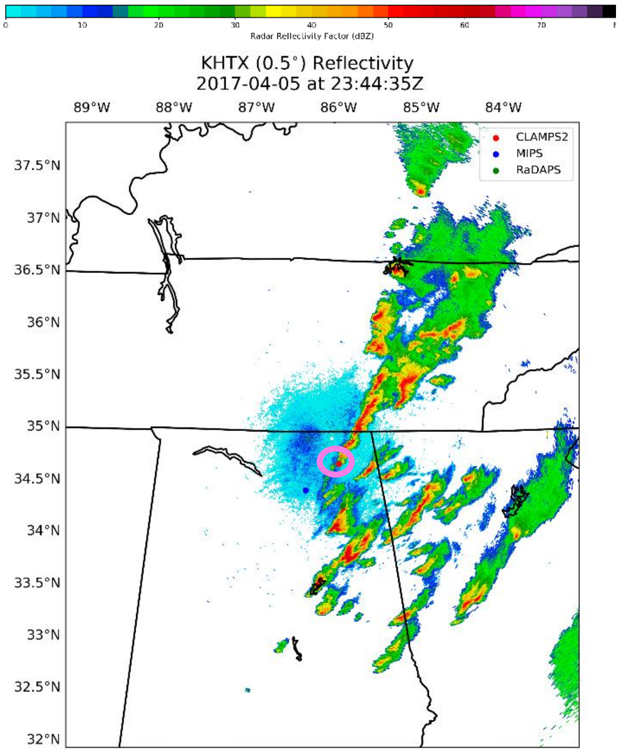

Fig 1: Radar satellite image of convection passage over CLAMPS (pink) [Image: VORTEX-SE 2017]

On 5 April 2017, A supercell thunderstorm directly passed over the CLAMPS deployment location at the Scottsboro Airport, Alabama (34.687 N, -86.005 W). Passage of the supercell occurred at approximately 23:45 UTC. To capture the progression of the boundary layer shifts between pre-convection to a convective state, minimum timescale must capture 2 to 6 hours before storm passage.

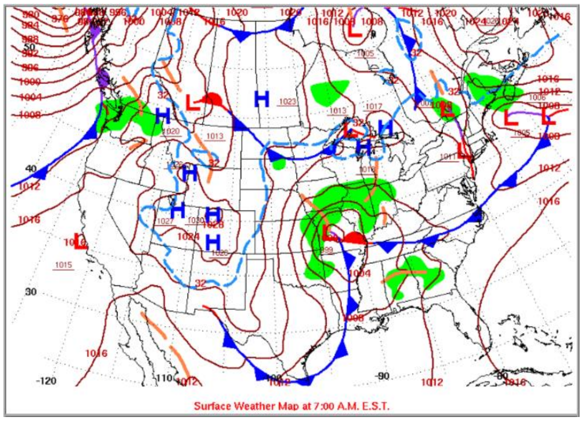

Fig 2: Surface weather on 04/05/2017 [map: NOAA Surface Weather Analysis]

Surface analysis of the case day was reviewed for further investigation. In the mid-afternoon at approximately 2:59pm CDT, the Storm Prediction Center (SPC) released an advisory about an outbreak of severe thunderstorms underway in portions of the Southeast. It was also mentioned that significant tornadoes with very large hail and damaging wind gusts were possible in eastern Alabama. Specifically discrete cells were ahead of the convection. It was stated that a few those cells could be strong, considering a warm/moist boundary-layer environment characterized by ample effective storm-relative helicity

Since the supercell of interest passed over the CLAMPS location, CLAMPS observations will be analyzed to explore the pre-convection environment during the 8 hours prior to storm passage. Thermodynamic and kinematic boundary layer observations will be examined to determine if there are signatures suggesting processes that support discrete mode convection and rapid environmental destabilization. The same observations will also be used to compare this single case of discrete mode convection pre-storm evolution to the composite environment hypotheses put forth by Pardun et al. (2021). These comparisons will include thermodynamic composites and SBCAPE and its contributions. All analysis was completed using the freely available Anaconda distribution of Python.

III. Results

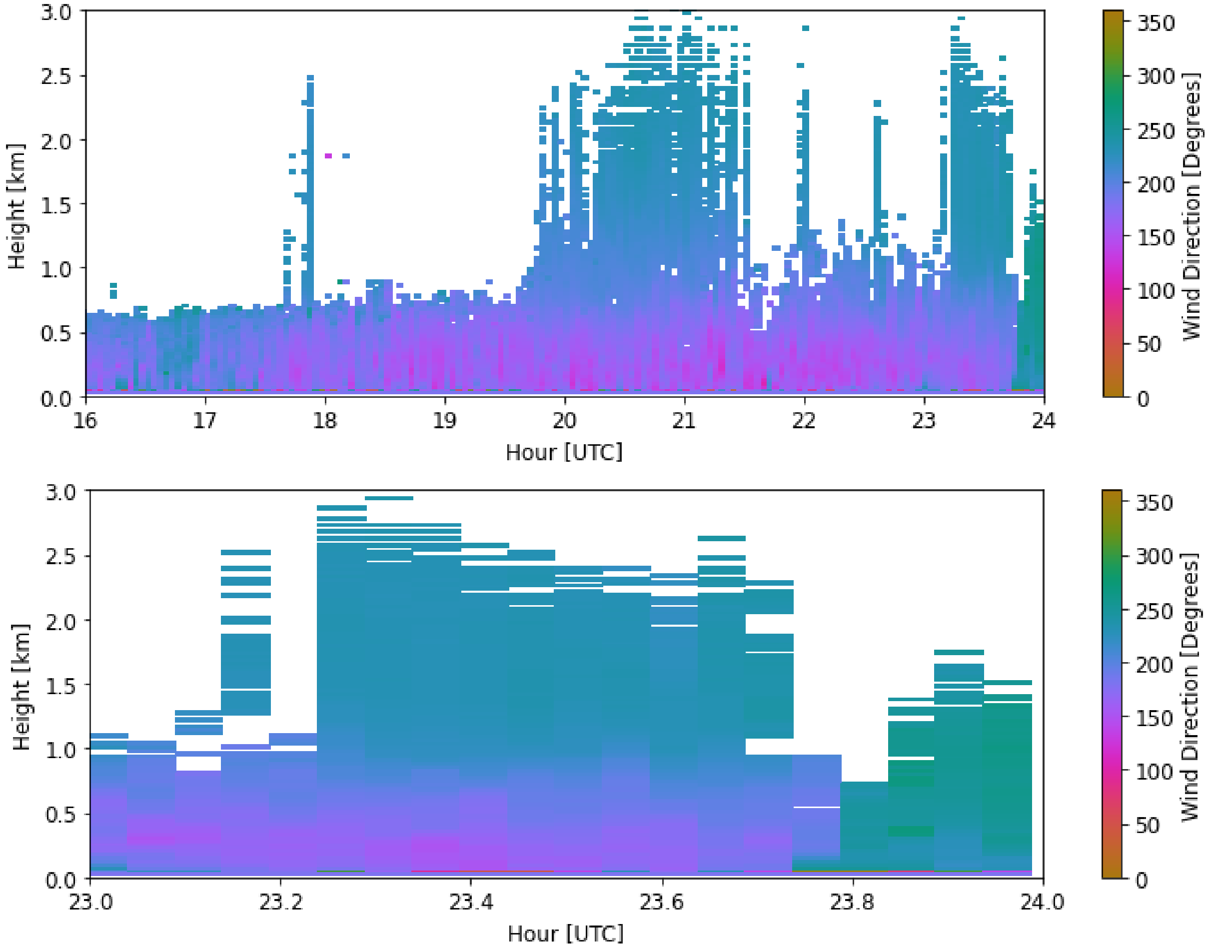

Fig 3: Wind direction time/height cross-section as observed by CLAMPS during the 8-hour pre-storm period (top) and focused on the near-stormenvironment 1 hour prior to storm passage (bottom).

CLAMPS observations show south easterly flow during the day. At approximately 23.8 UTC, there is a large shift in wind that switches to north easterly boundary passes and shows the supercell (or associated local boundaries such as outflow) passing over the observation location. The near storm environment diagram shows the shift more accurately at a closer viewpoint.

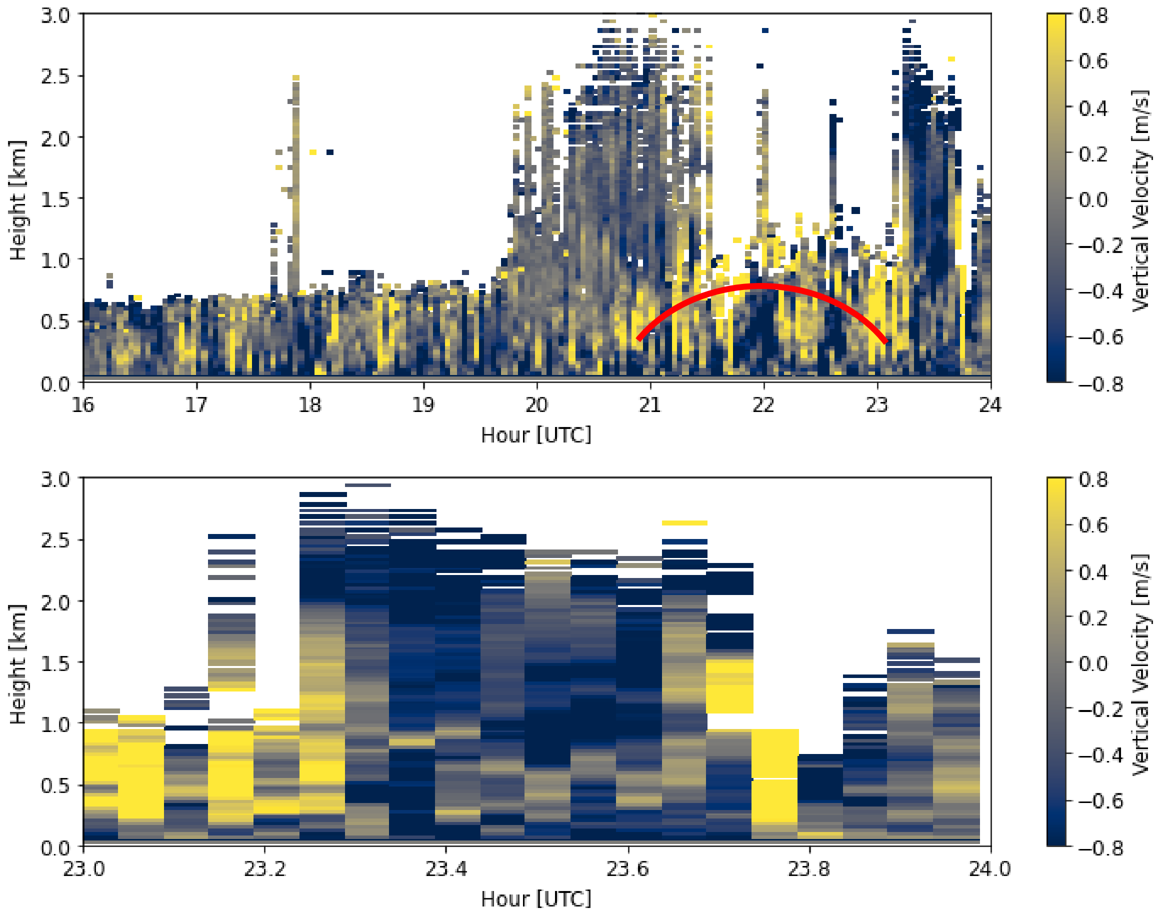

Fig 4: As in figure 3, now showingvertical velocity.

At the same time as the wind shift (about 23UTC), there is a sudden signal shown clearly in the near-storm diagram (Fig 4, bottom) where weak vertical velocity measurements give way to a strong positive motion as CLAMPS observed significant ascent. There is a prominent “arc” signal starting around 20z (red curve). Pardun et al. 2021 suggests arcs may be a trend for discrete convection. When present, the arc signal implies boundary layer mixing, well mixed thermodynamics, and thus an increased mixing height–all indications of destabilization in an environment ahead of discrete convection, and also lowering the lifted condensation level (LCL).

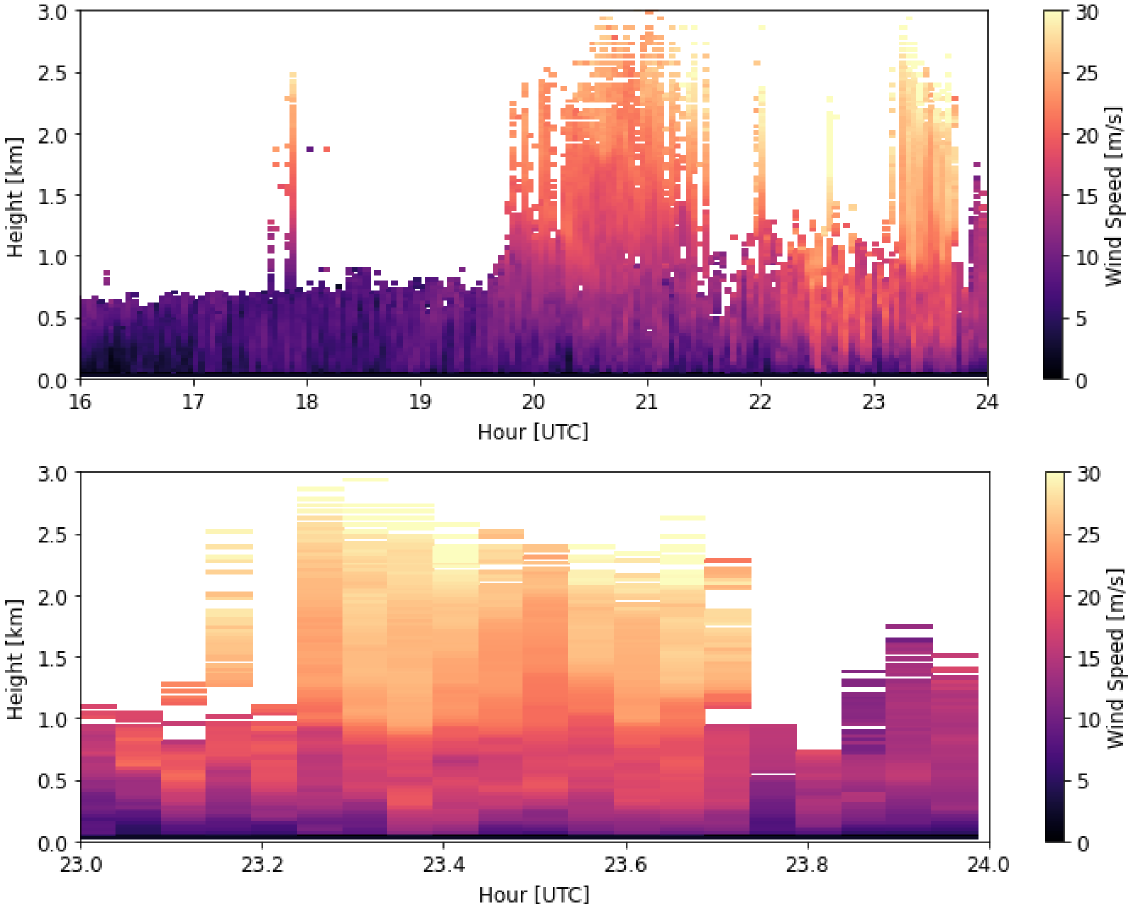

Fig 5: As in figure 3, now showing wind speed

Observed near-surface wind speed decreases from about 15 m/s to approximately 10 m/s.The wind speeds increase at 20UTC which enhances the wind shear prior to the storm. At 22UTC wind speed increases at about 500 m, specifically amplifying low level wind shear.The wind speed increases as mixing layer depth increases. Also, in the near-storm period, the storm inflow is likely observed (23.2-23.7 UTC increased winds from top moving downward with time).

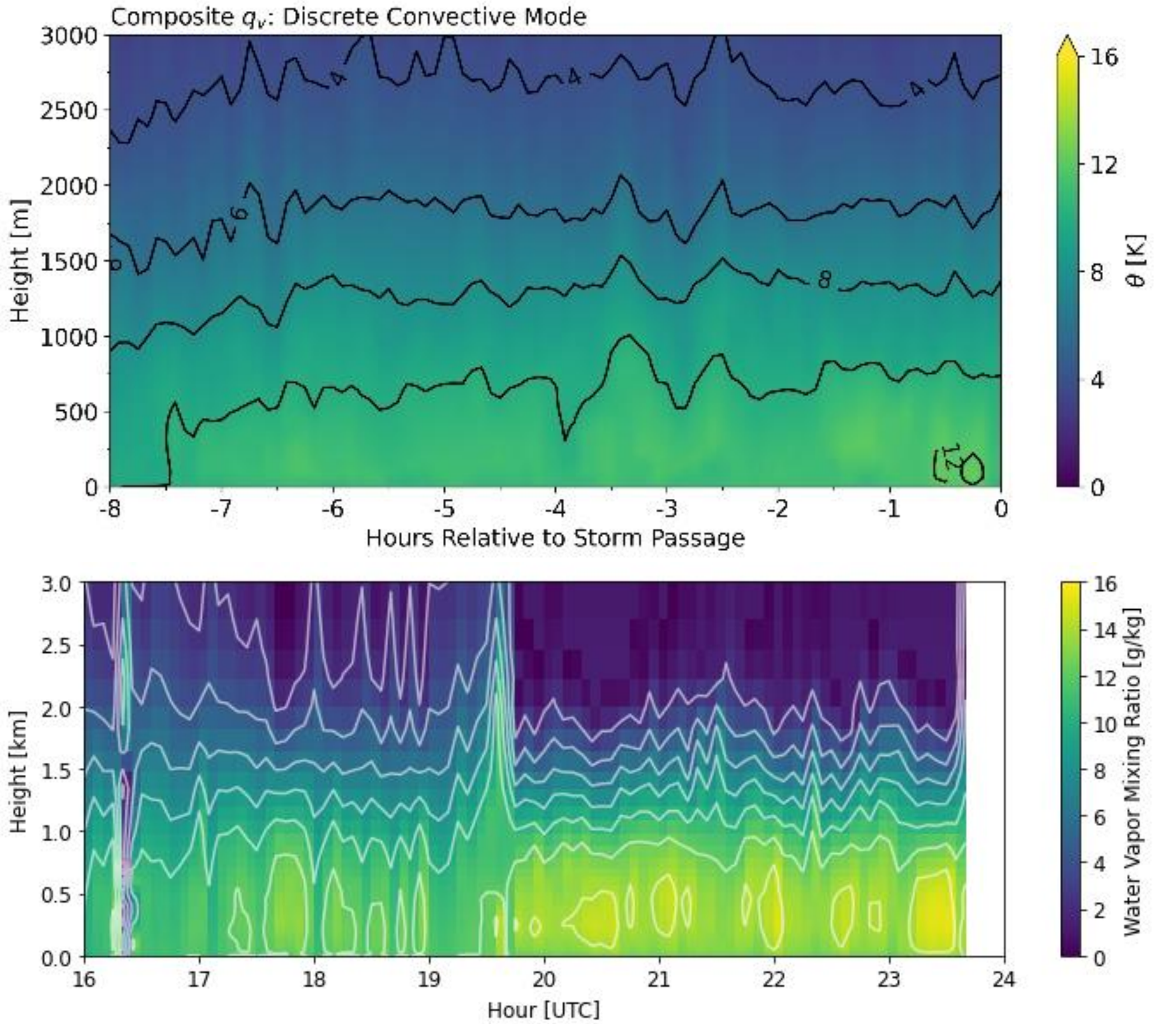

Fig 6: Moisture content time/height cross sections of previous composite case (top) and present individual case (bottom)

For the single case (bottom) there a large shift is evident around 20z. Pockets of moisture are observed in the lowest kilometer likely resulting from boundary layer mixing. Very similar gradients for both diagrams are present when viewing the largest amount of water vapor content near the surface. The moisture content increases comparably at around 20z. This is possibly a result of mixing and moist advection in lower altitudes, which assists environmental destabilization.

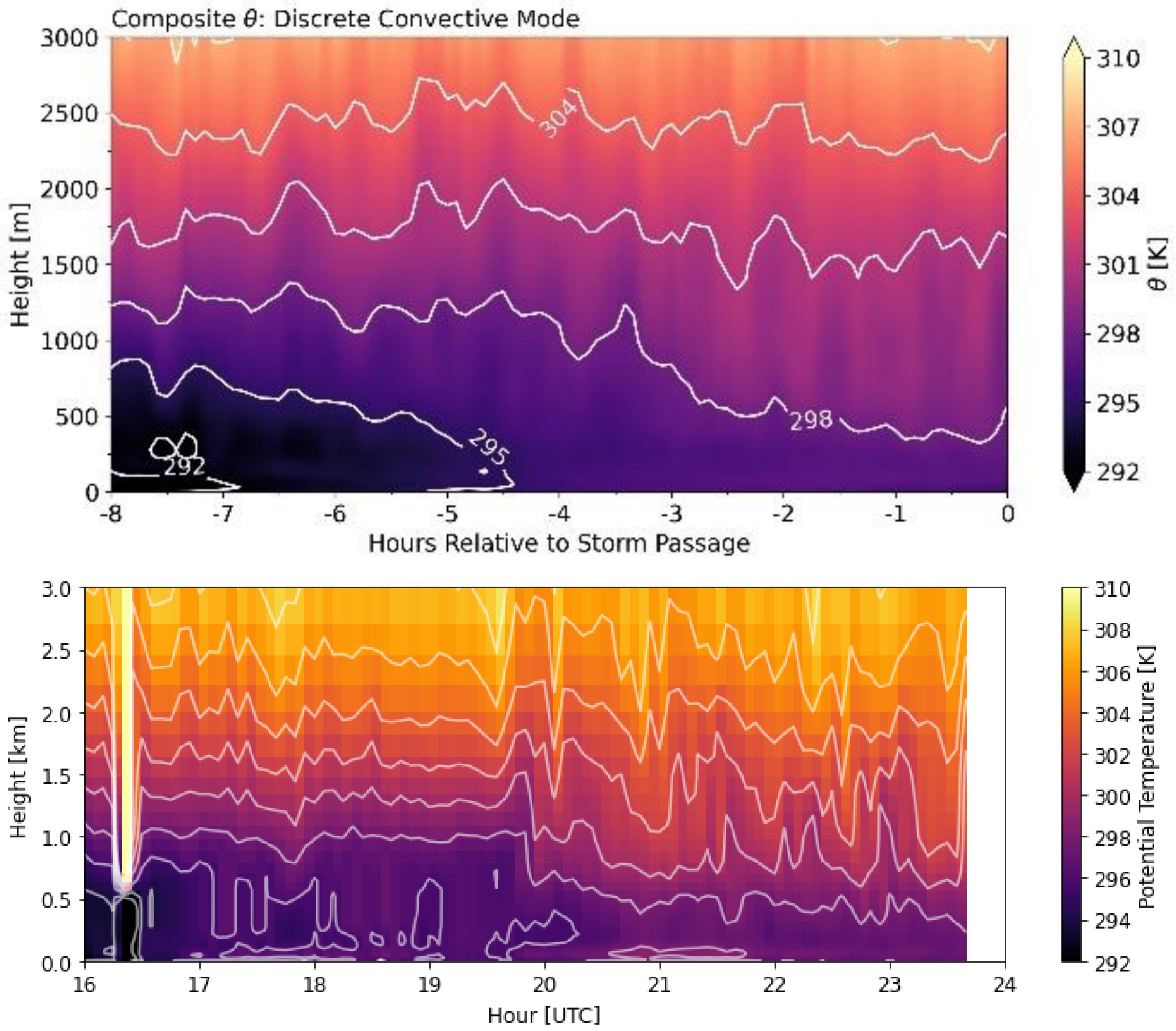

Fig 7: As in figure 6, now showing potential temperature.

Relatively similar potential temperature values represent the mixed layer in both the single case and the composite (Fig 7). For the single case (bottom), the mixed layer shown is about 0.5 – 0.75 km deep which accurately represents supercell conditions. For both cases, it is visible that the transition to the boundary layer becoming convective begins around 3 hours before storm passage.

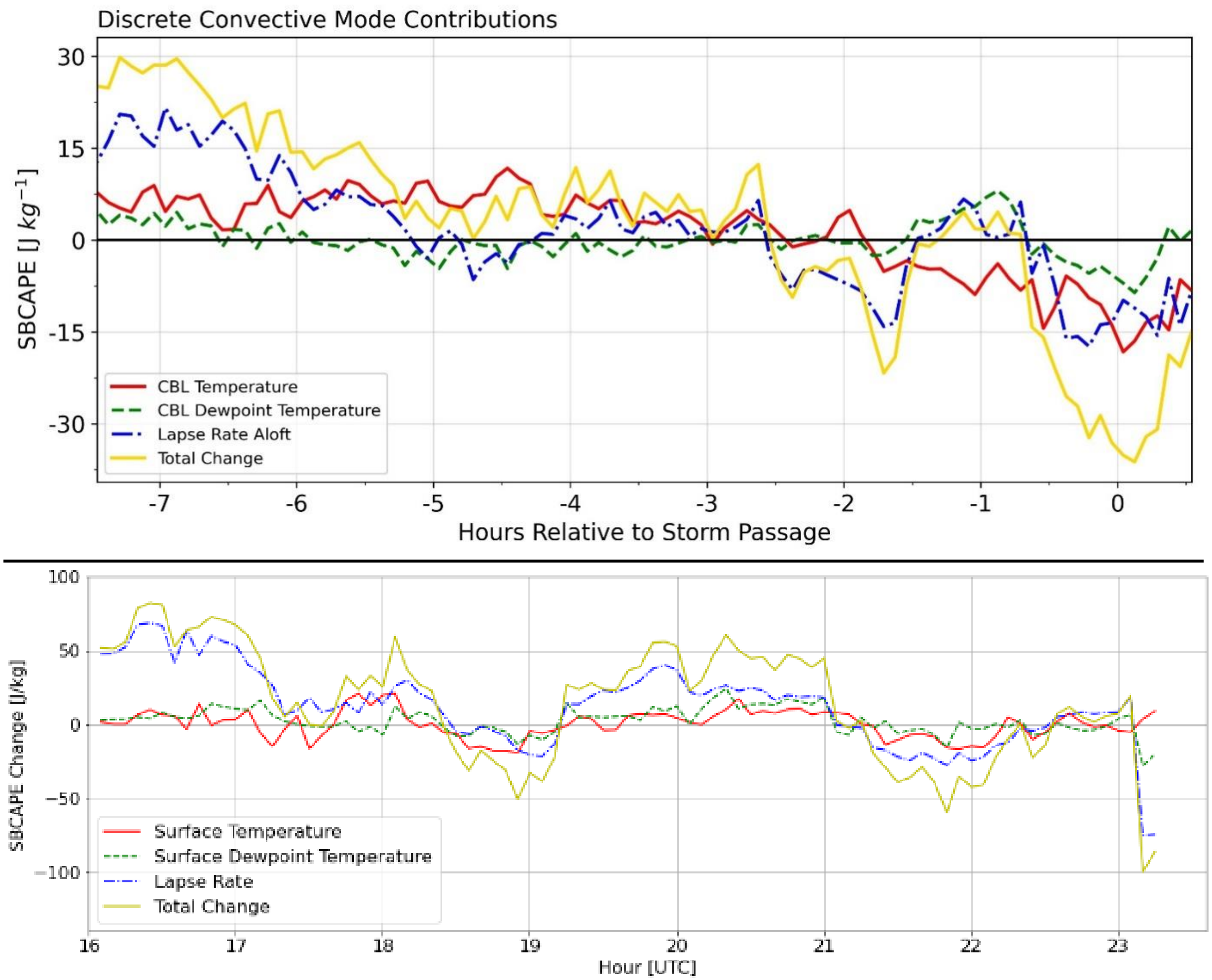

Fig 8: Surface-based convective available potential energy changes prior to storm passage for previous composite (top) & present individual case (bottom). Note the two panels do have different SBCAPE scales.

Results shown in figure 8 are the derivations of SBCAPE change over time and not *actual* values over pre-convection time period. The pockets of moisture seen in Fig 6 seem to have contributed for the supercell case (bottom) approximately 20 - 30 J/kg to the SBCAPE during the transition to convective state. The temperature also affected the progress by about 10 - 20 J/kg. The lapse rate is seen to contribute the most—up to 50 J/kg before convection state initiates. Interestingly, the general sinuosity of discrete convection appears to be very alike for the composite and individual case environments. The oscillation between destabilization and stabilization follows a similar pattern at around the same timeframes. This could potentially be a specific indication pattern for a discrete convection type, and supports the hypothesis put forth in Pardun et al. (2021).

IV. Summary & Discussion

Numerous results emerged from the discrete supercell case. Thermodynamic and kinematic boundary layer profiling observations at Scottsboro Airport produced interesting depictions of the pre-storm environment. Transition was prominent from pre-convection state to convective state around 20z, about 3 hours before the storm passes CLAMPS. After convection initiation, all variables examined had notable shifts in values. These multiple sources of convective support were found to have various amounts of influence.

Limitations were found while undergoing this study. Most constraints were associated with the instrumentation used. Doppler lidar has a limited effective range of 2 km (when pointed vertically), since outside the boundary layer the aerosol content is lower and can be limited further by low clouds and precipitation (Wagner et al. 2019), therefore both rain and cloud cover reduce data availability. The AERI has an automated precipitation-sensing hatch which can exclude data when the hatch closes for rain. Both units in general are not available for intra-storm environments. In consequence, incomplete data visualizations occur in diagrams since full time intervals were not entirely completed.

Likewise, considering the case study undergone was part of an undergraduate research program, time was especially a large restraint and inquiries could be reviewed farther. Both units in general are not available for intra-storm environments. In consequence, incomplete data visualizations occur in diagrams since full time intervals were not entirely completed. Likewise, considering the case study undergone was part of an undergraduate research program, time was especially a large restraint and inquiries could be reviewed farther.

Further research can possibly be done looking deeper into discrete convection SBCAPE derivations. There could be comparisons between individual cases of severe convection contrasting storms that produce tornadoes and storms that do not. Since there is a noticeable pattern in discrete cells, there is a chance that there can be a signal within the pattern that can identify definite tornadic cells, although it has not been looked into before at that extent. It could be considered for another study looking into a large number of discrete cases and carefully examining the oscillations.

From this research, it can be considered that comparing individual case studies can be found beneficial for understanding similarities and exclusivities within severe environments. Presently, research about southeast environments are primarily being completed through individual studies, with newer focus on *bulk* studies. From what work that has been executed so far, studying environments with such complexity has been somewhat limited with progressive results—in respect of small environmental variation analyses. The broadness of multi-case studies makes them inadequate to determine smaller sources of new propositions. Bringing bulk analysis and case specific analysis together appears to provide unique insight. Both composite and individual-type case context can hopefully lead to better understanding of the environment, along with forecasting tools in high-impact environments.

V. Acknowledgments

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